3D internal reconstruction of the case study

Laboratory investigations

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The main objective of the Heritage Within (HWITHIN) research project is to investigate what is hidden to our naked eye. One of the core actions of the project was to explore the use of Ground Penetrating Radar (GPR) and ultrasonic acoustic tomography to document and reconstruct precisely the interior of the constructive elements, almost on a stone-by-stone basis. However, precisely because it is not visible, the results obtained and the conclusions drawn cannot be verified with the reality.

In the case of the Carmo Convent, the structural elements under investigations are the neogothic compound piers of the main nave, reconstructed after the 1755 earthquake. There is insufficient information on the layout of the interior morphology of the pillar's cross-section. Additionally, finding relatable examples to compare to the compound pillars at the Carmo Convent are quite minimal, making it complicated for even initial assumptions to be established.

Therefore, the team decided to construct 1:1 stone replicas of parts of the neogothic stone masonry pillars (the shaft and the pedestal).

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The specimens were used to assess the feasibility and efficiency of the non-destructive tests applied (GPR and acoustic tomography) to determine the layout of their internal morphology. Since the cross-section of the real pillars of the Carmo Convent is unknown, the replica only precisely depicts the exterior layout of the columns. The shapes of the stones were established on initial guesses based on literature review. Once the limestones were cut, several cross-sectional set-ups were prepared, mainly accounting for a wide range of possible interior core materials (from fully empty core to a solid limestone block filling). Acoustic tomography was carried out for each assembly so that accurate comparisons between the tomographic maps could be made. Moreover, given the known inner composition of the laboratory specimens, the results can help to understand the potential of the tomographic techniques by comparing the results with the expected visible interior.

The present chapter shows some of the results obtained during the laboratory investigations, which were essential to interpret the ultrasonic tomography performed on-site at the old convent. The results confirm the potential of acoustic tomography techniques to convey an accurate idea of the cross-sectional elements within the pillar. The tomographic maps may not provide enough precision to determine exact dimensions of the materials and elements within the cross-section, but they can be complemented with GPR investigations and is always useful in a qualitative way, as it can provide information about the structural integrity of the materials and their arrangement.

Laboratory specimens

Two limestone specimens were built at the laboratory of the University of Minho (UMinho) to perform acoustic tomography tests at the laboratory. Both models represent the initial assumptions as to how the compound piers were arranged in reality. The first stone specimen represents a drum of the shaft of the compound piers, with the characteristic exterior curved shape, similar to what four cylindrical grouped columns might look like. The second specimen is composed of four rectangular stone blocks, allowing for simpler geometry and testing procedures. It corresponds to the assumption as to how the pedestal of the column would be built. Figure 1 depicts the two samples replicating the two parts of the piers of the Carmo.

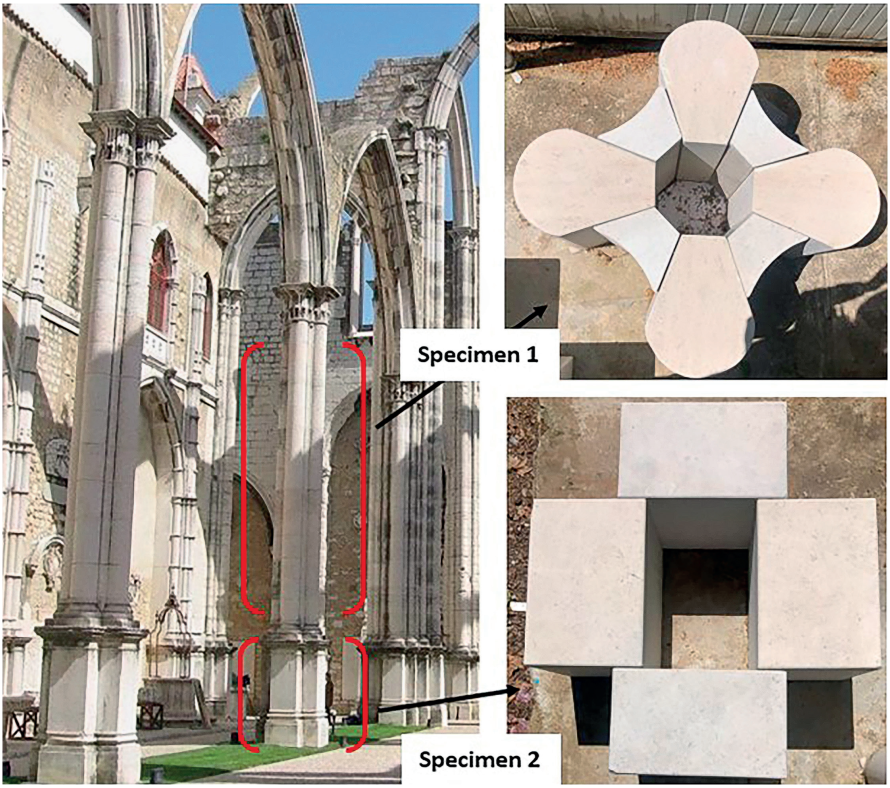


Figure 1. Lab test specimens replicas of different parts of existing piers: (1) shaft cross-section; and (2) pedestal cross-section.

Firstly, the team from the UMinho carried out sonic acoustic investigations on the stone masonry replica of the column shaft, varying the inner filling of the cross-section. Sonic and ultrasonic tomography are based on the same phenomena, consisting of evaluating the characteristics of the propagation of acoustic waves (either sonic or ultrasonic) through a construction element. Because of the different frequency of the sonic waves with respect to the ultrasonic waves, they can perform better in different situations. For example, sonic waves can reach longer distances while ultrasonic waves can provide more precise information but will not travel as far through dispersive (non-homogenous) media.

At a later stage, the CSIC/UPM group also came to the laboratory of the UMinho and performed some tomographic investigations on the lab stone specimens using the novel acoustic tomography automatic system. They carried out tomographic surveys of both specimens (shaft and pedestal) in an automatized way and experimented with different inner fillings (empty, mortared core, limestone block filling and even water filling).

Sonic tomography investigations on the lab specimens

With the intention of obtaining a better understanding of the ability of tomographic investigations to recognize different materials and inner arrangements, various materials and configurations were tested within the core of the study specimen. Five different configurations were constructed, and sonic tomography tests were carried out in each of them: (1) empty core and dry joints; (2) rubble filled core and dry joints; (3) sand filled core and dry joints; (4) limestone block core and dry joints; and (5) rubble mortar filled core and mortar filled joints. The different configurations are shown in Figure 2.

The tomography tests are carried out by placing the transmitter of the wave (instrumented hammer) on one specific point of the perimeter. Receiver transducers (accelerometers) are placed on different points covering the whole accessible perimeter of the specimen. Then, the transmitter is moved to another location and receiver transducers are again placed along the whole perimeter. As a result, a series of ray paths are obtained that cover the entire cross-section of the element. The time measurements of the waves traveling through are recorded from one point to another. The time measurements are then processed together and undergo an iterative inversion method in which a velocity

Figure 2. Different inner core configurations for the shaft specimen evaluated with the sonic tomography investigations.

distribution field can be determined within the material. The iterative procedure is meant to reduce the residuals until reaching convergence and the real-time is practically equivalent to the calculated time.

The velocity distribution map is displayed in a series of pixels representing a small area of the material sample. In this case, the pixels show the velocity value that it takes for a wave to pass through this area. Low wave velocity values typically indicate the probable presence of defects, voids, and obstacles. Increasing the number of pixels will create a more refined image, just as increasing the number of investigative points initially along the perimeter will usually produce better resolution. In these investigations, a total of 56 points were distributed along the perimeter.

The sonic tomographic tests resulted in velocity distribution maps for the different core filling configurations that can be compared with each other (Figure 3). The comparison helps to understand the effectiveness of this method for studying the cross-section of masonry pillars. Even though the exact dimensions of the limestone blocks are not precisely captured, the tomography is sensitive to the change of material in the inner core. Results for the specimen with empty core and dry joints show low velocities throughout the core and surroundings. When the inner core is filled with a solid limestone (specimen 4), the overall velocities throughout the core are significantly higher. Moreover, the high velocities in the core area indicate clearly that there is solid stone within its center.

On the other hand, the technique is not so sensitive to variations of loose heterogeneous material (e.g. rubble and sand materials). The technique is able to recognize the presence of a material (higher velocities at the core when compared with specimen 1), but the differences are subtle and might not be noticeable enough to make proper correlations and predictions on-site. The tests performed on the configuration with the rubble mortar core and mortared joints are particularly clear. Overall higher velocities indicate the presence of mortar filling the voids and

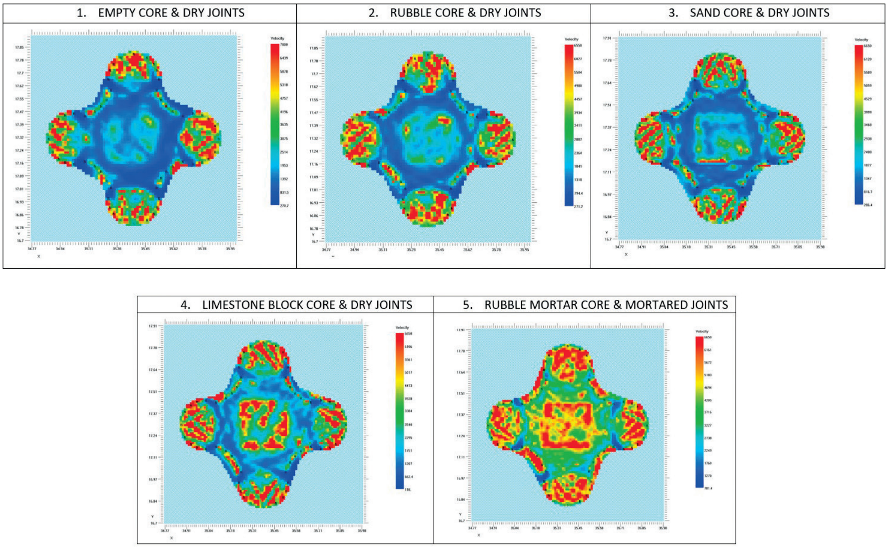


Figure 3. General comparison of sonic tomography results on the shaft specimen with different core filing configurations.

providing continuity to the medium. The internal core was also visibly filled with dense material and the joints between stone blocks can be clearly detected.

Fast sonic tomography investigations on the Carmo Convent

After the laboratory investigations, additional sonic tomography inspections were carried out at the Archaeological Museum of Carmo. The idea was to carry out fast manual measurements to have a direct comparison with the results obtained at the laboratory. Two columns were inspected: (1) the shaft of the reconstructed columns at the main nave that were also inspected with the ultrasonic tomography automatic system; and (2) the shaft of one of the two remaining original gothic half-columns at the west façade.

Fewer points were chosen along the perimeter (24 for the reconstructed pier and 11 for the original gothic columns). Nevertheless, results were conclusive (Figure 4a), as the difference with the lab specimens was clear. In the case of the reconstructed pier, the results show a homogeneous high velocity map throughout the whole specimen. No joints are evident and there is no clear distinction of a possible core. These results confirm the results obtained with the ultrasonic investigation, showing that the shaft is probably constituted by single blocks of limestone.

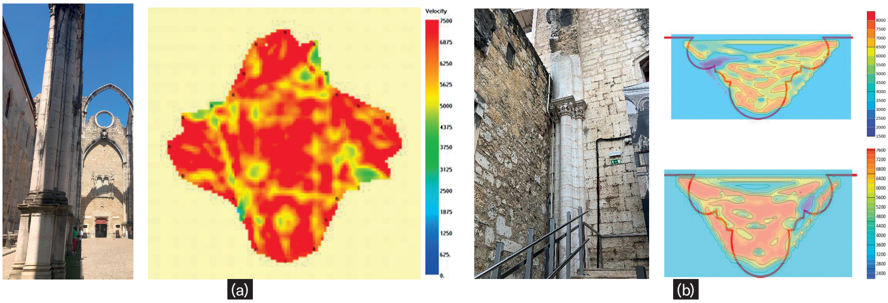


Figure 4. Sonic tomography results obtained on-site at the Archaological Museum of Carmo: (a) test performed on the reconstructed pier; and (b) tests performed on the original gothic column.

The tests performed on the original gothic columns (Figure 4b) are also revealing. In this case, the presence of the joint between the stone blocks is clearly detectable. The joints are visible from the exterior and the results indicate that they extend through the thickness. Possibly, each drum of the gothic column is composed of two blocks that alternate position along the height to guarantee better stability.

Ultrasonic tomography investigations on the lab specimens

Ultrasonic Tomography System (UTS) previously used to inspect the columns of Convent do Carmo was used to inspect the stone specimens. Figure 5 and 6 show the experimental setup in the pedestal and shaft specimens, respectively.

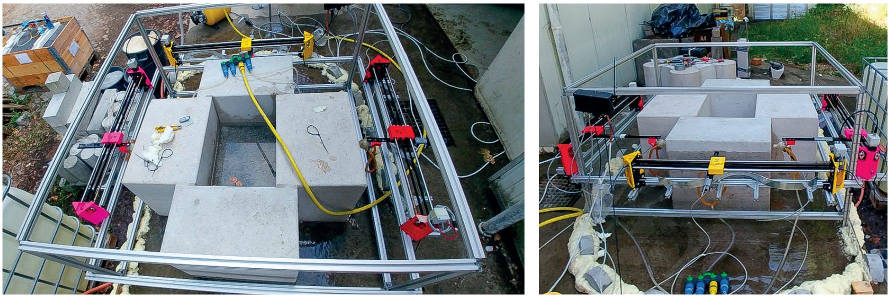


Figure 5. Ultrasonic tomography system on the pedestal specimen.

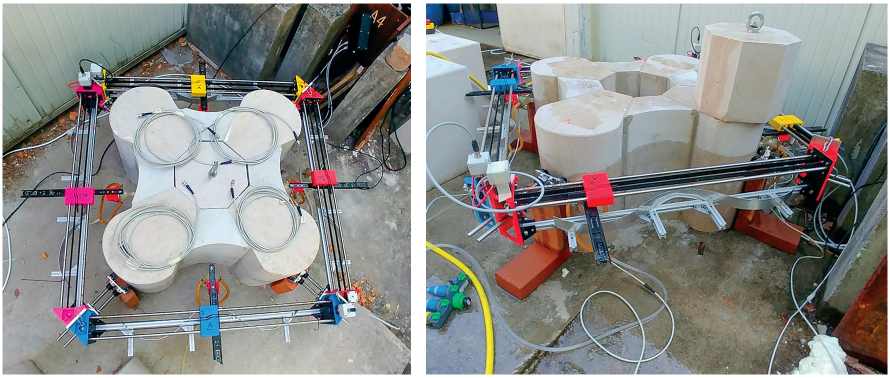


Figure 6. Ultrasonic tomography system on the shaft specimen.

Ultrasonic tomography tests on the pedestal specimen were made only in one block at three different heights corresponding to: empty core, mortar filled core and water filled core. It was impossible to inspect the internal face of the blocks due to the size of the nozzles. In Figure 7, the amplitude images of the received signal in one block of the pedestal specimens with different cores are shown, the blue color indicates high amplitude of the signal. The great regularity of the stone can be verified, in general, although small differences in amplitude are appreciated both in one of its corners and in the different heights inspected. It was not possible to see differences between the internal cores inspected because the ultrasonic waves do not propagate through it.

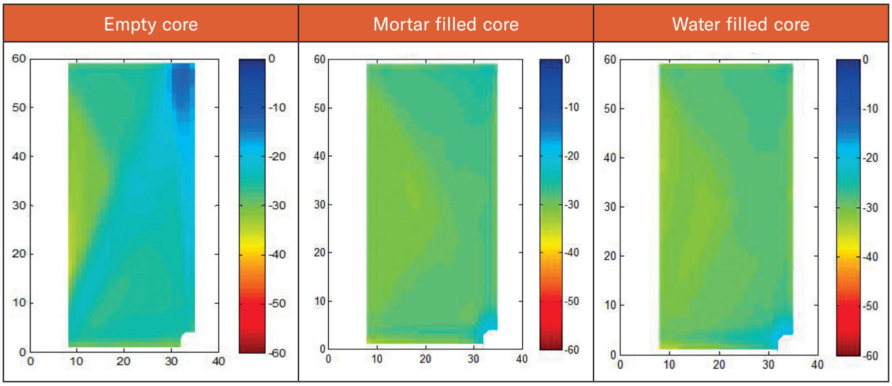
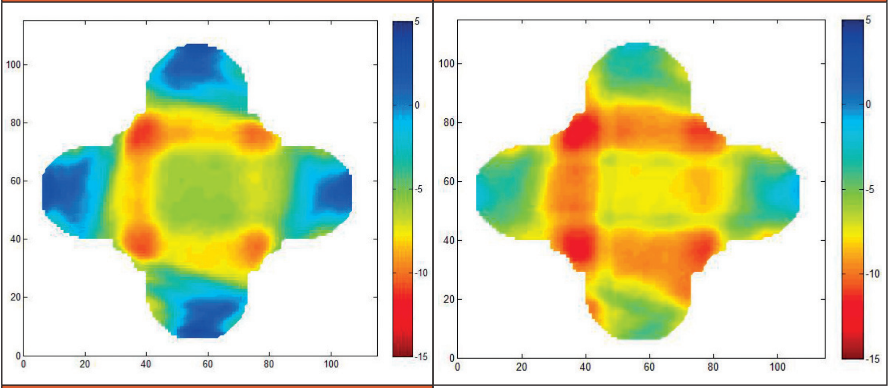


Figure 7. Ultrasonic tomography images from different configurations of one block of the pedestal specimen.

The tomographic reconstruction, as we have seen in chapter 5, is generated by the composition of all the ultrasonic rays that pass through the structure. In the case of the shaft specimen, most of the rays should pass through the core, therefore, in these tests, the core is filled with different materials to study the ultrasonic wave propagation. Ultrasonic tomography tests on the shaft specimen were carried out in three different configurations: empty core, limestone block core and rubble mortar filled core. In these inspections, all joints of the shaft specimen were sealed with mortar.

Figure 8 shows the amplitude tomography images of different configurations of the specimen shaft. Ultrasounds at the frequency used practically do not pass through the air and therefore when the core is empty, see Figure 8a. The same occurs when there is a layer of air between the stone blocks, see Figure 8b, the core will create a shadow in the adjacent areas, as seen perfectly reflected in the highly attenuated orange ring that appears in both cases, Figure 8a and 8b. In Figure 8c the ultrasonic waves can travel through the internal core and the shadow is lower.


a) empty core

b) limestone block core

c) rubble mortar filled core

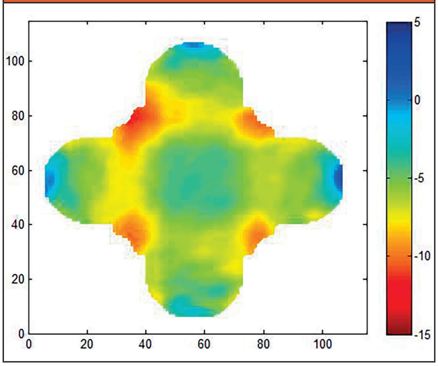


Figure 8. Ultrasonic tomography images from different configurations of the shaft specimen.