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Original article

A complete methodology for the mechanical diagnosis of statue provided by innovative uses of 3D model. Application to the imperial marble statue of Alba-la-Romaine (France)

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ABSTRACT

A multidisciplinary methodology is presented to assess the mechanical behaviour of a marble statue with complex fracture plans and localized cracks. First, a 3D model is generated by photogrammetry. Its underlying geometrical data provide valuable insight for the physical characterisation and the numerical analysis. Indeed, the ultrasound analysis, which is usually impossible on such a complex shape, is achieved thanks to the accurate measures of distance between transmitter and receiver obtained from the 3D geometrical model. Finally, an innovative use of FEM/DEM analysis is proposed to evaluate the mechanical relevance of a non-destructive basing system. Reflecting the advances of this collective work, the resulting pedestal solution is non-conventional since it is safe, not invasive and totally reversible. A particular attention is paid to use mainly open-source numerical tools from 3D acquisition through mechanical analysis in order to enable the reproducibility of the process.

1. Research aims

Innovative fields of competence are continuously requested by conservation and restoration in order to enrich the bodies of heritage and archaeological knowledge. Nowadays, advances in methods and tools dedicated to numerical modelling and physical characterisations, broadly contribute to enlighten the diagnosis analysis of historical artworks. However, 3D models provided by photogrammetry or laser scanning, are still not fully exploited by the practitioners to perform further insights into a computer-aided restoration process. This paper aims at presenting how an accurate 3D geometrical description of an artwork can be used to carry out an ultrasonic analysis and an advanced numerical computation, respectively performed to evaluate the damage level of material and to estimate the mechanical stresses generated by a basing system without intrusive bond. Above the proposed methodology, the objective is to use open-source numerical tools from 3D acquisition through mechanical analysis in order to enable the reproducibility of the process.

2. Introduction

By paying attention to the history [1,2], innovative fields of competence are continuously requested by conservation and restoration in order to enrich the bodies of heritage and archaeological knowledge. Nowadays, advances in methods and tools dedicated to numerical modelling and physical characterisations broadly contribute to enlighten the diagnosis analysis of historical artworks. Photogrammetry and laser scanning allow the generation of realistic 3D models that have been mainly used to constitute accurate documentations of architectures and heritages [3–5], web-based visualization systems [6,7] or virtual reality and multimedia museum exhibitions. Above their fascinating visual interests, such 3D models contain geometrical data, which is still not fully exploited by the practitioners to perform further insights into a computer-aided restoration process. The meshes generated from the point clouds have been used to virtually assemble dismounted historic buildings [8] or statues [9,10], to simulate their mechanical behaviour by Finite Element Method (FEM). For instance, the diagnosis of the lesions and stability of Michelangelo's David has been conducted thanks to FEM applied on the digital model of the statue [11]. The authors assess the risk of crack propagation under both static and dynamic conditions, although

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so far, the seismic response analysis was limited to a truss model to lower the computational cost. Later, dynamic analysis has been performed on 3D model to evaluate the seismic responses of statues and the structural ability to withstand road transport vibrations [12,13]. A third potentiality consists in virtually fitting the restoration process in order to visualize the path of the pins inside the volume [9]. Reassembly of fractured stones relies mainly on two techniques, which consist in drilling into the substrate and installing pins and/or gluing the contact surfaces by an adhesive. The former is a risky task since the restorer has to optimise the material thickness between the drilling and the skin to avoid any critical weakening of the artwork [14]. The mechanical efficiency of these restoration practices on the global stability and the local resistance of stone can thus be assessed numerically [13,15–17].

Numerical models and results have to be scaled by physical data (density, porosity, mechanical strengths, Young modulus...) obtained experimentally. Such data is generally measured by NDT techniques due to the patrimonial value of the studied artworks. Indeed, ultrasonic analysis is particularly reliable on marble to evaluate the damage level of basic architectural elements like gravestone [18] or column [19]. Since the accurate evaluation of the distance between transducers is required to calculate the ultrasound velocity, practical applications have been carried out only with simple and planar geometries [18,19]. Measurements on complex geometries are quite challenging and mostly estimated to perform the ultrasound analysis [20]. The depth of surface cracks on marble artworks can also be assessed using ultrasonic measurements [21] while difficulties to locate precisely the transducers and determining the distance travelled by ultrasound, are still a drawback of in situ experiments.

This article presents a complete methodology to face general issues related to the exhibition of an ancient marble statue on a pedestal. To illustrate its reliability, the methodology is applied to the mechanical diagnosis of a Roman marble statue found in Alba-la-Romaine (France) with the aim of designing an appropriate, fully reversible base, avoiding any material damage and optimising the legibility of the sculpture. Main stages of the analysis rely on using data from the 3D model: from the initial investigation with historians about the original posture, to the ultrasonic material characterisation and the simulation of the mechanical behaviour of the statue on its base.

3. Materials

3.1. Statue

The marble statue was discovered in a small sanctuary (sanctuary of Bagnols, France) during excavation of the Roman city in 1992 [22]. It was found into the ground, lying on its back, all the members and the head being broken. Those broken parts (arms, legs...) might have been used for lime production, which could explain that they are still missing despite the large site excavation. The broken statue is 1.5 m high and weighs 498 kg. It describes a naked athletic male with a military coat (paludamentum) on his left shoulder. Dated between 117 and 138 AD, it should preferentially represent Trajan Emperor and thus, constitute a rare testimony of the imperial cult attested by the quality of the execution and its iconographic, stylistic and technical characteristics.

The statue has been cleaned and some earth deposits have been removed just after its uncovering. The marble surface is in good condition, gently eroded and aged, but without any visible feature of degradation, except a coarse scratching mark on its belly and chest. Few thin cracks are noticeable close to the fracture planes of head and left arm. Two parallel cracks of ten centimetres length located in the left groin could be problematic when the statue is standing. The left leg has been broken above the knee and the right one at mid-thigh. The fracture planes of both legs are far from flat but describe sharp angles that end in acute bevel. Because of these complex fractures planes and the cracks on the left groin, the statue had never been stood up and positioned on a base.

3.2. Marble

The white marble is a fine-grained one with a maximum grain size (MGS) of 2 mm. Many millimetric greenish veins enriched in phyllosilicates (mica, chlorites) cross the statue vertically, underlining the lineation of this marble. A perpendicular and irregular vein of large calcite crystals crosses the statue just below its chest. Cathodoluminescence and isotopic analyses ($\delta\, ^{18}O/^{16}O = -4.72$ and $\delta\, ^{13}C/^{12}C = 2.50$) had been performed in 1994 by V. Barbin just after the discovering of the statue. It allowed to identify the marble as a Pentelic one (unpublished report, Reims University). Macro features such as greenish veinlets, maximum grain size and petrographic features observed on a thin section and compared to reference thin sections confirmed the Pentelic provenance: mean diameter around 0.5 mm, curved to embayed crystal boundaries, mosaic and lineated fabric [23].

3.3. Basing system

A non-intrusive and completely reversible basing system is chosen. The principle is to hold the statue on the internal part of the legs by means of a distributed contact surface over its external face without any chemical or mechanical bond (Fig. 1). Only the geometrical shape of this contact surface ensures the stability of the statue. The material of the base must meet 3 criteria:

- a comparable rigidity with respect to the marble to obtain a rigid behaviour of the whole assembly;
- a satisfying tensile and compressive strength to withstand external and accidental loadings;
- an ability to shape the complex geometry of the statue, which is maintained without any additional, support, pin or bond.

An alkali-resistant glass fibre reinforced concrete has been chosen to fulfil these requirements, the mechanical properties are detailed in Table 1. A thin interface layer of epoxy resin, softer than the stone and the concrete, is introduced between the statue and the base to avoid localised punching damage and allow a better contact stresses distribution.

The underlying deontological and aesthetic criteria leading to this choice are beyond the scope of this paper and will not be discussed here. Thus, the objectives are to propose a methodology to assist the conceptual design of the basing system and to validate its mechanical relevance.

Table 1
Physical properties of materials.

Material	Statue	Interface	Base
	Marble, class II	Epoxy resin	Ultra-high performance fibre-reinforced concrete
Density (kg/m^3)	2800	2200	2340
Young modulus (GPa)	45	6	30
Poisson's ratio	0.20	–	0.20
Compressive strength (MPa)	90	110	100
Tensile strength(MPa)	5.3	40	9