Article: An examination of pinning materials for marble sculpture
Author(s): Carolyn Riccardelli, George Wheeler, Christina Muir, George Scherer, and Joe Vocaturo
Source: *Objects Specialty Group Postprints, Volume Seventeen, 2010*
Pages: 95-112
Compilers: Carolyn Riccardelli and Christine Del Re

AN EXAMINATION OF PINNING MATERIALS FOR MARBLE SCULPTURE

CAROLYN RICCARDELLI, GEORGE WHEELER, CHRISTINA MUIR,
GEORGE SCHERER, AND JOE VOCATURO

ABSTRACT

The use of pins or dowels in repairing stone has been common since ancient times. Conventional wisdom in art conservation suggests that repair materials such as pins or adhesives should have similar properties (such as strength and modulus) to the substrate. Stainless steel continues to be the most commonly used pinning material even though it has a much higher elastic modulus than that of marble. When planning the repair of a sculpture that will remain in a controlled museum environment, the reasons for choosing stainless steel (corrosion resistance, coefficient of expansion) become less important, and thus open up a wider variety of choices for pinning materials. Therefore, a set of tests was designed with the goal of determining the performance of a join using pins with reported moduli ranging from 0.5 to 197 GPa. These pins were set into Carrara marble cores using an epoxy resin adhesive and subjected to compressive-shear stress. Under these conditions, fiber-based rods such as fiberglass and carbon fiber out-performed both stainless steel and titanium in that they were of sufficient strength to withstand the maximum static forces of the sculpture being repaired and did not damage the stone core before pin failure. From these tests, the best-performing pinning materials were used in making full-scale stone mock-ups to evaluate the overall performance of a pinning/adhesive bond system.

1. INTRODUCTION

This paper is a summary of research carried to determine the best conservation practices for Tullio Lombardo's *Adam*. The sculpture is one of the figures of the Vendramin tomb, which is now located in the church of *Santi Giovani e Paulo* in Venice. Dated 1490–1495, *Adam* is considered by scholars to be the most important monumental Renaissance sculpture in the Western Hemisphere (Remington 1937). It was acquired by the Metropolitan Museum of Art (MMA) in 1936.

In 2002, the sculpture fell when the pedestal beneath it collapsed. The sculpture, made of fine Carrara Marble, broke into several large pieces and many small fragments. The extremities of the figure, the arms, legs, as well as the decorative tree trunk, made up most of the fragments. The head and the torso were the least damaged and suffered minor losses.

The importance of the sculpture warranted a multidisciplinary collaboration to investigate new approaches to large-scale sculpture treatment. The Tullio team includes several conservators from the MMA's Sherman Fairchild Center for Objects Conservation (Lawrence Becker, Michael Morris, Carolyn Riccardelli, Jack Soultanian, and Richard Stone), members from the Department of Scientific Research (Marco Leona, George Wheeler), Curators from the Department of European Sculpture and Decorative Arts (Ian Wardropper, James Draper), as well as the supervisor of the museum's molding studio (Ronald Street).

In the time since the sculpture was damaged, the team has conducted extensive research in an effort to find the most suitable conservation treatment plan for this sculpture. Research has included CT scanning, 3-D laser scanning, and finite element analysis. Testing of conservation materials and methods has been systematically performed by teams of conservators, graduate students, and scientists.

2. BACKGROUND AND PREVIOUS RESEARCH

The high quality of *Adam*'s Carrara marble resulted in very clean breaks that fit together tightly. Thus, displacement of the fragments from added adhesive became a primary concern in choosing a treatment strategy. The characteristics of the breaks have guided the research approach throughout the project.

While many of the sculpture's breaks are in compression, there are a few critical joins that are in a combination of compression and shear (fig. 1). Some of the most critical joins are at the ankles where the weight of the entire sculpture rests on the smallest surface area. These breaks occurred at an angle approximately 45° from the base. Another break in compression-shear is at the knee where there is a wedge-shaped fragment bridging the shin and the thigh of the left leg. Finite element analysis[1] completed to date has shown that the load on any given join in the sculpture does not exceed 83 N/cm^2 (120 psi).

The tight joins found in the Tullio sculpture prompted the team to conduct adhesive testing with the goal of finding a strong reversible adhesive system with minimal glue-join thickness. Previous research has found that Paraloid B-72 alone or used as a barrier layer in combination with epoxy may be sufficiently strong under tension to be used as a structural adhesive (Podany et al. 2001).

Fig. 1. Model of *Adam*, made by Ron Street (Photograph by C. Riccardelli)

2.1 INTERFACIAL FRACTURE TOUGHNESS SUMMARY

Since 2005, the Tullio team has carried out several materials research projects. The goal of the first project was to find an adhesive system strong enough to withstand the forces in the sculpture but not displace the joins. Columbia University Graduate Student Mersedeh Jorjani carried out an investigation into the interfacial fracture toughness – or strength—of several conservation adhesives (Jorjani 2007; Jorjani, Wheeler, *et al*. 2009; Rahbar, *et al*. 2010). Nine common conservation adhesive systems were tested on samples made of Carrara marble. The tested samples consisted of disks containing an elliptical hole in the center. Multiple samples were tested with the elliptical hole oriented at different angles with respect to an applied load. The resulting tensile load was increased until the sample broke into two or more pieces. The critical load at which the fracture occurred for each loading angle was recorded.

The best-performing adhesive system tested was a 3:1 blend of Paraloids B-72 and B-48N (see table 1), which displayed an energy trend that was close to that of Carrara marble alone. It is interesting to note that although the fracture energy of the B-72/B-48N blend tested to be slightly lower than that of marble alone, most fractures occurred within the marble itself, and not in the glue join. The same types of fractures were reported by Podany et al. in their 2001 *JAIC* article. When looking at the overall performance of the nine adhesive systems the thermoplastics were found to be nearly as strong as thermosetting adhesives. All of the tested systems were determined to have high enough strength for use on Carrara marble.

On the basis of these tests, the B-72/B-48N blend was selected for the treatment of *Adam*, because of its strength and ease of reversibility. This adhesive blend also performed well in a glue-join thickness investigation carried out in coordination with the fracture toughness study, as it resulted in a thin enough bond-width as to not cause significant displacement of *Adam*'s joins.

Table 1. Recipe for thermoplastic adhesive blend

B-72/B-48N 3:1 Blend		
40 g B-72	54 g Acetone	6g EtOH
40 g B-48N	54 g Acetone	6g EtOH
Above two mixtures combined 3:1 by volume		

2.2 GLASS TRANSITION TEMPERATURE (T_g) TESTING

The goal behind combining the two thermoplastic adhesives was to adjust the T_g of B-72. It was thought that B-48N would raise the T_g of the blend and lead to better creep stability. Testing was carried out to determine the actual T_g of the adhesive blend. T_g testing was carried out at TA Instruments, facilitated by Dr. Gregory Smith of Indianapolis Museum of Art. The results were unexpected. The blend has a T_g of 46° C, only slightly higher than the tested T_g of B-72 alone (Smith 2010). It is interesting to note that in both cases the adhesives tested higher than the reported value, and in the case of B-48N substantially higher. The results of the T_g testing are given in table 2.

Table 2. Results of T_g testing

Adhesive	Tested T_g	Reported T_g
B-72	**45° C** (113° F)	40° C (104° F)
B-48N	**69° C** (156.2° F)	50° C (122° F)
B72-B48N 3:1 Blend	**46° C** (114.8° F)	n/a

2.3 CREEP TESTING SUMMARY

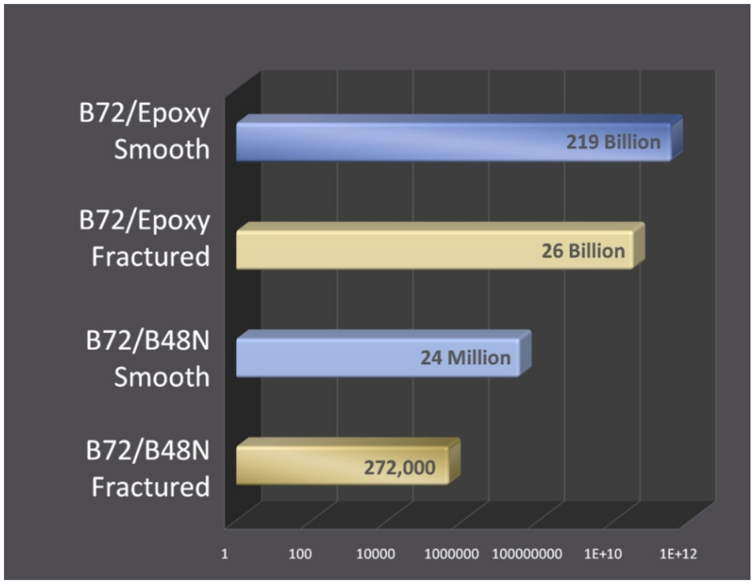
The Tullio team has also examined long-term stability of the tested adhesives, particularly in regards to creep. Columbia University Graduate Student, Andrea Buono, studied the creep behavior of adhesives for her Master's thesis using a testing procedure developed at the Princeton Center for Complex Materials at Princeton University; the study was overseen by Dr. Nima Rahbar (Buono 2009). The creep testing samples were prepared the same way as those for Jorjani's fracture toughness study. Two sample sets were prepared for each adhesive system, one with smooth join surfaces and one with fractured surfaces. A KG-B20 Krak-Gage[2] was applied to each sample, which was then connected to a voltage meter. The sample was subjected to a load that was increased in incremental stages until some deformation was detected. All testing was done at room temperature.

The results of the load testing were subjected to mathematical calculations in order to extrapolate the short-term results into predictions of creep life over the long-term. The results are given in table 3.

Thermoplastics performed as well as thermosetting adhesives when the lifetime of a sculpture is taken into consideration. The graph indicates a very long-term gestation period for adhesive failure caused by creep. The adhesives tested can be classified as a Feller Class A2 material, lasting at least 100 years (Horie 1987). The B-72/B-48N blend performed very well for a thermoplastic adhesive and ranked a close second behind the B-72:Epotek 301-2 sandwich.

It is interesting to note that creep life predictions for smooth samples were higher by many of thousands of years compared to fractured samples made with the same adhesive. A possible explanation may be that an adhesive on smooth surfaces creates a more consistent bond, devoid of flaws. This result brings to the forefront the importance of how a conservator applies adhesive, and that a continuous, consistent film is critical to the strength of a joint.

Table 3. Creep life predictions (in years) (Adapted from Buono 2009)



3. PINNING RESEARCH

3.1 MODULUS TESTING

In a similar approach to the adhesive research, the Tullio team aimed to find a pinning material that would be strong enough to impart additional mechanical strength in the break, but not be so stiff as to cause damage in case the sculpture is ever subjected to future impacts. The early stages of the pinning testing were carried out by Columbia University graduate student Christina Muir who reported the results in her Master's thesis (Muir 2008). The research was done in cooperation with the Tullio team as well as Wole Soboyejo and Nima Rahbar of the Princeton University Department of Mechanical Engineering

The pinning research began with basic modulus testing. Modulus of Elasticity (E) is an indication of the stiffness of a material. The goal of the study was to determine if the stiffness of a pinning material effects how it behaves and performs in contact with marble. A variety of materials were chosen with a range mechanical properties, and elastic moduli. Pins were chosen based on their published modulus values, listed in table 4.

Because it was not always clear how the reported values were calculated, systematic testing of all materials was carried out with a single consistent technique. Samples of each material were tested using an Instron 4201, following the procedure for the ASTM Standard Testing Method for Ceramic Whiteware Materials (ASTM Standard C674-88), which is a 3-point bend test. Rods measuring 9.5 mm in diameter were cut into 100-mm lengths and placed on bearing edges spaced 76.5 mm apart. A load was applied at the midpoint between the two supports (fig. 2). Five specimens of each material were tested until either the material failed or they reached full extension.

Material	Reported Modulus GPa
Teflon®	0.5
Nylon	2.1
Acrylic	2.8
Polycarbonate	3.9
Kevlar®/Nylon	5.5
Fiberglass	35
Marble	55
Titanium	103
Carbon Fiber Reinforced Plastic	Unrated
Stainless Steel	197

Table 4. Reported moduli of tested pinning material

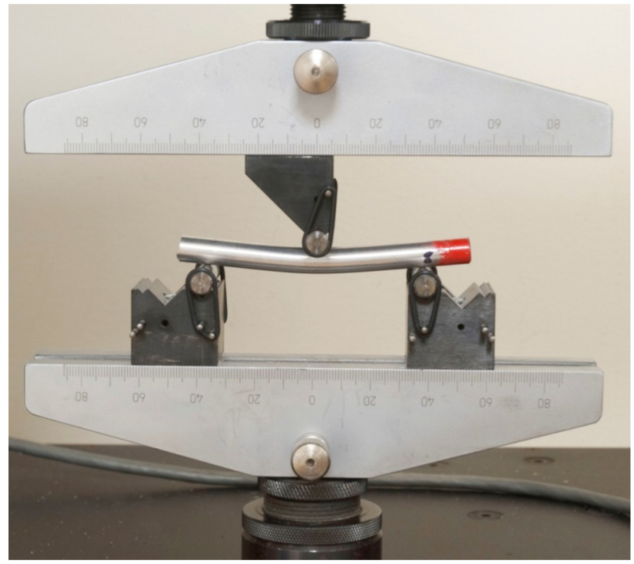


Fig. 2. Three-point bend testing technique (Photograph by C. Riccardelli)

The results are plotted in a graph of load *vs.* displacement. The graph describes two essential pieces of information about the pinning materials: the elastic modulus of a material—or its stiffness—and its mode of failure. The modulus of elasticity is determined along the initial slope of the graph as follows:

$$E = 4W^1L^3/3 \quad d^4$$

where:

W^1 = load coordinate of the selected point (N)

L = length of the span (mm)

= deformation coordinate of selected point; *i.e.* displacement (mm)

d = diameter of specimen (mm) (ASTM Standard C674-88 2006, 4).

Figure 3 shows stress/strain curves for brittle failure (as with marble) and ductile failure (as with stainless steel). In ductile materials there is an elastic region (a) where the graph is nearly linear, and a ductile region (b), where there is significant strain before failure brittle materials (c) deform elastically until fracture occurs, they do not experience plastic deformation before failure. Such stress/strain curves correspond directly to the force/displacement curves illustrated in the remainder of this paper.

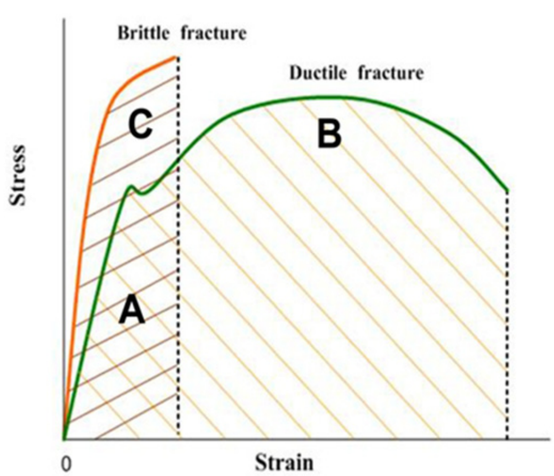


Fig. 3. Types of stress/strain curves

Stainless steel 316 is commonly used as a pinning material in marble sculpture, and has been chosen because of its strength and resistance to corrosion. The force/displacement graph produced from testing illustrates a typical ductile material with a linear elastic region and a long ductile region. It is in this ductile region that the material becomes permanently deformed as can be seen in the image of the tested samples (fig. 4, right). The calculated average modulus for stainless steel 316 was 55.58 GPa.

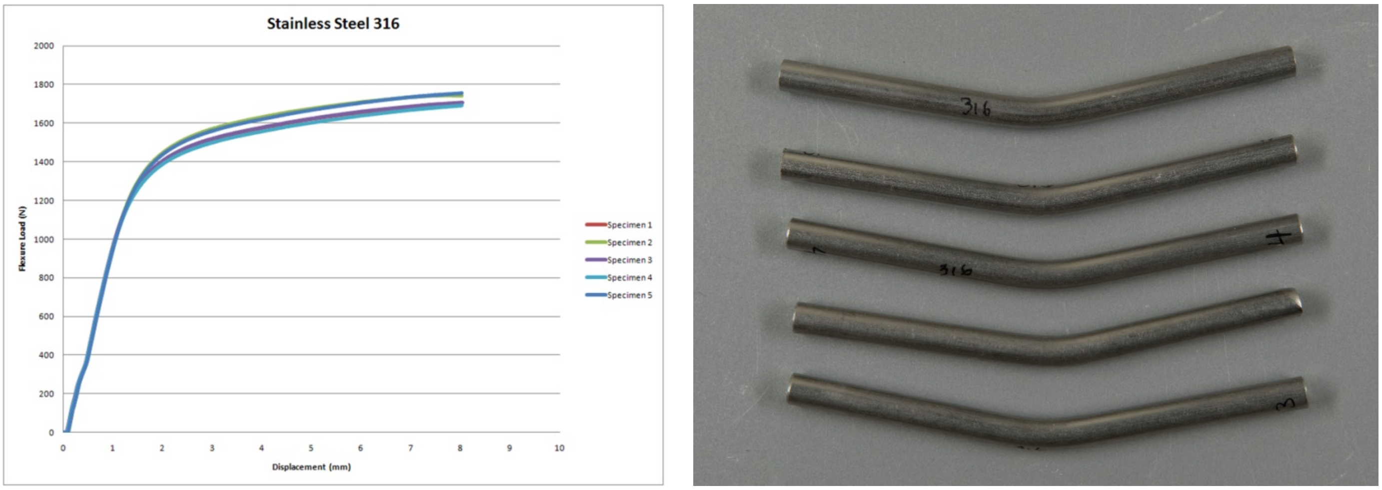


Fig. 4. (left) Force/displacement graph for stainless steel 316 rods
(right) Stainless steel specimens showing ductile characteristics after testing (Photograph by C. Riccardelli)

On the other end of the modulus spectrum, are mold-cast Akemi Akepox 2000 rods. These rods were made to help answer what might happen if a pin hole were filled only with epoxy and no other material. While epoxy is generally thought of as an extremely hard material as an adhesive, in this form it is quite weak. The resulting force/displacement graph (fig. 5) shows that the epoxy rods produced an elastic region with low slope followed by a period of elastic deformation, and finally brittle failure. The modulus was calculated to be 3.26 GPa, which is similar to the elastic modulus of acrylic (Plexiglas) rods.

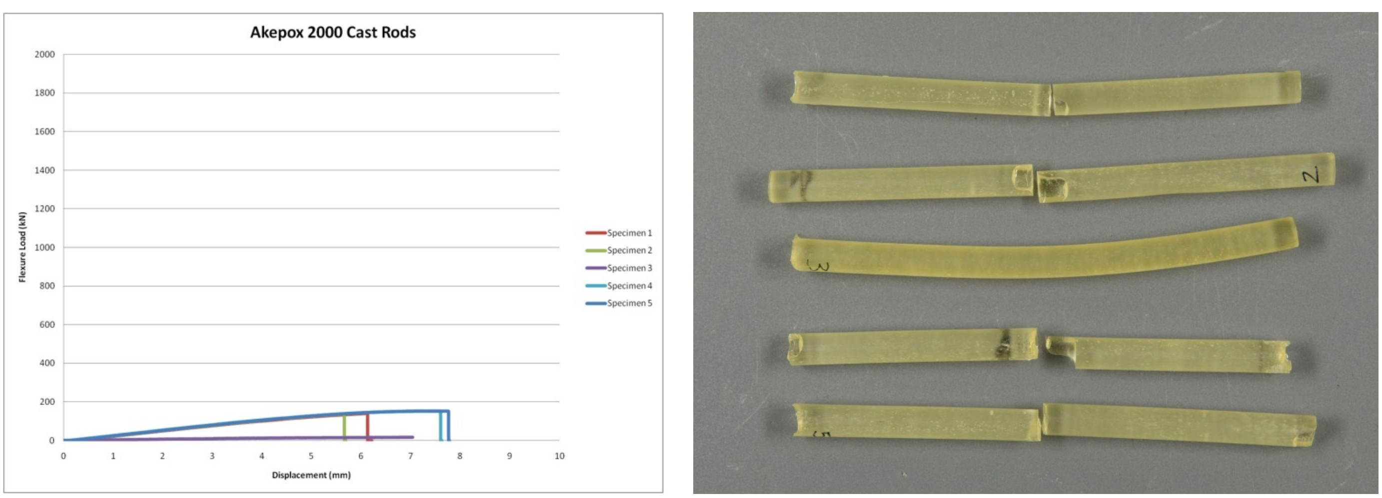


Fig. 5. (left) Force/displacement graph for Akemi Akepox 2000 rods
(right) Akemi Akepox 2000 specimens showing brittle failure after testing (Photograph by C. Riccardelli)

Carbon fiber reinforced plastic (CFRP) rods produced a graph with a steep elastic region, which is followed by a sudden failure, and then a wavy region. This type of failure, described as a kink, is typical of composite materials. It has neither a brittle or ductile fracture and the rod does not break in two (fig. 6, right). Rather, the vinylester plastic component fails but the fibers do not, thus producing a kink. The tested modulus of CFRP was 28.2 GPa.

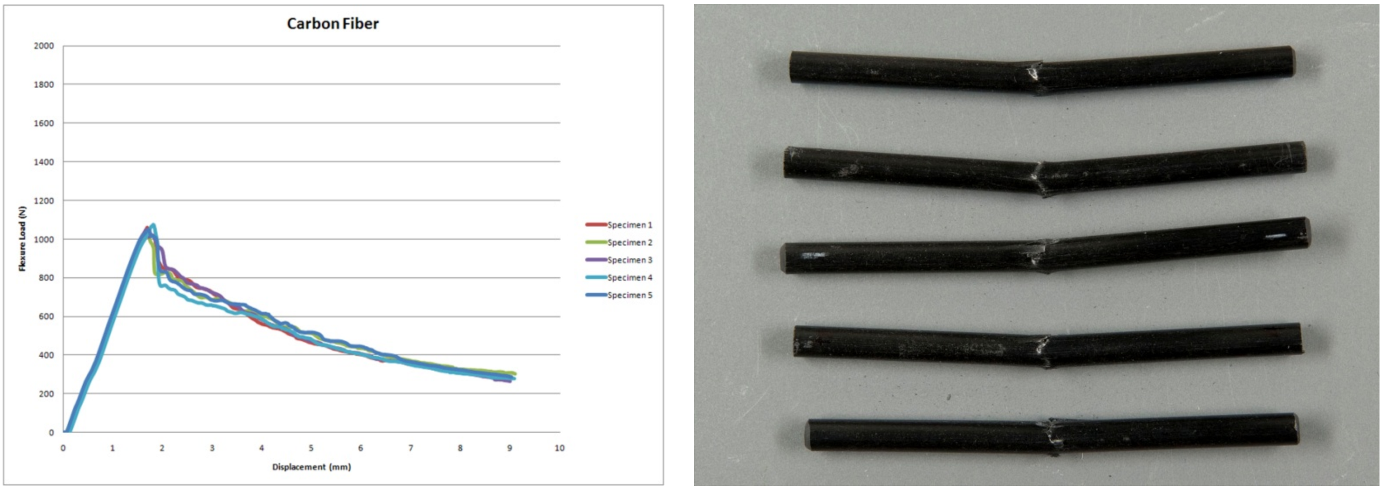


Fig. 6. (left) Force/displacement graph for CFRP rods
(right) CFRP specimens showing kinked failure after testing (Photograph by C. Riccardelli)

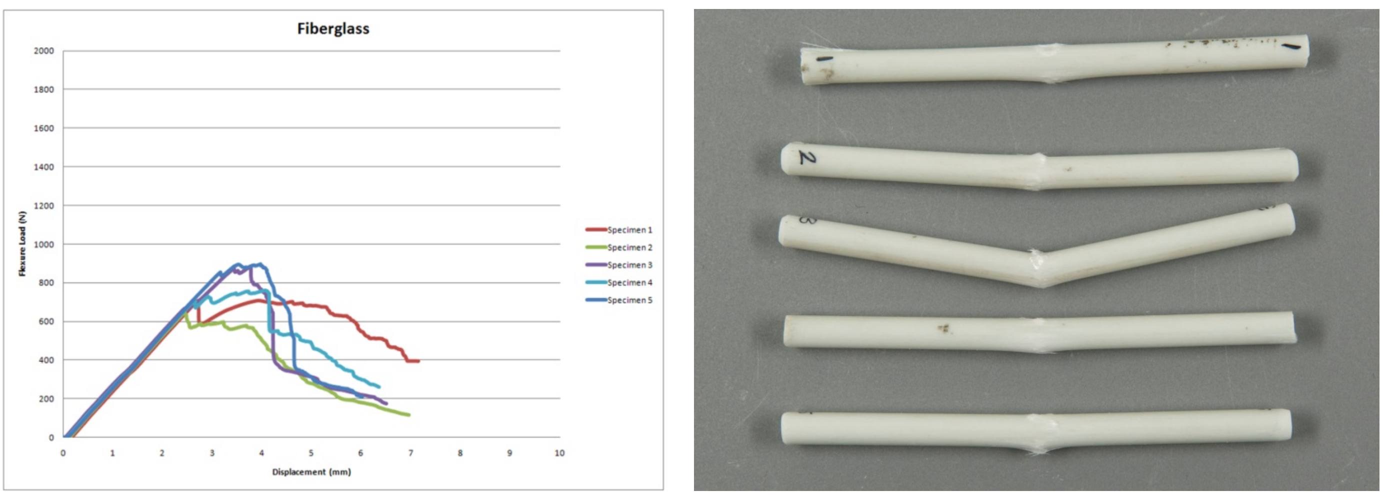


Fig. 7. (left) Force/displacement graph for structural fiberglass rods
(right) Fiberglass specimens showing kinked failure after testing (Photograph by C. Riccardelli)

Structural fiberglass rods are also fiber based composites; in this case fiberglass fibers are embedded in a polyester resin. There is a kinking failure mode, as with carbon fiber rods, but with a lower slope (fig. 7). The tested modulus for structural fiberglass was 14.8 GPa.

Finally, a set of 9mm diameter Carrara marble cores were drilled with a diamond core bit and subjected to 3-point bend testing (fig. 8). The tested modulus for Carrara marble was 6.7 GPa. This modulus is significantly lower than the reported modulus for Carrara because it describes the marble under compression. The three-point bend testing illustrates the weakness of marble in tension.

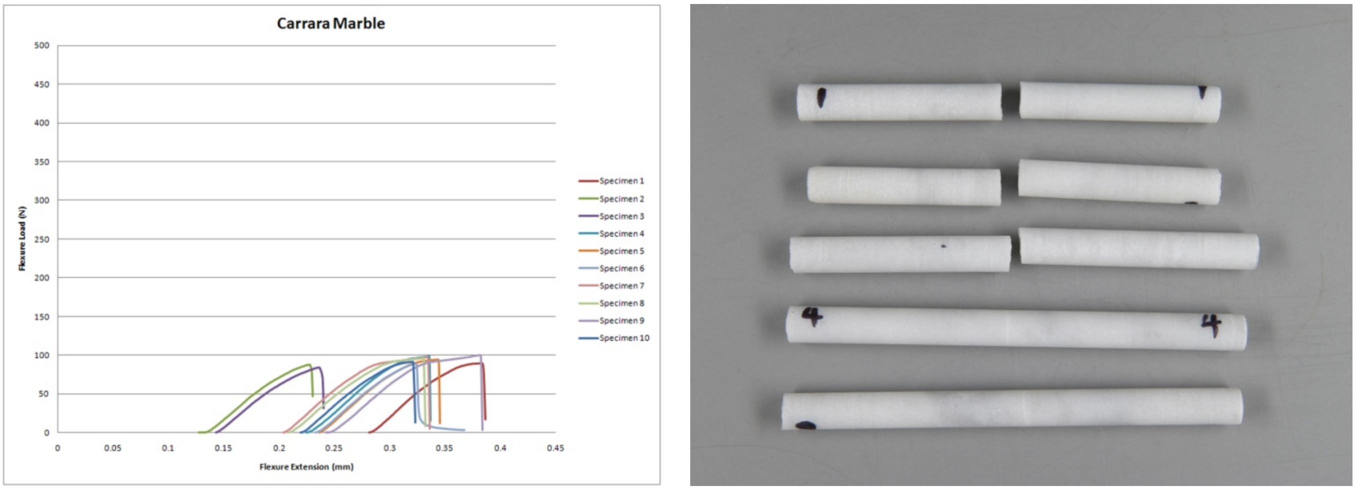


Fig. 8. (left) Force/displacement graph for Carrara marble cores
(right) Carrara specimens showing brittle failure after testing (Photograph by C. Riccardelli)

The results of the modulus testing are summarized in Table 5 5. The tested moduli differed quite a bit from the reported moduli, especially in the upper end of the range. Again, this exercise was done because the testing methods of the reported moduli were not given by their manufacturers, and a consistently obtained modulus for each material was desired.

Table 5. Results of elastic modulus calculations

Material	Reported Modulus	Mean Tested Modulus (GPa)
Teflon®	0.5	0.4
Nylon	2.1	1.5
Acrylic	2.8	2.2
Polycarbonate	3.9	1.9
Kevlar®/Nylon	5.5	2.8
Fiberglass	35	14.8
Marble	55	6.7
Titanium	103	41.6
CFRP	Unrated	28.2
Stainless Steel	197	55.6

3.2 SMOOTH SURFACE MOCK-UPS

After modulus testing was completed, a set of full-scale models representative of the critical joints in the *Adam* sculpture were prepared. This first set of samples was designed to look specifically at the pin itself. The specimens were designed so that they would essentially isolate the behavior of the pin without interference by the join surface. The goal of this testing was to determine what happens to the marble when there is no adhesive on the joining surfaces, being dependent on the pin to hold the system together.

3.2.1 Sample Preparation

The samples were made with Carrara marble cores, measuring 10.2 cm in diameter and 20.3 cm long. Each core was cut at a 45° angle across the center of the cylinder using a Buehler Slab Saw. The angled surface was smoothed to minimize friction between the upper and lower halves and to focus force on the pin alone. Pin holes were drilled with a Lunzer diamond core bit on a drill press equipped with a water swivel. Akemi Akepox 2000 epoxy resin was used to secure the pins in place. Adhesive was not permitted to get on the smooth angled surface of the marble. For this set of samples the pins used were 10.2 cm long with a diameter of 1.4 cm. The pins were set into one half of the cylinder first, filling the adhesive up to the angled surface of the marble. The next day, that half was flipped over and inserted into the second half which had just enough epoxy inserted into it so it did no overflow onto the smoothed angled surface (fig. 9, left). Following a full cure time, testing was carried out at Princeton University in the Department of Mechanical Engineering Laboratory using an Instron 8501 Mechanical Testing Machine (Muir 2008).

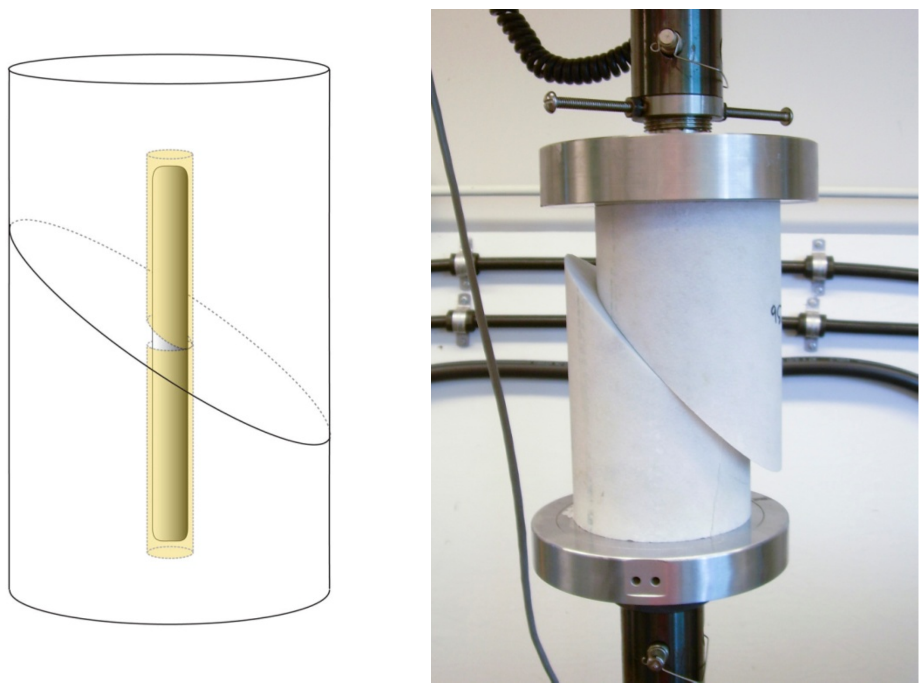


Fig. 9. (left) Diagram of smooth surface mock-up; yellow area indicates epoxy
(right) Smooth surface sample being tested in Instron (Diagram by C. Riccardelli, photograph by C. Muir)

All samples were subjected to gradually increasing compression loading at a rate of 0.01 mm/sec until there was failure of either the pin or the marble core. The combination of the downward compressive force of the Instron combined with the 45° angle results in an overall compression-shear force (fig. 9, right).

3.2.2 Stainless Steel 316 Testing Results

Stainless steel 316, with a calculated elastic modulus of 55.6 GPa is much stiffer than marble, which was tested to have a modulus of 6.7 GPa. When the specimen was pushed to failure, the pin remained intact, completely fracturing the core. A Y-shaped failure was typical for stainless steel as well as titanium (fig. 10). While the force required to reach failure (average maximum load: 77 kN) in this test is higher than normal forces that exist in Tullio's *Adam*—and likely most marble sculptures—it does give an indication of what might happen should a sudden impact occur.

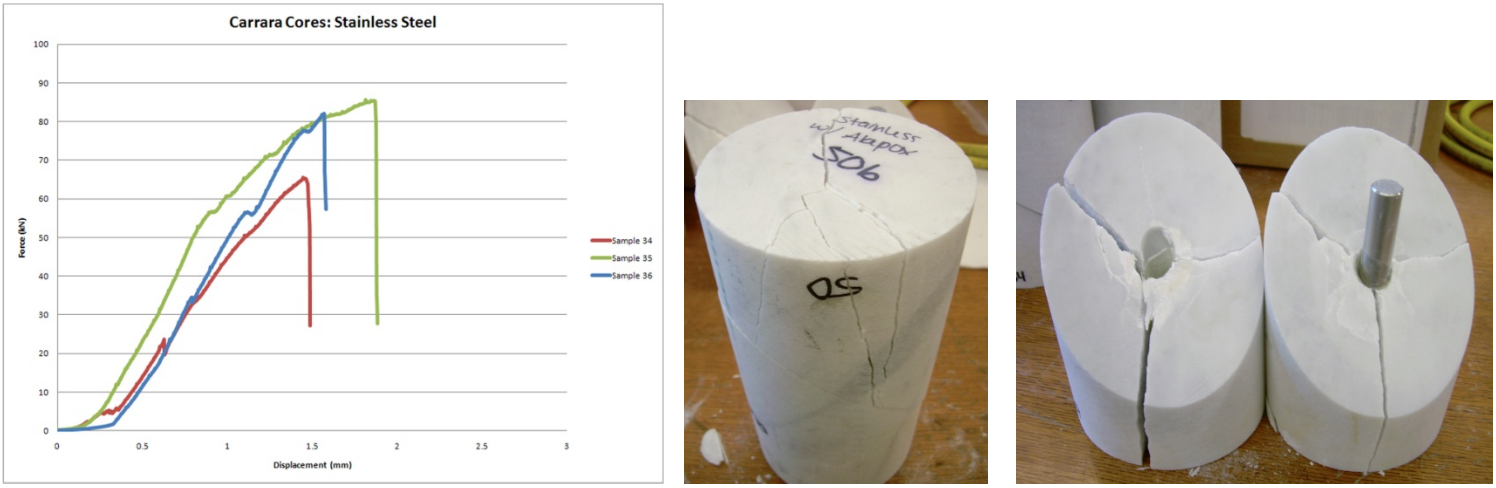


Fig. 10. (left) Force/displacement graph for stainless steel 316 in smooth surface Carrara core (center and right) Carrara cores after testing, severe damage to core (Photographs by C. Muir)

3.2.3 Carbon Fiber Reinforced Plastic Testing Results

Testing showed that CFRP rods have an elastic modulus of about 28.2 GPa. In all three carbon fiber specimens tested, the marble core remained intact. The pin failed at an average maximum load of 62 kN. In one sample, the pin just displaced and did not completely separate, displaying the kinking behavior typical of fiber based composite materials.

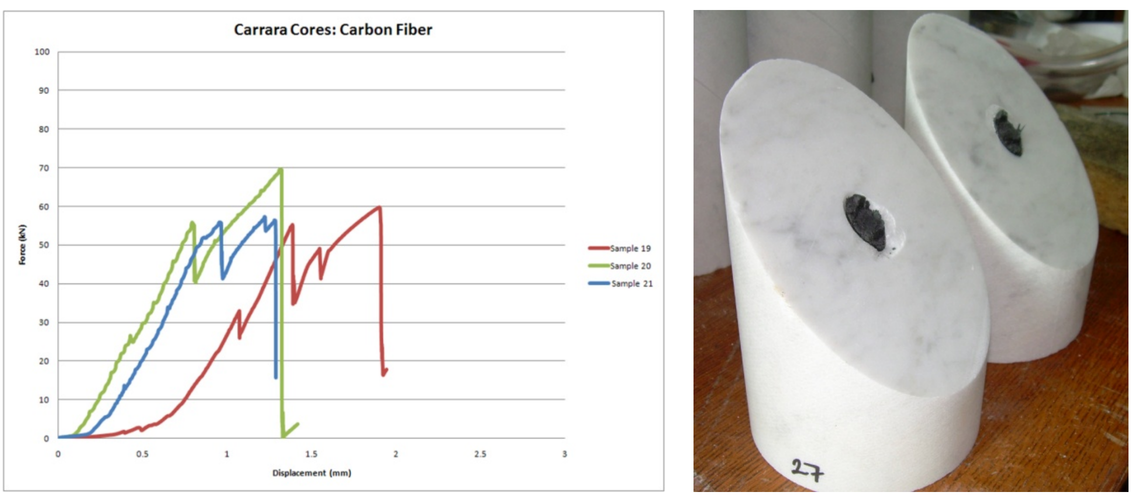


Fig. 11. (left) Force/displacement graph for carbon fiber rods in smooth surface Carrara core (right) Carrara core after testing, pin failure with no damage to core (Photograph by C. Muir)

3.2.4 Structural Fiberglass Testing Results

Not surprisingly, fiberglass behaved very similarly to CFRP, but failed at a lower maximum load. The modulus testing showed that fiberglass has an elastic modulus about two times that of marble. There was no damage to any of the marble cores with fiberglass pins, and all pins broke cleanly through (fig. 12). The average maximum load to break the fiberglass rod embedded in the marble core was 59 kN—10 kN less than carbon fiber rods.

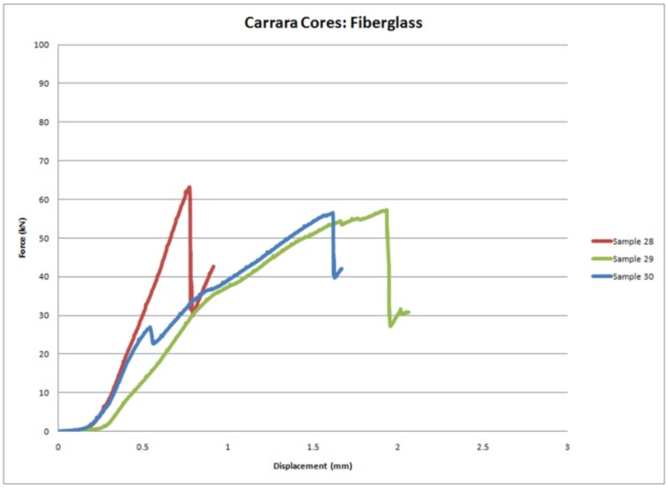


Fig. 12. (left) Force/displacement graph for structural fiberglass rods in smooth surface Carrara core (right) Carrara core after testing, pin failure with no damage to core (Photograph by C. Muir)

3.2.5 Polycarbonate Testing Results

Polycarbonate rods are in the low end of the tested moduli. When tested, these plastic rods did not cause any damage to the marble cores. Significant plastic deformation occurred to the rod, as can be seen in fig. 13. The average maximum load for polycarbonate was substantially lower at 32 kN.

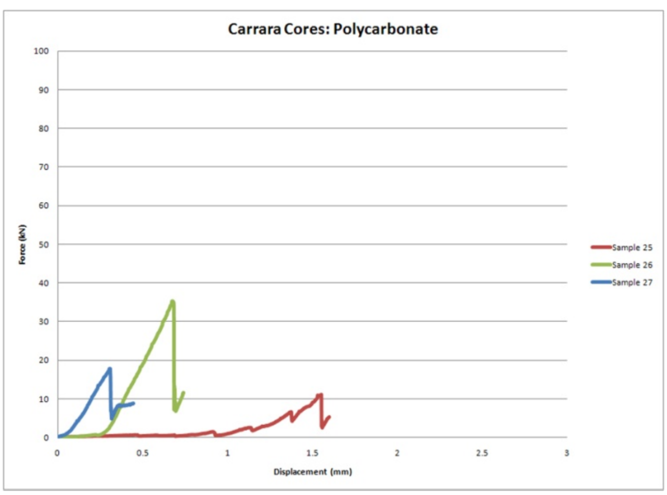


Fig. 13. (left) Force/displacement graph for polycarbonate rods in smooth surface Carrara core (right) Carrara core after testing, pin with plastic deformation (Photograph by C. Muir)

3.2.6 Summary

The smooth surface testing set showed that the average maximum load corresponds well with the tested moduli of the pinning materials. Metal pins with their high elastic modulus proved too stiff, and caused the marble cores to break apart under an applied load. Fiber pins performed better and did not cause damage to the stone. Rather, the pin failed at a relatively high applied load, indicating that these materials would be able to withstand the forces in a marble sculpture without causing damage to the stone in case of impact. Plastic pins with very low elastic moduli did not cause damage to the marble cores, but failed at an unacceptably low applied load.

3.3 FRACTURED SURFACE MOCK-UPS

Based on the results of the smooth surface tests, a selection of pinning materials were chosen for the fractured surface mockups. Titanium, CFRP, and structural fiberglass rods were chosen based on their promising performance in the smooth surface tests. This set of samples was designed as a mock-up of *Adam*'s ankle joins.

3.3.1 Sample Preparation

The fractured samples were prepared with the same 45° angle as the Carrara marble smooth surface set, but with a fractured join surface. The cores were smaller in scale—6.4 cm in diameter and about 15.2 cm tall. Because it was simpler to obtain and more affordable, the cores from this sample set were made of Vermont marble. Two pin-holes[3] were drilled into each core with a Lunzer diamond core bit. The pin holes were then coated with a generous barrier layer of 10% B-72 w/w in acetone, and allowed to sit for several days.

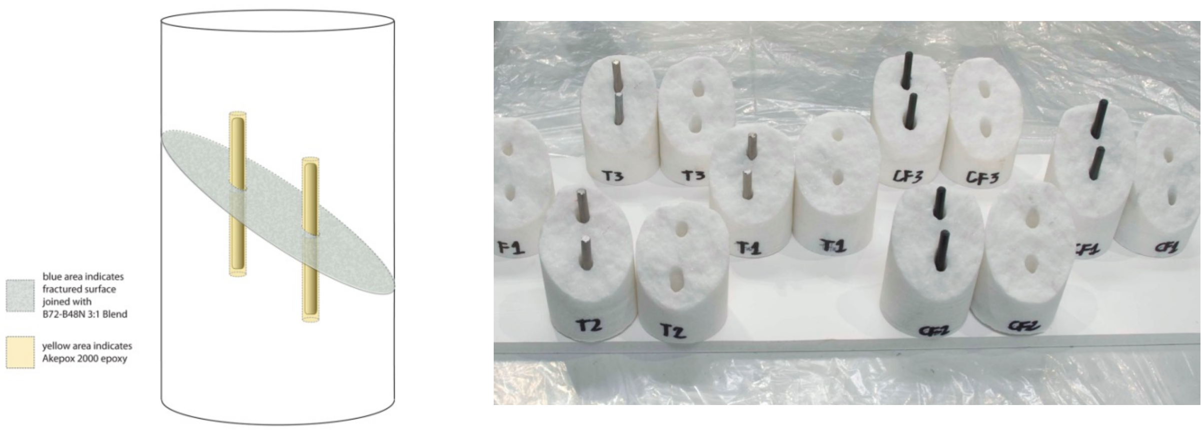


Fig. 14. (left) Diagram of fractured-surface mock-up (yellow area is epoxy, blue area is B-72/B48N blend) (right) Samples being prepared for joining (Diagram and photograph by C. Riccardelli)

Pins 0.635 cm in diameter and 5.1 cm in length were set into the pinholes using Akemi Akepox 2000 epoxy in a similar manner as described for the smooth surface specimens. The fractured surfaces were joined with the B-72/B-48N blend (fig. 14). For the testing, all samples were subjected to gradually increasing compression loading at a rate of 0.05 mm/sec until there was failure of either the pin or the marble core.

3.3.2 Titanium (Grade 2) Testing Results

Titanium has commonly been used to repair marble sculpture and outdoor monuments because of its resistance to corrosion and its coefficient of expansion similar to marble. As with the smooth surface cores, titanium caused damage to the marble. All three samples were severely fractured while the titanium pin inside the sample was only slightly deformed by the applied load (fig. 15). The average maximum load for titanium was 59.41 kN.

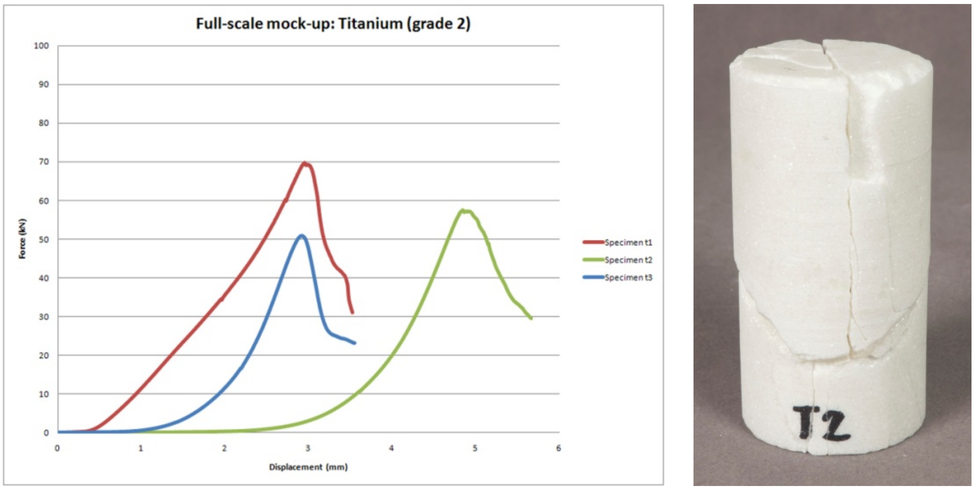


Fig. 15. (left) Force/displacement graph for titanium grade 2 rods in fractured-surface marble core
(right) Sample after testing showing damage to stone (Photograph by C. Riccardelli)

3.3.3 Carbon Fiber Reinforced Plastic Testing Results

While testing did not show any damage to the smooth surface cores with CFRP rods, there was cracking in two out of the three fractured surface mock-ups CFRP rods (fig. 16). The elastic modulus of CFRP tested quite a bit higher than marble itself, so it is not a surprising result. The average maximum load in this sample set was 57.03 kN.

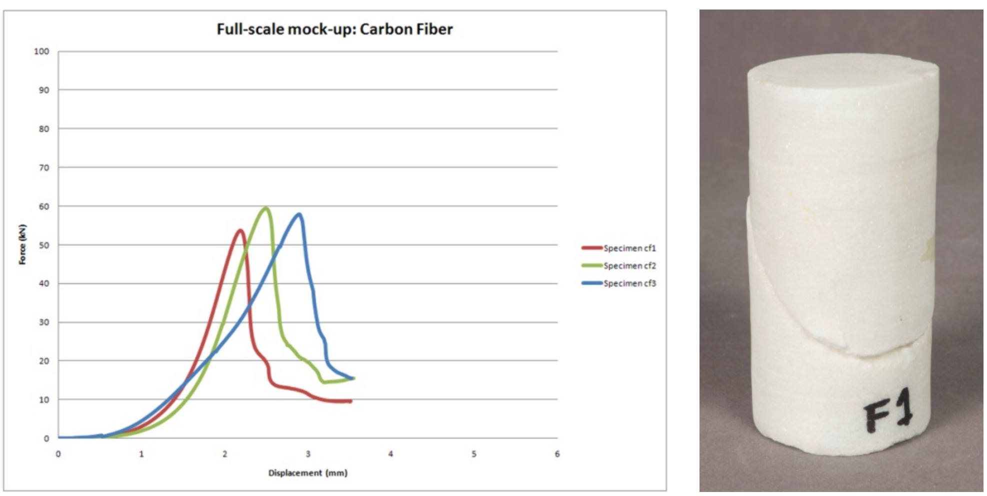


Fig. 16. (left) Force-displacement graph for CFRP rods in fractured surface marble core
(right) Sample after testing showing damage to stone (Photograph by C. Riccardelli)

3.3.4 Structural Fiberglass Testing Results

Structural fiberglass rods performed the best in the fractured surface mockups causing no damage to the marble cores. In each sample, both the adhesive in the join and the fiberglass pins failed before there was any damage to the marble core, creating an ideal pinning system (fig. 17). The average maximum load for fiberglass pins was 41.51 kN.

Fig. 17. (left) Force-displacement diagram for structural fiberglass rods in fractured surface marble core (center and right) Sample after testing showing no damage to stone and clean break of pin (Photographs by C. Riccardelli)

3.3.5 No-Pin Testing Results

A set of cores fractured at 45° angle was adhered with no pin holes and no pins. This set was adhered only with the B-72/B-48N blend. After testing, there was no damage to any of the marble cores (fig. 18). The average maximum load was 50.65 kN, more than 9 kN higher than the fractured surface sample set made with structural fiberglass rods.

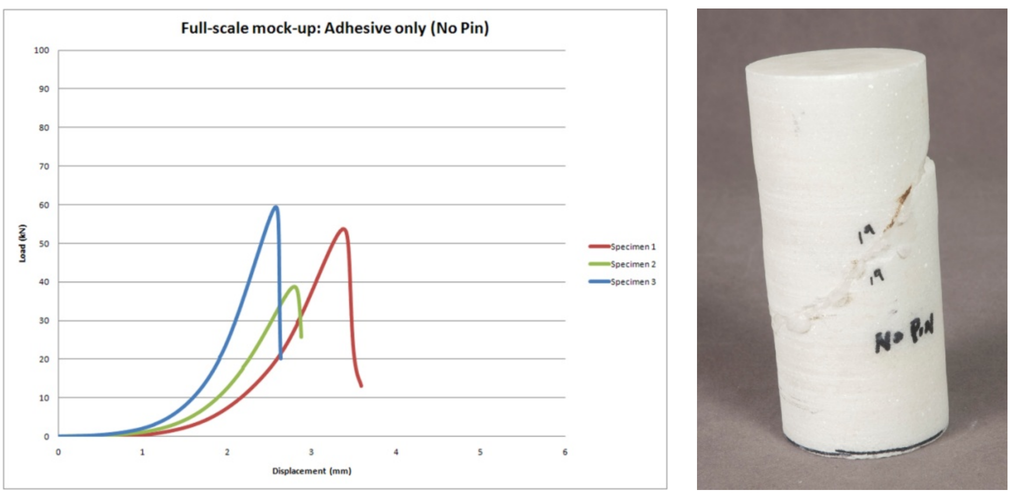


Fig. 18. (left) Force/displacement graph for fractured surface marble core with no pins (right) Sample after testing showing no damage to stone (Photograph by C. Riccardelli)

4. CONCLUSIONS

The use of pins or dowels in repairing stone has been common since ancient times. Conventional wisdom in art conservation suggests that repair materials such as pins or adhesives should have similar properties (such as strength and modulus) to the substrate. Stainless steel continues to be the most commonly used pinning material even though it has a much higher elastic modulus than that of marble.

When planning the repair of a sculpture that will remain in a controlled museum environment, the reasons for choosing stainless steel (corrosion resistance, coefficient of expansion) become less important, and thus open up a wider variety of choices for pinning materials. Fiber-based rods such as fiberglass and carbon fiber out-performed both stainless steel and titanium in that they were of sufficient strength to withstand the maximum static forces of the sculpture being repaired and did not damage the stone core before pin failure. It is significant that the set of fractured surface mock-ups prepared with adhesive only—and no pins—out-performed the sample set prepared with the best–performing fiberglass rods. All pins tested in the fractured surface mock-ups showed strength several orders of magnitude greater than the actual loads on the sculpture.

Will any of the joins on the *Adam* be pinned? It is the wish of the Tullio team to be as minimally invasive as possible, and to scale back the conventional approach to structural sculpture conservation. The jury is still out.

ACKNOWLEDGEMENTS

The author wishes to thank her colleagues at the Metropolitan Museum of Art for their collegial support while the Tullio Team has pursued this research, especially George Wheeler, Michael Morris, and Lawrence Becker. This project would not be possible without the cooperation of scientists at the Princeton University School of Engineering and Applied Science, who have provided guidance in sample preparation, testing protocols, as well as interpretation of data. The graduate interns, Mersedeh Jorjani, Christina Muir, and Andrea Buono have been crucial to the completion of this research. Thank you to Joannie Bottkol for her assistance in sample preparation. Finally, the authors would like to thank curators Ian Wardropper and Jim Draper who have patiently supported this project.

NOTES

1. Finite Element Analysis (FEA) is accomplished by a computer model of a material that is analyzed for specific results. FEA is often used as a method of predicting failure by identifying problem areas and theoretical stresses within a material.

2. The Krak-Gage is a critical part of the fatigue-crack growth testing method. It is a thin, photo-etched, low-resistance metal foil, which functions as a DC transducer. The gages are bonded to the test specimen, and they yield a linear change in resistance vs. crack length. A propagating crack in a test specimen simultaneously propagates through the Krak-Gage. The change in voltage from the displacement of the Krak-Gage is translated to the attached Fractomat voltage meter and subsequently recorded by data acquisition software. The software then graphs crack length (a) *vs.* time (t). http://www.krak-gage.com/krakgage.html

3. At the time of sample preparation, the Tullio team was considering using two small pins in the ankle in order to counteract the natural torque of the figure, as was determined by finite element analysis. Since that time, the team has decided to return to a single-pin scenario.

REFERENCES

ASTM Standard. C674-88. 2006. *Standard test methods for flexural properties of ceramic whiteware materials.* West Conshohocken, PA: ASTM International. DOI: 10.1520/C0674-88R06.

Buono, A. 2009. *Adhesives for marble and their creep behavior.* Master's thesis, New York: Columbia University.

Horie, C.V. 1987. *Materials for conservation.* London; Boston:Butterworths.

Jorjani, M. 2007. *An evaluation of adhesives for marble repair.* Master's thesis, New York: Columbia University.

Jorjani, M., G. Wheeler, C. Riccardelli, W. Soboyejo, and N. Rahbar. 2009. An evaluation of potential adhesives for marble repair. In *Holding it All Together: ancient and modern approaches to joining, repair and consolidation*, ed. Janet Ambers, Lynne Harrison and David Saunders. London: Archetype Publications. 143–149.

Muir, C. 2008. *Evaluation of pinning materials for marble repair.* Master's thesis, New York: Columbia University.

Podany, J., K. M. Garland, W. R. Freeman, and J. Rogers. 2001. Paraloid B-72 as a structural adhesive and as a barrier within structural adhesive bonds: evaluations of strength and reversibility. *Journal of the American Institute for Conservation* 40(1): 15–33.

Rahbar, N., M. Jorjani, C. Riccardelli, G. Wheeler, I. Yakub, T. Tan, and W.O. Soboyejo. 2010. Mixed mode fracture of marble/adhesive interfaces. *Materials Science and Engineering: A* 527(18-19): 4939–4946.

Remington, P. 1937. Adam by Tullio Lombardo. *The Metropolitan Museum of Art Bulletin* 32, 49(3): 58–62.

Smith, G. 2010. Personal communication, e-mail message to author. Senior Conservation Scientist, Indianapolis Museum of Art, Indianapolis IN.

SOURCES OF MATERIALS

Akemi Akepox 2000
Stone Boss
26-04 Borough Place
Woodside, NY 11377

Paraloid B-72, Paraloid B-48N
Talas
330 Morgan Avenue
Brooklyn, NY 11211

Vermont and Carrara marble
ABC Stone
234 Banker Street
Brooklyn, NY 11222

All pinning materials
McMaster Carr
P.O. Box 5370
Princeton, NJ 08543-5370

CAROLYN RICCARDELLI holds an M.A., certificate of advanced study (C.A.S.) in conservation from Buffalo State College and a B.A. from Newcomb College of Tulane University. She is a Professional Associate of AIC and served as program chair for OSG in 2010. Carolyn is currently associate conservator in the Sherman Fairchild Center for Objects Conservation at the Metropolitan Museum of Art, where she specializes in large scale objects. Address: Metropolitan Museum of Art, Sherman Fairchild Center for Objects Conservation, 1000 Fifth Avenue, New York, NY 10028-0198. E-mail: carolyn.riccardelli@metmuseum.org

GEORGE WHEELER is Director of Conservation of the Historic Preservation Program at Columbia University. Address: 400 Avery, 1172 Amsterdam Avenue, New York, NY, 10027. E-mail: gw2130@columbia.edu

CHRISTINA MUIR Address: Mesick-Cohen-Wilson-Baker-Architects, 388 Broadway Albany, NY 12207. E-mail: cmuir@mcwb-arch.com

GEORGE SCHERER is William L. Knapp Professor of Civil & Environmental Engineering at Princeton University School of Engineering and Applied Science, Dept of Mechanical and Aerospace Engineering. Address: Engineering Quad, Room E-319, Princeton, NJ 08544. E-mail: scherer@princeton.edu

JOE VOCATURO Address: Princeton University, School of Engineering and Applied Science Dept of Civil and Environmental Engineering, Engineering Quad, Room E-209B, Princeton, NJ 08544. E-mail: vocaturo@princeton.edu