Exploring portable Ultrasonic Pulse Velocity avails in the Conservation Assessment of Plaster Sculptures in Museum Environment

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Abstract

Ultrasonic pulse velocity (UPV) is generally used in Civil Engineering as an *in situ* and non-destructive methodology to assess the condition of construction materials. Given the fact that non-contemporary sculpture was traditionally made with similar materials – stone, wood, clay or plaster – a hypothesis arose regarding the possible contribution of UPV for the conservation assessment of sculptures with stone-based materials. Plaster is a fragile material, very susceptible to internal and external fractures, alterations and losses. Museum sculptures cannot be moved to a laboratory, due to conservation protocols and therefore portable UPV could, in theory, play an important role in assessing these artistic structures *in situ*. There are scarce references to such a methodology, and its implementation implied a partnership with Soares dos Reis National Museum (Porto, Portugal) for an experimental approach to three plaster sculptures made by A. Soares dos Reis: "St. Joseph", "St. Joachim" (both made in 1880) and "Narcissus" (1881). The aim of this study was to assess if portable UPV could help to detect superficial and internal damages and differences between the original plaster and added materials.

Keywords

UPV, Sculpture, Plaster, Conservation, Museum, Soares dos Reis.

1. Introduction

The National Museum Soares dos Reis (NMSR), in Porto, Portugal, houses numerous treasures and unique pieces of artwork in its collections. Beyond the ancient building itself and the collections of silver tableware, of 16th-20th century Portuguese ceramics, of the paintings of Portuguese artists from 19th century, the museum shelters monumental statues (1m to 3m high) sculpted by António Soares do Reis (1847-1889).

Soares dos Reis is one of the most notable Portuguese sculptors. He graduated at Porto Academy of Fine Arts, and then studied at École des Beaux-Arts in Paris, from 1867 to 1870, and afterward, in Rome. He won several international prizes and became a professor at Porto Academy of Fine Arts. His work is recognized worldwide and represents a very important example of the European 19th century realist sculpture. The main part of his finest collection is held at the NMSR.

Some of his most interesting works had to be made of plaster beforehand, as plaster is a necessary intermediate step in sculpture, but studies dealing with plaster artworks are almost inexistent, despite several European museums possess large collections of plaster works. These artworks used to be considered secondary, since they were copies, moulds, studies or proofs.

The properties of plaster are mainly due its porosity, which is tailored by the weight ratio water/plaster (W/P). Higher porosity turns it more reactive (by increasing the contact area) and more brittle (the voids are defects in the matter) [Kingery, 1976]. The porosity can also foster the adsorption of impurities, flying particles, and the development of microorganisms [Potgieter-Vermaak et al., 2005]. The main published works deal with the cleaning and the conservation of plaster sculptures [Kuntze, 1984; Doulgeridis & Kliafa, 2006; Wolbers & Little. 2007; Beale et al. 1977]. The proper conditions for exposition in museums and the specificity of each plaster block demand a deep study in order to identify its physical and chemical damages and the causes of degradation, but a general or systematic recipe is still lacking [Kuntze, 1984; Palha et al., 2012].

2. Overview of UPV and its application on Cultural Heritage

Ultrasound Pulse Velocity technique (UPV) is a nondestructive technique of common use in civil engineering and other areas to assess the integrity and quality of structural concrete, stone, metal, wood and other hard materials, by measuring the speed and attenuation of ultrasonic waves passing through the element being tested [Lawson et al., 2011].

The UPV technique consists of introducing a pulse or a train of pulses of ultrasonic longitudinal waves through a transducer into one surface of the material, which then travel through the material and are received by another transducer on another surface, with the transit time (or the Time of Flight - ToF) of the pulses being measured by the instrument, and this procedure is repeated at least twice. The distance between the centres of the transducers, *d*, is divided by the average ToF to obtain the pulse velocity:

$$V = \frac{d}{ToF} \quad (1)$$

In general, the velocity of mechanical vibration propagation for each material is dependent on the balance between the elastic and inertia coefficients, as described by the expression:

$$V = \sqrt{\frac{coefficient\ of\ elasticity}{coefficient\ of\ inertia}} \quad (2)$$

For solids, the coefficient of elasticity, also known as the elastic modulus or Young's modulus *Y*, is a measure of the material's stiffness and its ability to resist deformation when subjected to external forces. A higher Young's modulus, which characterizes the rigidity of a body, contributes to a greater velocity of propagation, while an increase in density (or volumetric mass) ρ increases inertia and reduces the velocity of propagation. Therefore, equation (2) can be expressed as:

$$V = \sqrt{\frac{Y}{\rho}} \quad (3)$$

Measuring the velocity of propagation of ultrasounds in materials allows for assessing their integrity, particularly the presence of cracks or discontinuities (which may result in empty time readings), voids (which may cause lower calculated velocities than in solid material), or the presence of intercalated materials. In such cases, the measured velocities may be higher or lower than those of the material being inspected, depending on the characteristics (rigidity and density) of the foreign material.

In recent years UPV has been applied on artworks. Marble, wood and other materials have been tested by ultrasonic probing techniques in order to assess the level of degradation, namely rock sculptures located at open air subject to weathering conditions [Pamplona et al., 2010; Akoglu et al., 2020].

A study on Michellangelo's masterpiece, David, made of Carrara marble, has allowed to better define the severity of the cracks present on the legs [Pascale et al., 2015].

Combining the inspiration of the research on David with the expertise within our team to perform UPV on concrete and rock [Vasconcelos et al., 2008], this work proposes an exploratory approach to evaluate the use of UPV to assess the conservation condition of plaster artworks.

No previous references of UPV application on plaster artworks were known to the authors in the beginning of this project. The literature provides wide ranges of values for the velocity of sonic or ultrasonic waves in plaster, from less than 1000 m/s measured in decorative ancient plasters, dating back to the Celjuk period [Caner, 2003], to modern gypsum building plasters presenting velocities up to 2400 m/s [Lanzón & García-Ruiz, 2012]. Wang et al. [Wang et al., 2017] provide a detailed description of their methodology and findings on the application of UPV technique to mortars with ultrasound velocities ranging from 3315 m/s to 3926 m/s.

3. Experimental techniques and procedures

Plaster rods were cast and tested in the laboratory to assess their ability to sustain ultrasonic pulses, to measure the velocity of propagation and to try coupling materials different from the gels used on concrete and rock.

The experimental apparatus used for this work consists on a portable Proceq Pundit Lab (+), which comes with two pairs of transducers of different operating frequencies. The larger transducers have 2'' in diameter (approximately 5 cm) and operate at a frequency of 54 kHz. The other set of transducers have a diameter of 1'' (approximately 2,54 mm) and the frequency is 150 kHz. For the sake of simplicity, the two sets of transducers will be addressed as big and small when presenting the data collected.

There are three possible arrangements to mount the transducers as is depicted in Figure 1. The direct transmission is the most accurate but of limited use in plaster sculptures, due to the varying shapes of the surfaces (making it very difficult to find suitable places to place the transducers) and due to the presence of internal voids which may lead to signal attenuation or extinction, because of the longer path of the waves inside the material relative to the direct distance between the transducers. The indirect transmission is not as accurate, as the path length is uncertain and the amplitude of the signal is much lower when compared to the direct transmission. However, this arrangement was easier to set up as the shapes of our subjects leave not much room to put the transducers to work otherwise. And finally, there is the semi-direct, with a precision in between the other two methods.

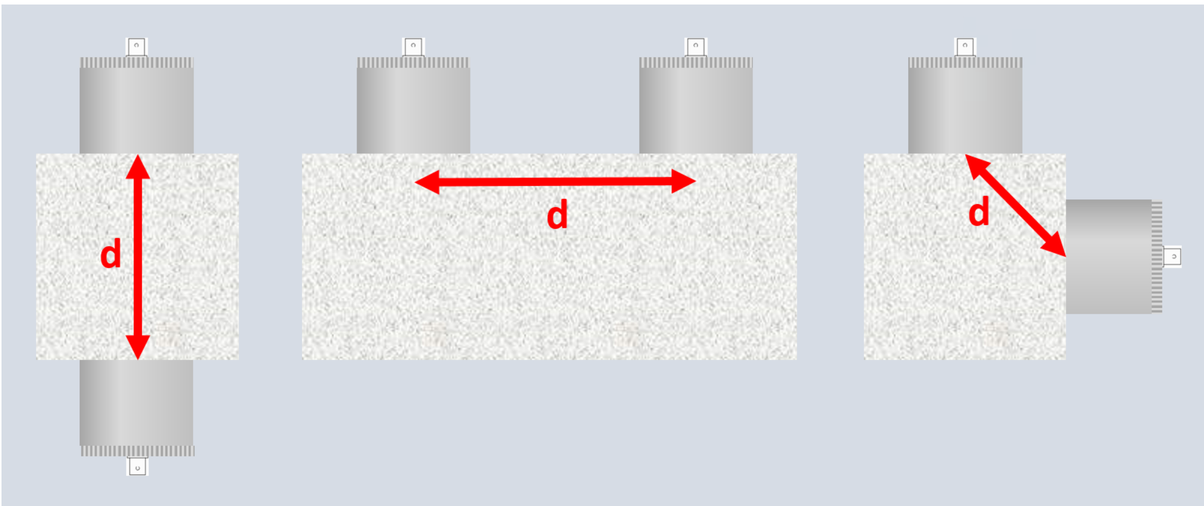

Figure 1 – Different types of measurements:
a) direct, b) indirect and c) semi-direct. ***d*** is the distance between the centres of the transducers.

Good mechanical coupling between the transducers and the surfaces is required. This enables to transmit and receive efficiently the vibrations between the transducers and the surface of the artwork. If the contact area is reduced because of superficial irregularities, porosity, or its curvy shape, in the interfaces will occur mainly reflection than transmission and the quality of the signal is degraded and may be lost. Ordinary groom stick used to make superficial cleaning of plasters has proven to be just fine for this purpose.

4. Selection of the artworks for UPV trials

At MNSR, Porto, three plaster artworks by Soares dos Reis were probed by UPV: St. Joseph (Figure 2), St. Joachim (Figure 3), both made in 1880, and Narcissus from 1881 (Figure

4). The first two were made as working references for the final granite sculptures that were commissioned for the Capela do Divino Coração at Capela dos Pestanas (Almada Street, Porto). The last one was created to support his application as a professor to Porto Academy of Fine Arts. The plaster originals were offered by Soares dos Reis himself to the Academy.

Even though these pieces present a satisfactory conservation state, suitable to be publicly exhibited, a first visual inspection has shown some damage to their bases, such as fractures repaired with some kind of hard cement. St. Joseph also shows a few scratches on the front side and some areas with a slightly different colour on the backside, denouncing superficial restorations. St. Joachim has some superficial restorations in the front and Narcissus has some damage to his right leg. There are no records of previous damage identification, reparation works or materials used for any of these plasters.

Figure 2 – St. Joseph (1880), Soares dos Reis, plaster, height: 172cm, width 70 cm, depth 46 cm. Museu Nacional Soares dos Reis, Porto, Portugal. Inventory sheet: http://www.matriznet.dgpc.pt/MatrizNet/Objectos/ObjectosConsultar.aspx?IdReg=309247

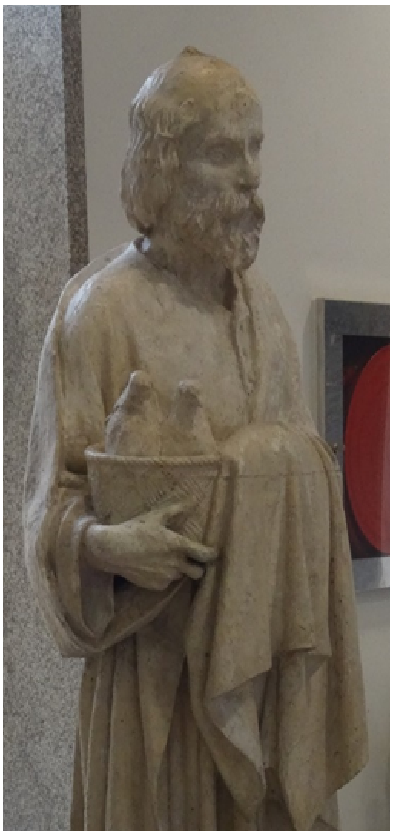

Figure 3 – St. Joachim (1880), Soares dos Reis, plaster, height 174 cm, width 65 cm, depth 45,5 cm. Museu Nacional Soares dos Reis, Porto, Portugal. Inventory sheet: http://www.matriznet.dgpc.pt/MatrizNet/Objectos/ObjectosConsultar.aspx?IdReg=309248

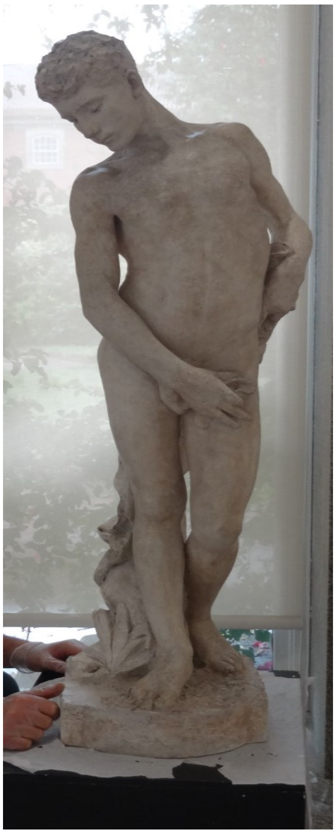

Figure 4 – Narcissus (1881), Soares dos Reis, plaster, height 120 cm, width 37 cm, depth 35 cm. Museu Nacional Soares dos Reis, Porto, Portugal. Inventory sheet: http://www.matriznet.dgpc.pt/MatrizNet/Objectos/ObjectosConsultar.aspx?IdReg=307662

5. Results and data analysis

5.1. Laboratorial tests

To evaluate the adaptability of UPV to plaster, to test different coupling materials, and to determine the velocity of ultrasonic wave propagation in plaster, preliminary laboratory tests were conducted using plaster rods measuring 15.7x4x4 cm³.

Several specimens were produced by mixing plaster of Paris (calcium sulfate hemihydrate - $CaSO_4$, $0.5H_2O$) purchased from SIGEL (Portugal) with water, using different water/plaster weight ratios (W/P) such as 0.7, 0.75, 0.8, and 0.85. For each ratio, three sample rods were fabricated.

To ensure efficient transmission of vibrations between the transducers and the materials being tested, a mechanical couplant is necessary. Typically, gels or silicon-based greases are used to fill the superficial pores of the material and create a thin film to maximize the contact patch between the surfaces of the material and the transducers. However, for artworks, a gel or grease is not a viable option. Therefore, several plasticine-like materials were tried and showed to be suitable mechanical couplers, even though they created a thick layer between the contact areas. Moreover, they didn't leave any stains on the surfaces of the plaster rods.

In order to determine the ultrasound velocity of each rod, the distance between the centres of the transducers was measured and the time of flight (ToF) readings were taken three times. The average ToF value is then used to calculate the velocity, as per equation (1).

Table 1 shows the average ultrasound velocity for each W/P ratio, obtained through direct measurements with small transducers (f=150 kHz).

Table 1 – Direct measurements with small transducers - Average ultrasound velocity for different water/plaster (W/P) ratios.

W/P (%)	Average ultrasound velocity (m/s)
70	2295
75	2386
80	2419
85	2319

Globally, the average ultrasound velocity measurements for the plaster samples tested at different W/P ratios lie in the range of 2350 ± 100 m/s. Changing the type of transducers (Big instead of small) and performing indirect or semi-direct measurements did not yield significant differences in the results.

To assess the effect of internal cracks on the UPV signal, a partial cut was made using a manual saw on two samples with W/P ratio of 85. One sample was cut vertically, creating a channel with a depth of 2.03 cm, while the other had a channel depth of 3.20 cm, both extending through a height of approximately 4 cm. The measurements were taken for the three samples in multiple sets, and showed an increase in ToF of 8% to 13% for the smaller cut and 18% to 44% for the deepest cut relative to the solid sample. Furthermore, the calculated velocity for the two samples with partial cuts showed a decrease ranging from 8% to 11% and from 15% to 31%, respectively. It is worth noting that the velocities measured for the initial samples without cuts were within a 4% range.

The positive outcome of the laboratorial tests was encouraging to take the experimental apparatus to the Museum and perform UPV measurements *in situ*.

5.2. UPV at the Museum

At the beginning of the experimental work, it would not be possible to anticipate the range of *v* values for healthy plaster manufactured 140 years ago, whose original composition (the water and plaster ratios) is unknown. There was also no previous record of the types of damage, alterations, or repairs performed on each piece and how each of these cases would cause more or less significant deviations from the normal *v* values. The only reference in terms of values was the laboratory results with plaster specimens (around 2400 m/s), for which the W/P ratio varied between 70% and 85%.

St. Joseph was chosen to be the first piece to be tested due to the abundance of flat areas, or areas with a small curvature, where the two types of transducers (small and big) could be placed, as well as allowing to perform the three types of measurements (direct, indirect and semi-direct). The results obtained have shown that using the small transducers is suitable to almost every situation, with the exception of one joint at the back, for which the big transducers, with lower frequency and longer wavelength, were able to overcome the loss of signal when using the shorter wavelength of the small transducers.

This is in accordance with the recommendations of the manufacturer, as stated in the user manual [Proceq SA, 2017]: the higher frequencies (associated to the small transducers) are recommended to be used in fine grained material and refractory bricks, while lower frequencies (associated to the big transducers) are more adequate for concrete, wood and rock.

The next one was St. Joachim, which has less and smaller flat areas than St. Jopseph. Measurements through the joints were straightforward. It showed no need to use the big transducers for each available area scanned with the small ones.

The last one, Narcissus, is smaller in size compared to the previous plasters and also the shapes and details present reduced flat areas, which do not favour the use of the big transducers.

Both Joaquim and Narcissus did not present perpendicular flat surfaces large enough to carry out semi-direct measurements.

5.2.1. St. Joseph

Direct, indirect and semi-direct measurements, either with the small or the Big transducers, were taken all over the statue, wherever the transducers could be mounted on. The head yielded an interesting and sound set of results, indicating a good state of conservation. The front of the statue, with so many curved surfaces does not offer many chances to perform all kinds of measurements and the use of both sets of transducers. Many superficial marks all over the surface (lines, small holes, and others) does not tell much about the conservation state beneath, but some of them will reveal to be important after these UPV tests. The back side presents numerous areas with a different color and texture from the rest of the piece. A systematic and thorough scan of the backside was performed. The base is a very damaged part and many repairs and some cracks can be seen with the naked eye.

All the results obtained from St. Joseph are displayed in Figure 5. The different types of measurements and each set of transducers are discriminated on the plot, which represents the velocity for each measurement *versus* the distance between the transducers. This is a convenient way to look into the distribution of the data collected.

There is a wide range of values for the calculated velocity. If we consider a reference value of 2500 m/s and an interval of more or less 20% (from 2000 to 3000 m/s), we can then look at the points outside this range and search for reasons which might explain those values.

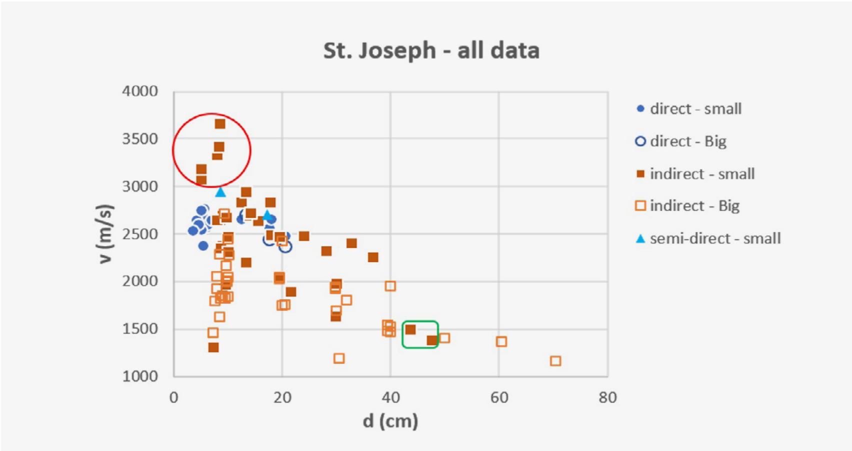

Figure 5 – St. Joseph data. Velocity versus distance between the transducers.

The points in the upper left part of the plot above 3000 m/s (inside the red circle) correspond to indirect measurements along the base, where many fractures and dents were repaired with some type of hard cement, which has a higher propagation velocity of mechanical waves in relation to plaster. Without information about the repair cement and when it was applied, the only way to identify it is to collect a sample and analyze it using chemical techniques.

There is also a visible fracture at the base for which consolidation has been attempted in the past, but the fracture persists as no signal goes through it (Figure 6).

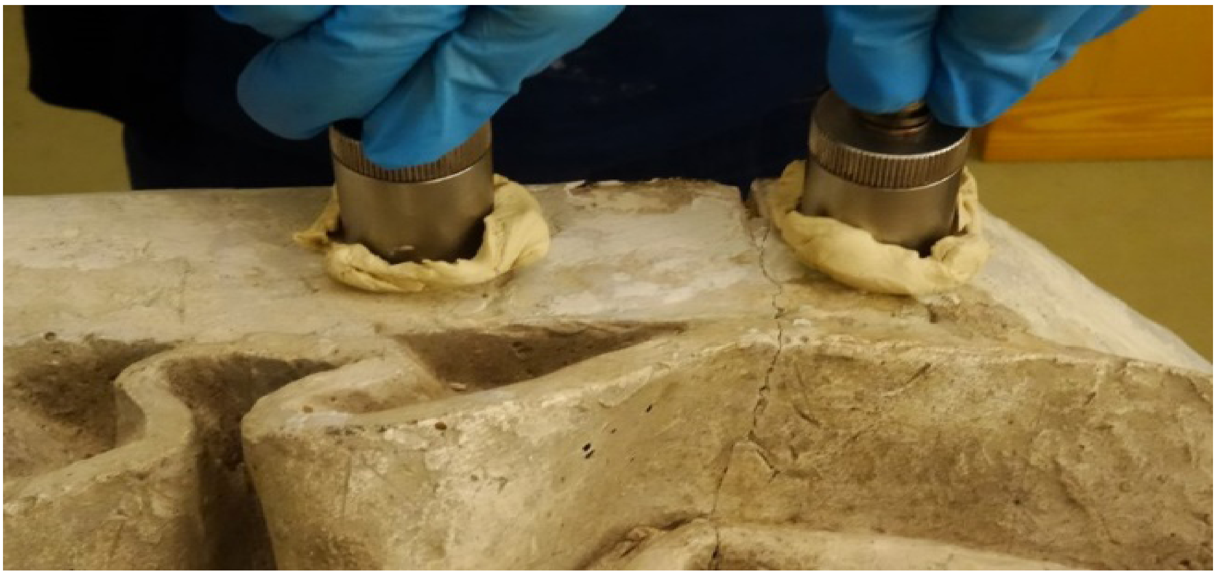

Figure 6 – A fracture at the base that has been repaired, but the signal is not transmitted through it. The white stain visible on the surface and inside the fracture is part of the repairing material.

The two points framed by the green box are from a larger set of measurements along a strip on the front part that crosses a joint and includes a small carved triangle-shaped incision (Figure 7). The signals measured through the joint are regular but, unexpectedly, those through the triangular shape revealed to be tricky. That triangular incision seemed to be a superficial mark, casually made by someone, but the long ToF measurements indicate that it is an insertion filled with a material different from the original plaster or whose bonding may not have been well consolidated.

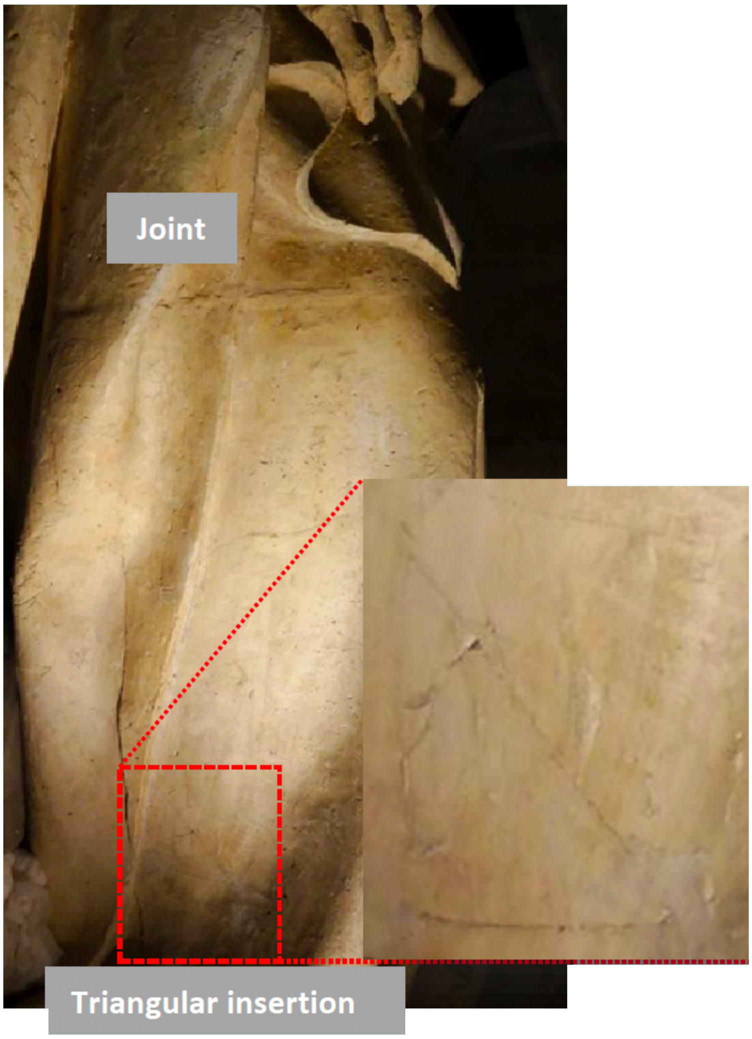

Figure 7 – The ultrasound waves do not propagate across the triangular insertion but they do through the joint.

All other values under 2000 m/s are from the back, where a few large spots have been repaired with some unknown material. In Figure 8, a clear contrast can be seen between the original plaster and the surface additions. In these cases, the ToF measured across original plaster and repaired areas was systematically long.

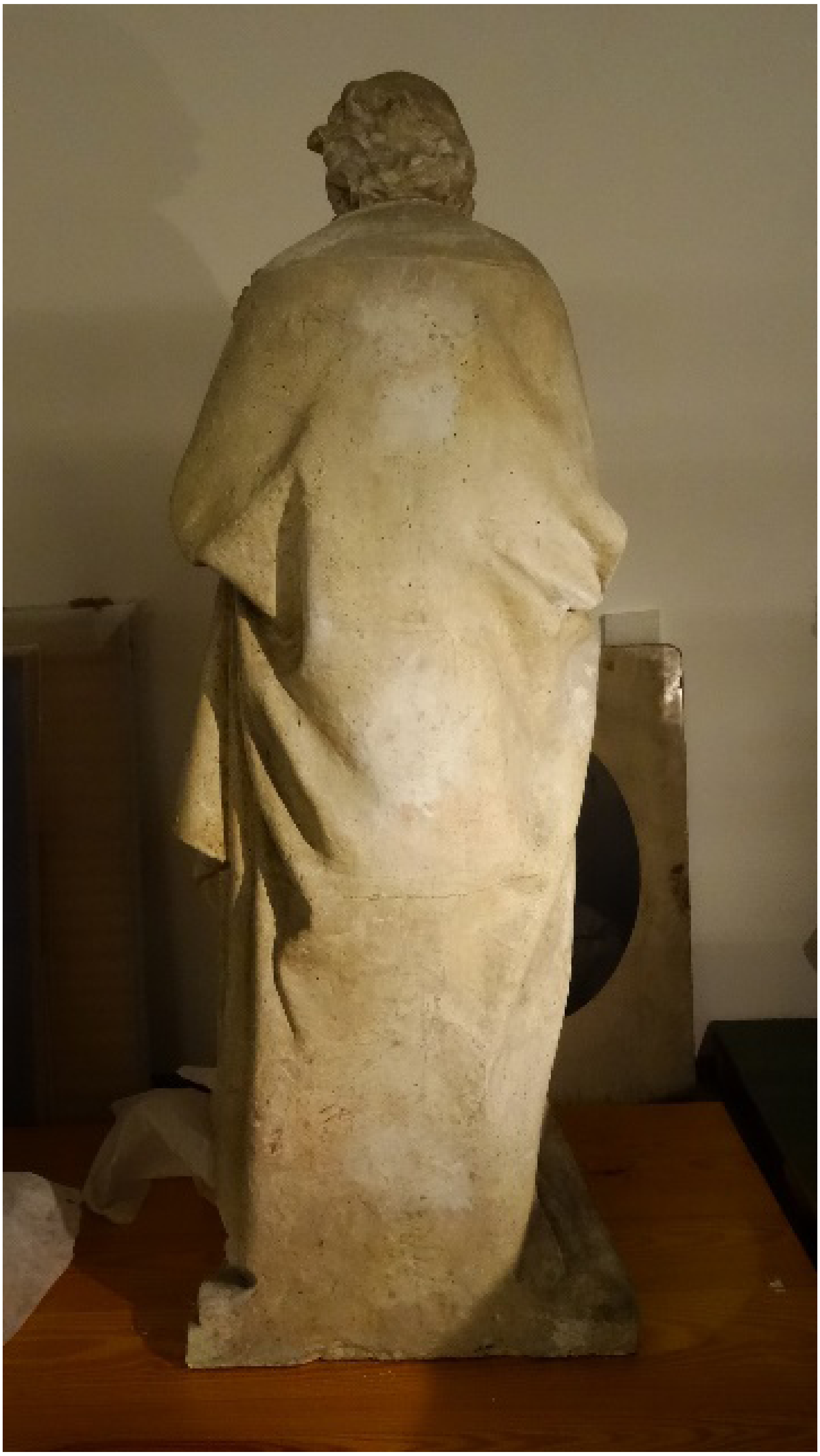

Figure 8 – The transmission of ultrasounds across the brighter areas is reduced and, in some cases, can only be achieved with the lower frequency of big transducers.

In summary, the use of UPV in this plaster artwork allowed us to verify that the head is in very good conservation state. A very discreet triangular shape at the front reveals itself as a repair insertion. The back has areas that were repaired, but the material used and its depth are unknown. Finally, the numerous visible damages on the base were repaired with an unidentified type of cement with mechanical properties very different from the original plaster, as in some cases, ultrasonic vibrations cannot penetrate the boundaries between the two materials.

5.2.2. St. Joachim

From the same year as St. Joseph, St. Joachim is another Soares dos Reis plaster sculpture. A similar set of measurements was carried out and the results (which are all displayed in the insertion of Figure 9) are very similar. All joints are well consolidated, allowing the transmission of the higher frequency signals with no alterations, thus avoiding the need to use the big transducers (with lower frequency).

A few repairs with a cement-like material at the base and at one folder of the clothing, yielded velocity values above 3000 m/s. Conversely, measurements through a visible crack at the base gave velocity values under 2000 m/s, suggesting that the crack may not be consolidated, although it appears to be partially repaired on the inside (see the inset in Figure 9). If these repair materials are alike or different from others already found, this can only be verified by taking samples and analyzing them.

Putting aside these abnormal values from the measurements, the remaining values are represented in the main plot of Figure 9, and all but two are within the range of 2000 to 3000 m/s. These two were obtained at the same location, in another fold of the cloak very close to a joint, where both direct and indirect measurements were possible to obtain. Further inspections on this particular site are required to find the reason for these high values of the velocity.

Like the previous piece, this one is in a very good state of conservation, and although some damages are visible, mainly on the base, they are fewer in number than in the case of St. Joseph.

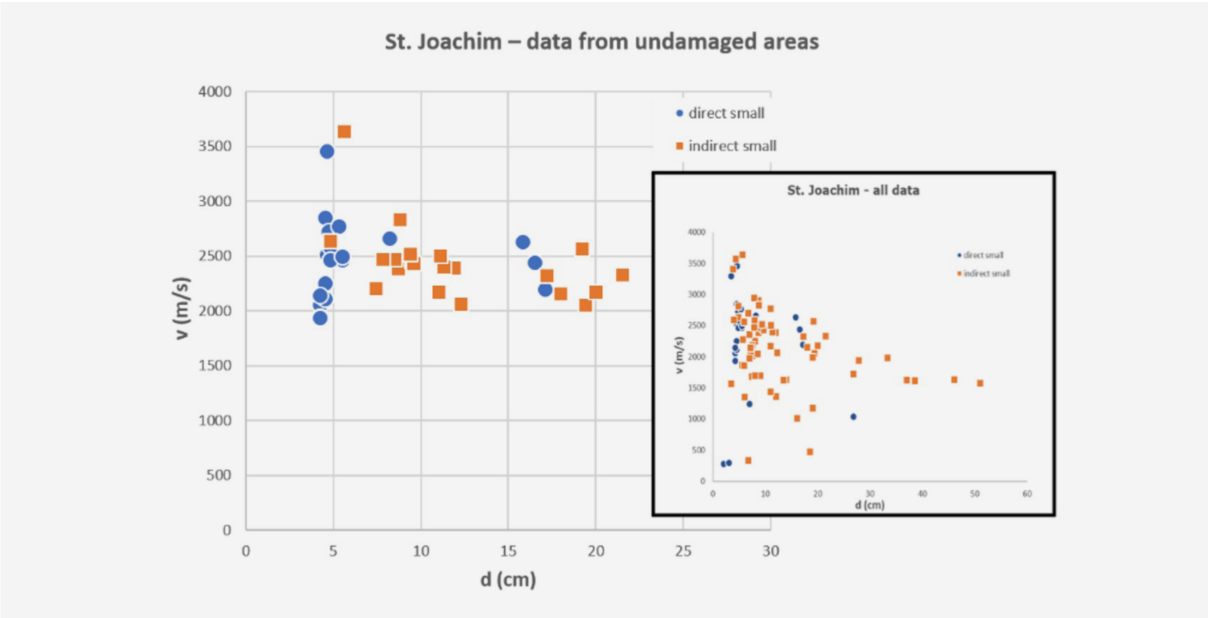

Figure 9 – St. All the data from St. Joachim collected are shown in the insertion picture. The main plot does not show the points collected at damaged and repaired areas identified by visual inspection.

5.2.3. Narcissus

Direct and indirect measurements were taken from the head to the base, including the limbs and the torso, using only the small transducers. The data collected are shown in the plot of Figure 10. A few points are highlighted for further discussion and Figure 11a shows the exact sites where some of these values were obtained.

Surrounded by a red ellipse, a few direct measurements on the right leg were troublesome to obtain and the calculated velocities were very low. These results led to a visual inspection and a thin long horizontal crack was found in the interior part of the right thigh. An indirect measurement was taken at this site, with the crack between the transducers, resulting in the orange square displayed in this dataset.

The indirect measurements taken on the outside of the right thigh, fixing one transducer and displacing the other (Figure 11a), gave regular results except the last one (measurement #45), which was taken through another small crack on the surface.

Point #46 corresponds to an indirect measurement through a V shaped mark on the surface, below the right knee (Figure 11b) and is one of the lowest values of velocity.

Measurements #37, #38 and #47 are those which present the highest velocities. They were collected at the right leg above and below the cracks and mark just mentioned.

Points #52 and #53 are direct measurements taken between the hips. The lower values of the velocity are due to the internal void, which makes the waves travel a longer path that the distance measured between the transducers. This void is to be expected, as the front and back were cast separately and then joined together, leaving a hollow space between them.

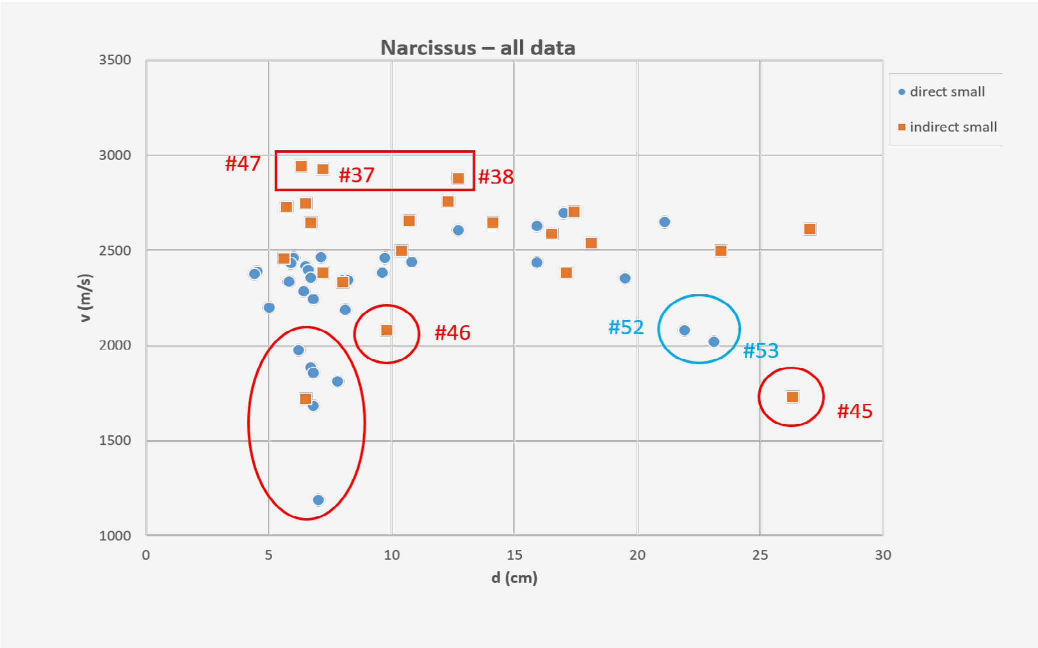

Figure 10 – Data collected from Narcissus, with a few highlighted points that need to be discussed.

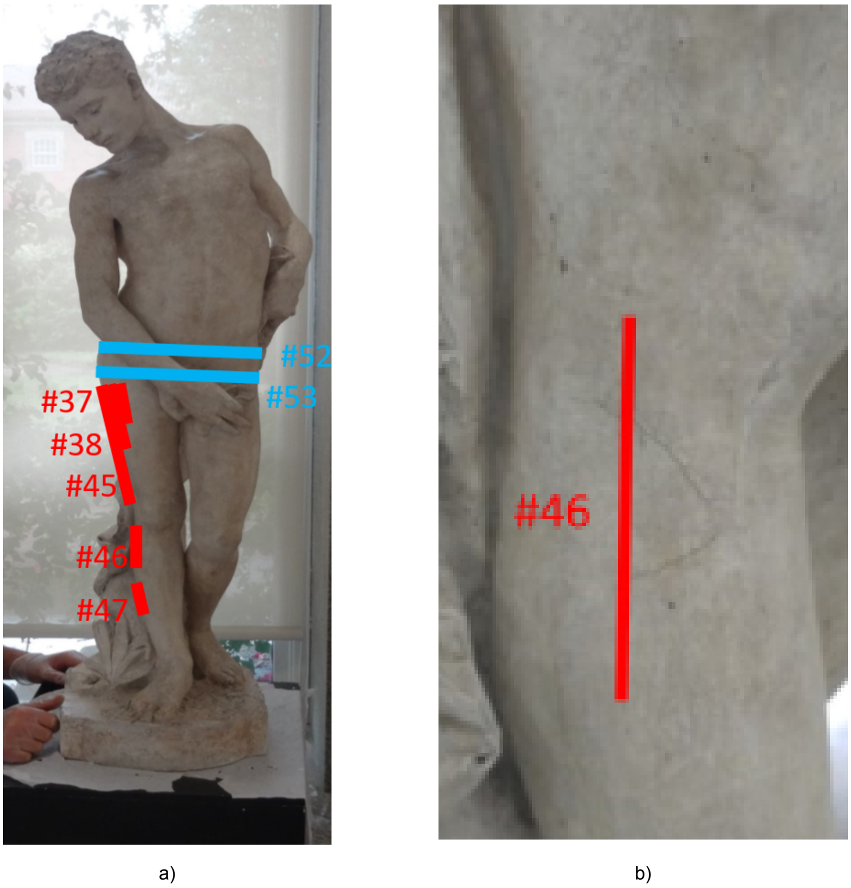

Figure 11 – Highlighted data points from Narcissus (a); data point #46 was measured through a V shaped mark (b).

This artwork appears to be in very good state of conservation, except for the right leg, where a few cracks are visible in the internal and external sides. To determine whether these cracks are related, further mechanical analysis is recommended.

6. Conclusion

Based on the experimental results obtained in this study, it is clear that portable ultrasonic pulse velocity can be used as a valuable technique in the conservation assessment of plaster sculptures. The methodology proved to be effective in detecting both internal and superficial defects in the sculptures.

A wide distribution of results for the velocity of ultrasounds in plaster should not be unexpected. Both the porosity and the hydration level are not constant throughout a large artwork (indeed they should present significant gradients over millimeters of depth) and their variations affect directly the rigidity (Young modulus) and the volumic mass (density), which in turn determine de velocity of mechanical waves in the material.

Each individual value obtained for the velocity is not significant by itself and must be assessed in the framework of a series of measurements. High or low values or velocity relative to a reference value for the material are an indication of alterations occurring in the shortest straight path between the transducers.

The consistency of the recorded ToF is also an important criterion. Each point of data is obtained after three measurements of ToF and the average value is used in the calculations. Most of the times the three ToF values are not much different of each other and the acquisition procedure is straightforward. But there are situations in which the acquisition takes longer than usual and the values obtained are not that close to each other. That prompts the user to make additional measurement but consistency seldom appears though. That is a clear hint to look for some external or internal defect that can justify the inconsistency.

From the three plasters of Soares dos Reis presented in this study, a few common problems were detected by the UPV and could be corroborated by superficial visual inspection. The areas affected in each piece are not uncommon (the bases are the most prone to suffer impacts) and after 140 years it is no surprise that some other sites on each subject have suffered a few hazards. Some of the repairs are in clear contrast to the original material, others are very well disguised, and some could be found with the aid of UPV.

This first approach of using UPV to probe the conservation state of plaster artworks has revealed to be promising. Being portable and easy to apply it may yield the first clues to identify deterioration issues beneath the surface that may be further explored with conventional assessment techniques.

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