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A multimodal study of pinning selection for restoration of a historic statue

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ABSTRACT

Current practices for repair of fractured stone architecture and monuments rely on drilling into the substrate and installing metal pins, providing component alignment and resisting shear and tensile stresses. Adhesives such as acrylic resin may reinforce the pins at the interface with the stone. This research studies failure modes in the repaired areas of the statue *Adam* (Tullio Lombardo *c.* 1490–95) to ensure the artwork's longevity. Six materials as pins were investigated to repair fractured Carrara marble specimens. Furthermore, the results of finite element simulations were correlated with experiments on pinned join repairs. The simulations and experiments concluded that fiberglass pins outperformed metal pins. The fiberglass pins provided maximum strength to withstand the static forces of the repaired sculpture, without damaging the substrate before pin failure. From the simulation results, a ranking of the pin materials quantified the overall efficiency of the system. The ratio of join displacements at the tension stress limit to the compression stress limit in Carrara marble indicates the join performance, where 1.0 represents equal strength in tension and compression. The fiberglass pin achieves a ratio of about 0.80, from which we conclude that sudden join failure may be prevented, a desirable trait for monumental conservation.

1. Introduction

This paper investigates and categorizes pin performance in the repair of fractured marble, supporting the restoration of the statue *Adam* by Tullio Lombardo *c.* 1490–95. The goals of this research are to study the failure modes in repaired areas, to analyze repair methods for adverse effects to the artwork's longevity, and to maintain relevance to both preservation and conservation of historic artifacts and architecture. The statue was repaired by conservators and restored in 2014 after the pedestal supporting the statue collapsed in 2002. The accident caused the sculpture to fracture into 28 large pieces and hundreds of smaller ones. Further information on the history of the statue and the subsequent research and treatment from the art conservator's point of view can be found in [1–3] for the interested reader. Previous work conducted on the glued joins can be found in [4,5]. Ultimately, only three joins were selected for structural pinning.

In general, conservation of sculptures is the process to repair and make a sculpture whole again. Generally, conservators follow several principles. The original materials should remain intact and the repairs should not cause long-term damage. The restoration should be completely reversible, if possible. In the case of using a pinning repair to reconnect a break, the pinning site should not cause crack initiation in the sculpture. The process is difficult and time-consuming since the methods can be invasive. Therefore, the traditional method of drilling and installing pins is never undertaken lightly. Specifically within the bounds of the conservation of *Adam*, the goal was to maintain a tight join and a thin bond line. The breaks were fresh and the mating surfaces still fit tightly together, much different than with other historic sculpture with breaks that may be centuries old. Selecting adhesives to make the thinnest bond thickness was critical to recreate *Adam* as he was, reported in [4,5]. A second but equally important consideration was to design a repair system that would be as minimally invasive as possible with the least number of pins and drilled holes. This required careful analysis of the stresses on the sculpture in its entirety and across the join locations. Along with the pin number and locations, the pin material was a critical choice. From considerable study of the history and past applications in [3,6,7], conservators needed a pin that would not create stresses above what Carrara marble can endure.

Here we combine experimental and numerical studies of structural pin materials in the high stress zones of the *Adam* statue that was in need of repair. Six pin materials were selected for experimental study to reconnect two halves of a cored marble cylinder, cut at a 45° angle, and secured by a pin to create a join repair scenario similar to the actual fracture of the *Adam* statue. Two repair methods were studied, one without an adhesive and one with an epoxy adhesive, termed dry and wet repairs, respectively. In the wet join repair, the epoxy secured the pin in drilled holes in the marble substrate. No epoxy was permitted

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on the diagonal join surface. The numerical analyses were performed using finite element analysis (FEA). The FEA were validated by the results from the experimental work. FEA were also used to study the failure mechanisms in the repaired system. The stresses in the marble substrate around the repair area and the pin were simulated as the result of an enforced joint displacement. By understanding the possible failure mechanisms in the join repair, this study identified the pin material most suitable to repair this statue. The locations in need of a structural pin were identified previously [6] as the left knee and both ankles of *Adam*. Because of the inclination angle of the anticipated pins to the fracture lines, the pins in those locations needed to resist both tensile and shear stresses. For the structural repairs to be successful, the pin should not cause any further damage to the marble once placed, and thus not adversely affect the artwork's longevity. This project highlights the implications of engineering mechanics and numerical modeling in the conservation of art, sculptures, monuments, and buildings.

1.1. Background

The importance of combining science and conservation has not been understated. Idelson succinctly put it "The most authentic and irreplaceable contribution that conservation scientists can bring to the knowledge of heritage and to the improvement of the conservation techniques is in the different point of view that derives from the prevalence of natural sciences in their formation" [8]. Simply put, conservation needs science and vice versa. Outlined below are a few recent examples of collaboration between these engineering disciplines and conservation that are relevant to the work presented here on Tullio Lombardo's *Adam*.

The marble statue of *Neptune*, dating from the 3rd century CE, was retrieved from the Rhone River and restored in 2012. *Neptune* is currently on display at the Arles Museum of Antiquity in Arles, France. Michel et al. reported in [9,10] the results of numerical analysis that supplemented the physical repair of this monumental sculpture. This included 3D digital imaging of the individual pieces to evaluate reassembly options. Then, alignment pins and high-tension tie rods were installed to connect the components. A numerical analysis was performed that included grout between pieces, specific interface elements, and 1D structural elements representing the pins and tie rods. This analysis yielded stresses in the rock substrate that did not exceed accepted limits as found in the literature. However, the zone surrounding the structural elements was not analyzed for local stresses caused by anchorage. The behavior of the marble in simulations was considered linear elastic, and the stresses in marble were evaluated at the end of the analyses with regard to tension and compression stress limits. Additionally, anisotropy was neglected. The contact surface between marble pieces was modeled by frictional constraints.

Components of the grand scale project to restore the Acropolis of Athens monuments, including the Parthenon temple, were reported by Kourkoulis et al. in several publications: [11–14]. Of most interest to this work is [15], in which the effect of inclination angle to the fracture line of a threaded titanium rod was studied. The rod was installed to repair fractured epistyle pieces of Pentelic marble, and secured in the substrate with cement mortar. Scale model join repairs were fabricated and tested, and then modeled in FE using linear elastic material properties with isotropic behavior. The interfaces between the rod, mortar, and marble were defined with frictional constants. The finite element results were validated by comparing the force-displacement results of the repaired join with the experimental result, finding good correlation.

And while not reported on scientifically, the restoration of the statue *Juno*, 2nd century CE, by the Objects Conservation and Scientific Research Labs at the Museum of Fine Arts, Boston approached the problem in a similar manner over a two-year process of analysis and design which finished in 2013 [16]. The goddess' head, attached sometime after her initial creation, had been installed using an iron rod. This rod corroded over time, severely damaging the neck. Furthermore, a fracture spanned across her midsection. The conservators chose a post-tension rod to stabilize her torso, installed by drilling through down through the neck and anchored by plate beneath the waist. A new stainless steel pin reattached her head. Other pins were also installed at the base of the sculpture for stabilization through the supporting pedestal.

Common themes persist in the conservation efforts. First, NDT techniques are used to determine the stability of monumental pieces and any existing pins. Second, a 3D scan is performed to obtain a full digital model of the monument. Third, FE modeling supplemented either the physical restoration or specimen mockups of the restoration. The FE modeling may be created from the 3D scans or simplified geometry. Within the FE modeling, most often elastic properties are assumed and the contact between surfaces is greatly simplified by frictional constants.

2. Materials and methods

The mechanical performance of six pinning materials as join reinforcement for the marble statue *Adam* were studied: super-corrosion-resistant 316 stainless steel, high-strength lightweight carbon fiber reinforced polymer, highly corrosion-resistant grade 2 titanium, structural fiberglass reinforced polymer, impact-resistant polycarbonate, and Teflon® PTFE. The pin materials were commercially available at the time of experiments (McMaster-Carr, Elmhurst, IL, USA). The behavior of the each material as join reinforcement was then experimentally and numerically investigated.

2.1. Carrara marble

Carrara marble is a metamorphic rock quarried from the northwestern part of the Alpi Apuane region surrounding Carrara, Italy. It is a natural building material, and as such is characterized by microcracking [17]. It is widely used in monumental sculpture because of its homogeneity in appearance and composition. Furthermore, it is highly workable due to its rather low stiffness. It is a medium-grained white marble with intersecting grey veins. Composition is 99% calcite; the remainder is pyrite, quartz, albite, and white mica. Due to the nearly homogenous fabric, this marble has been used in rock-deformation experiments, where it has been shown to be nearly isotropic in relation to crystallographic orientation [2,18]. During metamorphic formation, it is prone to annealing which removes visible traces of deformation, and under large shear strains the grains are highly twinned [19]. It exhibits a high degree of dilatancy, where the material expands as it shears due to highly interlocked grains [20]. Microcracking is highly anisotropic and propagates inter and intra-granularly along grain boundaries. Flexural strength is dependent on specimen size, but is notch insensitive in testing, [17], and at confining pressures below 30 MPa Carrara marble is characterized by brittle fracture [21,22]. Alber and Hauptfleisch report the Young's modulus of Carrara marble is 49 GPa (7100 ksi), Poisson's ratio is 0.19, density is 2.65 g/cm^3, and porosity is 0.4% [22]. Jaeger and Hoskins report the uniaxial tensile strength is 6.9 MPa (1000 psi) [23], and Wong and Einstein report the uniaxial compressive strength is 84.63 MPa (12,200 psi) [24].

Consistent among experiments regarding microcracking of Carrara marble, a distinct transformed white area forms prior to coalescence of microcracking, which is needed to accommodate plastic deformation [25]. This white area is a location to three types of microcracking: inter- and intra-granular and spalling. The white areas also lead to tensile wing cracks and shear cracks; the white area was classified as a microcrack development zone [26]. These white patches were also found to coincide with macroscopic crack development, but white patches and cracks developed slightly differently under quasistatic and dynamic strain rates [27].