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CONDITION ASSESSMENT OF TWO FIRE-DAMAGED HISTORICAL MARBLE SCULPTURES FROM BODE MUSEUM IN BERLIN BY NONDESTRUCTIVE ULTRASONIC TECHNIQUE

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ABSTRACT

Stone artworks, especially those made of marble, usually suffer significant damage when exposed to fire. To conserve such fire-damaged artworks, it is necessary to conduct a comprehensive assessment of their condition using appropriate methods to provide the basic information necessary for their conservation. This study aims to assess the condition of important historical marble sculptures from the sculpture collection of the Berlin State Museums, which were exposed to two disastrous fires in the last days of the Second World War. Despite the great importance of these historical sculptures and the serious damage they suffer due to exposure to fire, many of them still lack adequate condition assessment. The study therefore presents a simple, fast, and effective method to evaluate the condition of the sculptures using nondestructive ultrasonic technique, based on an improved damage classification system developed previously by the first author. The results of this study confirm the effectiveness of ultrasonic technique in assessing the condition of marble sculptures. The general condition of the studied sculptures was assessed and the level of damage in each part was determined and mapped on the sculptures. Consequently, appropriate conservation procedures for the sculptures were suggested, depending on the extent of their damage. This allows specialists to identify the appropriate measures to preserve the sculptures and to plan and prioritize the necessary conservation interventions. The results of ultrasonic velocity measurements also provide a basis for evaluating the effectiveness of future conservation treatments and monitoring the condition of the sculptures in the long term.

KEYWORDS: Marble sculptures, Ultrasonic technique, Fire-damaged stone, Condition assessment, Germany

1. INTRODUCTION

Fire can cause significant damage to stone objects, particularly those made of marble. Marble is mainly composed of calcite crystals, which exhibit thermal anisotropic dilatation. When heated, calcite crystals expand along the c-axis and contract along the other crystallographic directions. This anisotropy makes marble more susceptible to temperature and thermal stresses. In general, low temperatures (up to around 300 °C) result mainly in discoloration of natural stones mostly due to oxidation processes (Biró et al., 2019; Chakrabarti et al., 1996; Sippel et al., 2007). These color changes may not only alter the aesthetics of the stones but may also affect their durability as they indicate mineralogical changes in the stones (Chakrabarti et al., 1996; Sasińska, 2014; Sippel et al., 2007). On the contrary, high temperatures (above 500 °C) result in more serious damage to natural stones as they can cause significant changes in their physical, chemical, and mechanical properties. This is especially true for natural stones exposed to very high temperatures (above 800 °C) where the occurrence of mechanical failure is common for different types of stones (Biró et al., 2019; Gomez-Heras et al., 2009; Ozguven & Ozcelik, 2014). Large fires can thus be very destructive to natural stone as temperatures as high as 1300 °C can be reached (Deldicque & Rouzaud, 2020). Speaking specifically about marble, Ahmad (2020) showed that temperatures above 200 °C produce significant microcracking in marble. Different values for the critical temperature for marble beyond which the stone undergoes considerable loss of its mechanical strength have been reported in the literature. These values range usually between 400 and 800 °C (Biró et al., 2019; Vidana Pathiranagei et al., 2021; Yang et al., 2021). In general, the damage of marble at temperatures up to around 600 °C is mainly controlled by the anisotropic thermal expansion of calcite and its fabric characteristics (Sippel et al., 2007). At higher temperatures, however, marble undergoes structural and chemical changes as a result of decomposition of calcite into calcium oxide and carbon dioxide, which begins at 600 °C and proceeds rapidly beyond 800 °C and is accompanied by a loss of mechanical strength (Biró et al., 2019; Sippel et al., 2007). This calcination process and the subsequent hydration of the resulting calcium oxide to calcium hydroxide may form the main effect of fire, as it involves significant volume changes that may intensely affect the structure of the stone and lead to further damage, such as spalling of the outer surface layers (Biró et al., 2019; Ozguven & Ozcelik, 2014; Sasińska, 2014; Sippel et al., 2007). In extreme cases, the cohesion of the marble may be so weakened that it can crumble into powder (Chakrabarti et al., 1996). In addition to the above-mentioned forms of damage, represented by discoloration, cracks and chemical changes in fire-damaged stones, fires produce smoke and soot that can adhere to stone surfaces and stain them (Chakrabarti et al., 1996; Gomez-Heras et al., 2009; Grissom et al., 2016). It may also affect the permeability of the stone and cause further damage by, for example, salt weathering (Chakrabarti et al., 1996; Gomez-Heras et al., 2009).

In short, fire has considerable impacts on natural stones, especially marble. These impacts can be so disastrous for the stone that they may eventually lead to its complete structural damage. To avoid this, it is necessary to properly conserve fire-damaged stone materials and monitor their condition regularly. While there is still a lack of a clear scientific approach to conservation of fire-damaged stone materials, there is no dispute that conservation treatments should be based on a comprehensive and careful assessment of the condition of the objects. Ultrasonic technique is considered one of the best methods available for assessing the condition of marble objects and structures due to its effectiveness, ease and speed of use, and the possibility of its application in the field. Above all, ultrasonic technique is a nondestructive technique that does not cause any damage to the objects being investigated and does not require sampling, which is very important when dealing with art objects of great significance, such as sculptures and the like. Ultrasonic technique is mainly based on measuring the velocity of ultrasonic waves inside the stone. This ultrasonic velocity depends, amongst other things, on the deterioration state of the marble stone. As explained above, deterioration of stone is associated with changes in its structure, which are often represented by loss of stone cohesion and mechanical strength and the development and widening of cracks. By correlating the velocity of ultrasonic waves inside stone with the changes occurring in the stone at different levels of damage, it is possible to develop relationships that can be used to assess the condition of marble objects based on simple measurements of the velocity of ultrasonic waves inside the stone. Many researchers have studied the relationship between ultrasonic velocity and the basic properties of marble at different damage levels. On this basis, some of them have developed systems for classifying stone damage based on ultrasonic velocity measurements. One of the most famous of these is the system developed by Köhler (1991) to classify marble damage based on the relationship between ultrasonic velocity and porosity in Carrara marble. The first author has recently conducted an extensive study on various types of historical marbles that are widely used in archaeological objects and structures in the Mediterranean region and developed a better relationship between ultrasonic velocity and porosity of marble (Ahmad, 2020). Based on this, an improved classification system was proposed to assess the condition of archaeological marble objects and structures by measuring the velocity of ultrasonic waves inside them. This classification system, which has been successfully applied to assess the condition of historical marble statues in Jordan (Ahmad & Al-Bashaireh, 2021), will be applied in this study to assess the condition of fire-damaged marble sculptures from the sculpture collection of Berlin State Museums.

The sculpture collection of Berlin State Museums, located in the Bode Museum, is one of the largest collections of ancient sculptures in Germany. The collection contains sculptures from the ninth to the late eighteenth century and features important Italian and German masterworks (Streich, 2015). During the Second World War, most of the valuable collections of the Bode Museum (then called Kaiser-Friedrich-Museum) were stored in the control tower of the anti-aircraft bunker in Friedrichshain in Berlin to protect them from Allied bombing raids. However, in the last days of the war, shortly after the Soviet Army took control of the Friedrichshain district, two catastrophic fires of still unknown and debatable origin broke out in the bunker and destroyed many of the works of art stored there. The first fire occurred on the night of May 5 to 6, 1945 and destroyed the first floor of the tower. While the second fire occurred between May 14 and 18, 1945, and caused a major destruction to the upper floors of the tower as well, where the artworks of the sculpture collection and many works of art from other Berlin Museums were stored (Chapuis & Kemperdick, 2015; Rastorguev, 2015; Richter & Sandles, 2012; Streich, 2015).

After this disaster, the artworks that could be salvaged from Friedrichshain's bunker were seized by the Soviet Army and transported, along with other German collections, to the Soviet Union. A large part of the confiscated artworks, including hundreds of objects from the sculpture collections, were returned to the German Democratic Republic (GDR) in the late 1950s (Chapuis & Kemperdick, 2015; Rastorguev, 2015; Richter & Sandles, 2012; Streich, 2015). Most of these sculptures were severely damaged by the fire; some of them even disintegrated or broke into pieces. Therefore, restoration work was carried out on many of them whether in the Soviet Union, in the GDR or after the reunification of Germany (Streich, 2015). Notwithstanding the obvious damage caused to these sculptures by the fire, most of them are on display today in the Bode Museum as they still retain their artistic quality.

Despite the importance of these sculptures and the numerous problems that they suffer from because of exposure to fire, scientific studies about them, especially regarding the assessment of their condition, are still few and insufficient (e.g., Richter & Sandals (2012); Streich (2015, 2017)). Although the sculptures are currently on display, no proper condition assessment has been conducted for most of them since their repatriation to Germany. This may prevent taking the necessary measures to conserve these sculptures in a timely manner and may lead to their further deterioration. This study aims, therefore, to contribute to filling this gap and providing the required information on the condition of these sculptures to identify and plan the necessary conservation and restoration work for them. While using ultrasonic technique to assess the condition of art objects might not be innovative as many such examples can already be found in the literature, the application of the technique on extremely fire-damaged marble sculptures constitutes a special, little studied, case and contributes to existing knowledge by adding new data that can be used not only to monitor the condition and deterioration of these sculptures in the long term but also to confirm the validity and effectiveness of the ultrasonic technique for such applications. Furthermore, this study involves the application and verification of an improved empirical system for classifying marble damage that has been recently developed (Ahmad, 2020), and provides an example of how ultrasonic velocity measurements can be interpreted and used to guide conservation decisions for historical marble objects.

2. MATERIALS AND METHODS

2.1 The Investigated Sculptures

In the summer of 2022, the first author conducted nondestructive ultrasonic velocity measurements on 20 fire-damaged historical marble sculptures from the sculpture collection in the Bode Museum to assess their condition. In this study, the results of investigations carried out on two of these sculptures, namely Standing Mary with child and the sculpture of Humility, are presented. Below is a brief description of these two sculptures.

2.1.1. Standing Mary with child (German: Stehende Maria mit Kind)

The sculpture of Standing Mary with child (Fig. 1) is made of marble, possibly from Carrara although no proof of this has yet been provided. The slightly smaller-than-life-size sculpture has a height of 147.5 cm, a width of 52 cm, a depth of 29 cm and weighs about 180 kg. It is characterized by the fine detailing of its three main viewing sides and the precision of its decoration. The sculpture dates to around 1340 and was acquired in 1896 as a gift from a princely patron, supposedly from Pisa (Kunz, 2014; SBM-MBK, 2024).

During the Second World War, the sculpture was stored in the Friedrichshain anti-aircraft bunker, where it was damaged by fire. It was broken into many pieces (Fig. 1-d) and suffered various forms of damage including chipped edges, burnt and damaged surface with fine punctures, and several missing parts (Streich, 2015). However, the majority of the sculpture's original surface is still preserved.

The sculpture was transported to the Soviet Union, most likely in 1946, where it was restored by reassembling its existing fragments and reconstructing some of the missing parts with gypsum as indicated in the Soviet restoration report, which briefly document the conservation works carried out on the object by Soviet restorers during the period from 1945 to 1958 (Streich, 2015).

In 1958, the sculpture was returned to Berlin, where some restoration work was also carried out on it. At least, restoration work carried out after 1978 included the reconstruction of the boy's right and left arms with mortar and the reattachment of the fingers of Mary's right hand, as well as supporting the hand with two metal bars (see Fig. 1-c) (Streich, 2015).



a) in 2022 ***b) in 2015*** ***c) in 1979***


d) before restoration between 1945-1958 ***e) before 1945***

Figure 1. Standing Mary with child (a) the condition in 2022 (by the first author); (b) in 2015 (from Streich (2015)); (c) in 1979 (from Streich (2015)); (d) before restoration between 1945-1958 (from Streich (2015)); (e) before 1945 (from Streich (2015)).

2.1.2. Humility (German: Humilitas)

The sculpture of Humility (personification of humility) (Fig. 2) is made of marble. It measures 76.5 cm high, 27 cm wide, and 18 cm deep, and weighs approximately 45-50 kg (SBM-MBK, 2022; Streich, 2015). The origin of the statue is stylistically attributed to Genoa in Italy. The sculpture dates to the end of the fourteenth century (around 1386) and was acquired in 1913 as a donation (SBM-MBK, 2022).

The sculpture was stored in the Friedrichshain anti-aircraft bunker during the Second World War, where it was damaged by fire in May 1945. The intermediate storage place of the sculpture after the 1945 fire disaster is unknown. There is also no information about the restoration work that may have been carried out on the sculpture in the Soviet Union or later in East Germany (Streich, 2015).

The main information about the investigated sculptures is summarized in Table (1).

a) in 2022

b) in 2015

c) in 1980s

d) before 1945

Figure 2. Humilitas (a) the condition in 2022 (by the first author); (b) in 2015 (from Streich (2015)); (c) in 1980s (from Streich (2015)); (d) before 1945 (from Streich (2015)).

Table 1. A summary of the main information about the studied sculptures (SBM-MBK, 2022, 2024).

Title:	**Standing Mary with child (German: Stehende Maria mit Kind)**	**Humility (German: Humilitas)**
Inv. No.	2301	6742
Current location	Bode Museum, Small dome	Bode Museum, Room 108
Material	Marble	Marble
Dimensions	147.5 cm high, 52cm wide, and 29cm deep	76.5 cm high, 27 cm wide, and 18 cm deep
Mass	approx. 180 kg	approx. 45 -50 kg
Period	around 1340	1386/1400
Place of origin	Stylistically Rhine-Meuse (Rhine-Maas) area (?) Historical location Pisa? Historical location Italy?	Place of origin stylistically Genoa Place of acquisition: Rome Origin (General) Genoa
Type of ownership:	Property	Property
Date of acquisition:	1896	1913
Acquisition type	Donation: a gift from a princely patron	Donation

2.2. *Methods and Measurements*

The condition of the investigated sculptures was mainly assessed by non-destructive ultrasonic technique. The velocity of the longitudinal ultrasonic waves (Vp) in direct transmission method was measured at different points on the sculptures. The ultrasonic velocity measurements were carried out using a portable ultrasonic device (UKS 12) from Geotron Elektronik. The system is composed of an ultrasonic generator USG 20, a 50 MHz Philips scopemeter, as well as a transducer combination of a flat shaped 250 kHz transmitter (UPG 250) and the corresponding receiver (UPE-T). To measure the ultrasonic velocity with direct transmission method, the ultrasonic transmitter and receiver are placed on two opposite points on either sides of the sculpture and the time needed for the ultrasonic wave to travel between these two points is measured and recorded (Fig. 3). By measuring the distance between these two points, the velocity of ultrasonic wave inside the stone can then be calculated. For a better contact between the ultrasonic transducers and the surface of the sculpture, an elastic coupling material (Plastic-Fermit) was used.

The number of measurement points required for each sculpture depends on its size, condition, and accessibility, as well as on the nature and purpose of the investigation (Ahmad et al., 2009; Ahmad & Al-Bashaireh, 2021; Köhler, 2018b). In order to obtain as much information as possible about the sculptures examined, the largest possible number of measurement points were selected for each sculpture that could be accomplished within the time available. The average velocity of at least three measurements was calculated for each point.

The condition of the marble sculptures was assessed and categorized using the classification system developed by Ahmad (2020) (Table 2). The average ultrasonic velocity measured at each point was mapped onto the sculpture and the surrounding areas were colored according to the corresponding damage category. To achieve proper mapping, ultrasonic velocity was measured in several locations around each point of measurement to help identify the boundaries of areas having the same class of damage.

Figure 3. A photograph of performing ultrasonic velocity measurements on the sculpture of "Standing Mary with child" in Bode Museum.

The accuracy of ultrasonic velocity measurements is assumed to be ± 10% (Ahmad, 2011; Ahmad et al., 2009; Ahmad & Al-Bashaireh, 2021; Simon, 2001). However, different factors can affect the accuracy of ultrasonic velocity measurements and make them more difficult to interpret (Albrektsson et al., 2011). More details about the process of measuring the velocity of ultrasonic waves of sculptures and the factors affecting the accuracy and reproducibility of the results can be found in (Ahmad & Al-Bashaireh, 2021). In addition, simple visual examination was also conducted on the sculptures to identify the main visible forms of damage such as cracks, material loss, and discoloration.

Table 2. The classification system of marble damage (Ahmad, 2020).

Ultrasonic pulse velocity (Vp) [Km/s]	Damage Class	Color	Description
> 5.0	1	Green	Sound – unweathered
3.5 – 5.0	2	Cyan	Increasing porosity
2.5 – 3.5	3	Yellow	Granular disintegration
1.5 – 2.5	4	Magenta	Danger of breakdown
< 1.5	5	Red	Complete structural damage

3. RESULTS AND DISCUSSIONS

The results of the condition assessment of the examined marble sculptures using ultrasonic velocity measurements are shown in Figure (4) and summarized in Table (3).

For the sculpture of Standing Mary with child, the average ultrasonic velocity of 92 measurement points is 1.94 km/s, which falls within the fourth class of damage, that is danger of breakdown, according to Table (2). This means that the sculpture has been damaged so badly that it may collapse or break into pieces when subjected to sufficiently high stresses.

In general, the sculpture contains areas with varying levels of damage. However, only one small area shows damage of the second class, corresponding to increasing porosity, while the rest parts of the sculpture exhibit more serious damage from granular disintegration to complete structural damage. This variation can be attributed to several factors, such as the varying degree of exposure to fire of its different parts, the dimensions of these parts, and the restoration work carried out on the sculpture. In fact, most parts of the sculpture suffer from very advanced damage of the fourth and fifth categories, which represent the danger of breakdown and complete structural damage respectively. Some parts of the sculpture may thus not be able to support their own weight.

The condition of the sculpture of Humility is not much different from that of Standing Mary. The sculpture has a slightly higher average ultrasonic velocity of 2.12 km/s, which corresponds to the fourth class of damage represented by danger of breakdown. The sculpture shows areas with advanced damage ranging essentially between granular disintegration and complete structural damage, except for one area exhibiting a lower level of damage that corresponds to increasing porosity.

Normally, a systematic comprehensive assessment of the condition of sculptural marble is required to properly identify and plan necessary conservation treatments. Such a comprehensive assessment should not only be based on investigating the internal structural damage of marble, which can effectively be accomplished by ultrasonic velocity measurements, but also include an investigation of the penetrative and superficial aspects of marble damage using other appropriate investigation methods such as water absorption methods, surface roughness measurements, detailed visual examination and three-dimensional laser scanning (Ahmad & Al-Bashaireh, 2021; Köhler, 2018a; Vandevoorde et al., 2013). However, in severely damaged marble sculptures, as in the sculptures examined here, ultrasonic velocity measurements alone can be sufficient to provide an adequate condition assessment for planning future conservation treatments. This is because the damage in this case has exceeded the point where the penetrative and superficial aspects of damage are no longer of great importance when compared to the internal structural damage that has occurred.

In addition to ultrasonic velocity measurements, the sculpture were visually examined to identify the visible signs of damage. In general, both sculptures exhibited various forms of damage that include cracks, breaks, surface loss of materials, and dark and white discoloration and deposits. Although the two sculptures still retain most of their original parts, there is a noticeable progressive loss of material in some of their parts. A simple comparison of the photos of the sculptures between 2015 and 2022 clearly shows that some parts, particularly in the sculpture of standing Mary, have been lost over the past few years.

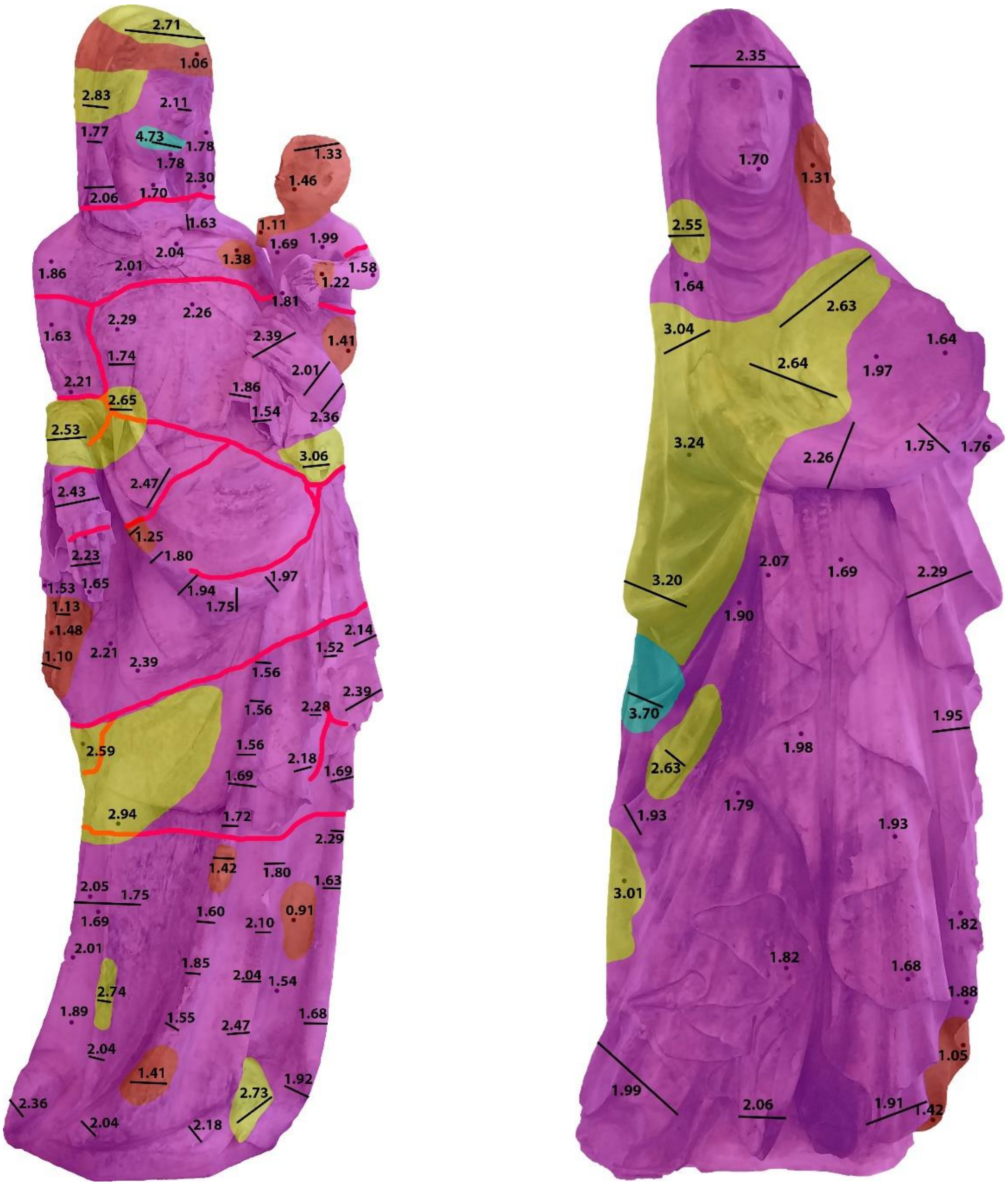
Considering this advanced and severe damage exhibited by the two examined sculptures, interventive structural conservation treatments seems to be indispensable, especially for the parts with damage of the fourth and fifth classes, corresponding to danger of break down and complete structural damage. The proposed interventions include the consolidation of weak and fragile parts of the sculptures (areas with damage class 3 and higher) and the stabilization and support of their heavily loaded parts. At least, all parts with ultrasonic velocity below 3 km/s need to be conserved by consolidation or other suitable conservation measures (Menningen et al., 2020). Marble with ultrasonic velocity below the threshold value of 3 km/s exhibit usually damage ranging from extensive granular disintegration to complete structural damage. It is worth mentioning here that the consolidation material and its application method should be carefully selected in order to avoid adverse effects (Menningen et al., 2020). Ultrasonic technique can be used to evaluate the effectiveness of the applied consolidation treatments by comparing the results of ultrasonic velocity measurements before and after treatment.

In addition, it is necessary to take and apply appropriate preventive conservation measures such as providing regular maintenance for the sculptures and protecting them against sharp fluctuations in climatic conditions and possible shocks and vibrations. It is also important to minimize, where possible, the movement and transportation of the sculptures. When this is necessary, the sculptures should be carefully handled, particularly areas with damage class 3 and higher. Furthermore, the condition of the sculptures should regularly be monitored through periodic ultrasonic velocity measurements conducted every five to ten years (Ahmad & Al-Bashaireh, 2021).

Decisions regarding the operations and actions taken to enhance the aesthetic and interpretive aspects of these sculptures, such as cleaning and removing stains, discoloration and other effects of fire, and the reconstruction of missing parts, must be carefully considered. Sometimes, it may be safer to defer the implementation of these works and actions until after the consolidation and strengthening of the sculptures, even if the consolidation makes the task of performing them harder. Remedial works carried out to treat these superficial aspects of damage may compromise the stability of the sculptures and lead to greater damage if carried out before treating the internal structural problems of the sculptures and consolidating their weak parts.

Table 3. Summary of the results of ultrasonic velocity measurements of the examined sculptures.

Sculpture	**Standing Mary with child (Inv. No. 2301)**	**Humility (Inv. No. 6742)**
Measuring date	11th of August, 2022	9th of August, 2022
No. of measured points (n)	92	36
Average Vp ($V_{p\text{-}avg}$) [km/s]	1.942	2.116
Minimum Vp ($V_{p\text{-}min}$) [km/s]	0.909	1.051
Maximum Vp ($V_{p\text{-}max}$) [km/s]	4.729	3.703
Average Damage Class (DC_{avg})	4	4
Minimum Damage Class (DC_{min})	5	5
Maximum Damage Class (DC_{max})	2	2



a) Standing Mary with child *b) the sculpture of Humility*

Figure 4. Mapping the damage classes of the sculptures based on ultrasonic velocity measurements and the adopted classification system (Table 2). The red lines indicate visible breaks and cracks, while the black lines and dots indicate the directions of ultrasonic measurement; the dots refer to front-back vertical directions.

4. CONCLUSION

The aim of the present study was to assess the condition of two historical marble sculptures from the Bode Museum in Berlin, which were damaged by the fires that broke out in Friedrichshain's bunker in May 1945. The condition assessment of the sculptures was carried out by means of nondestructive ultrasonic velocity measurements. The level of damage in each part of the sculptures was determined and mapped onto their surfaces. The results showed that both sculptures essentially exhibit an advanced damage of the fourth and fifth classes, which correspond to danger of breakdown and complete structural damage, respectively. Such damage can cause the sculptures to collapse when subjected to external pressures. Some parts of the sculptures may not even be able to support their own weight. Consequently, interventive conservation treatments, especially for the treatment of internal structural damage, appear to be essential. Based on this assessment of the current condition of the two sculptures, the necessary interventive conservation treatments and the preventive measures for their proper handling have been identified and proposed.

The results of this study confirm the validity of ultrasonic technique for assessing the condition of marble sculptures and determining the necessary interventive treatments and preventive measures for their conservation in a simple and nondestructive way.

These results can also be used to evaluate the effectiveness of the conservation treatments to be applied on the sculptures by measuring the enhancement achieved in ultrasonic velocity after treatment. In addition, the results of ultrasonic measurement provide a baseline for long-term monitoring of the condition of the sculptures and their deterioration process.

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