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# The Treatment of Tullio Lombardo's *Adam*: A New Approach to the Conservation of Monumental Marble Sculpture

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When the pedestal supporting Tullio Lombardo's marble *Adam* collapsed, there were no witnesses present in the Vélez Blanco Patio where the sculpture was displayed. However, its timing was documented almost to the second by a security camera programmed to scan the galleries at eight-second intervals. Images from the camera showed that on October 6, 2002, at 5:59 p.m. and 30 seconds, the floor was clear; at 5:59 p.m. and 38 seconds, the head of *Adam* was on the floor of the patio.

Museum Security discovered the sculpture that evening, and the tragic consequences of the collapse were immediately apparent. On impact, this lifesize sculpture broke into twenty-eight large pieces and hundreds of smaller fragments. Fortunately, the head, face, and torso, still connected to Adam's right thigh, were relatively unscathed in the fall, but the arms, which bore the brunt of the impact, and the lower legs suffered major damage.

The decision to reconstruct the sculpture and restore this Renaissance masterpiece as closely as possible to its appearance before the accident was made almost immediately. From the outset, however, it was clear that the treatment of the broken sculpture would be a formidable project, posing an unusual, perhaps even unprecedented, series of challenges with little in the way of past practice to draw upon. When faced with reassembling large-scale stone sculpture, conservators are most often dealing with ancient, archaeological sculpture, its surfaces weathered by burial. Because break surfaces have eroded over time, fragments do not fit together securely, if at all. The major challenge for conservators in these cases is to correctly align and join elements with few points of contact. Gaps and losses between fragments are common and often need to be bridged by adhesives or fill materials. In contrast, the Museum's shattered *Adam*, with newly fractured surfaces that in most cases mated perfectly, presented a different set of challenges. Reassembly required a treatment approach that would retain the tightness of the joins. Equally important was a method that would limit handling of the sculpture and position the heavy fragments precisely without abrading the fresh, vulnerable break edges.

Furthermore, the reassembly of large-scale sculpture has historically relied on the use of multiple iron or steel pins bridging each fracture, supplemented more recently by structural adhesives such as epoxy resins. While generally effective in structural terms, these methods have been seen by a growing body of conservators as overly aggressive and

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liable to damage the surrounding stone in the event of later stress on the join. The importance of *Adam* warranted a critical evaluation of the use of pins and adhesives and an investigation into less invasive and more reversible approaches.

The significance of *Adam* and the complexity of reconstructing freshly broken monumental sculpture also warranted a team of specialists from both inside and outside the Museum who could bring the insights of various disciplines to bear on a conservation project so unlike those usually encountered. Thus conservators, conservation scientists, and curators were joined and supported by materials scientists and engineers in an exceptional multidisciplinary collaboration to determine the best course of treatment for the sculpture. Lawrence Becker oversaw the project when he became Sherman Fairchild Conservator in Charge of the Museum's Sherman Fairchild Center for Objects Conservation in 2003. He was primarily responsible for putting together the core Tullio team. Conservator Carolyn Riccardelli, a specialist in the conservation of large-scale sculpture, was the principal conservator and was involved in most every aspect of the project from fragment retrieval to fills. Michael Morris, a sculpture conservation specialist hired specifically for the project, collaborated on all stages of the treatment of *Adam*. Conservator Jack Soultanian, an authority on European sculpture, conducted the examination and had primary responsibility for all aesthetic aspects of the treatment, including cleaning, retouching the fills, and surface integration. George Wheeler, a consulting scientist at the Museum, was primarily responsible for materials research related to the project. Laser scanning, virtual modeling, and collaborative work on finite element analysis was performed by Ronald Street, a specialist in 3D imaging, molding, and prototyping. In addition to a select group of conservators who served as consultants, many curators, interns and fellows, scientists, engineers, designers, media specialists, and administrators contributed immeasurably to the project. Details on their roles are given in the "Acknowledgments" at the end of this article.

From the beginning, our research strategy and testing protocols were directed toward developing a treatment that would join the fragments securely with reversible, stable materials compatible in strength and stiffness with marble, and with minimal drilling to accommodate pins. The methods developed from this effort provided what we believe to be a new model for best practices and standards in the conservation of large stone sculpture. While the specific circumstances of *Adam*—the fragility of the fracture surfaces and the tightness of the joins—dictated our approach, our research and test results are applicable to a broad range of stone conservation problems.

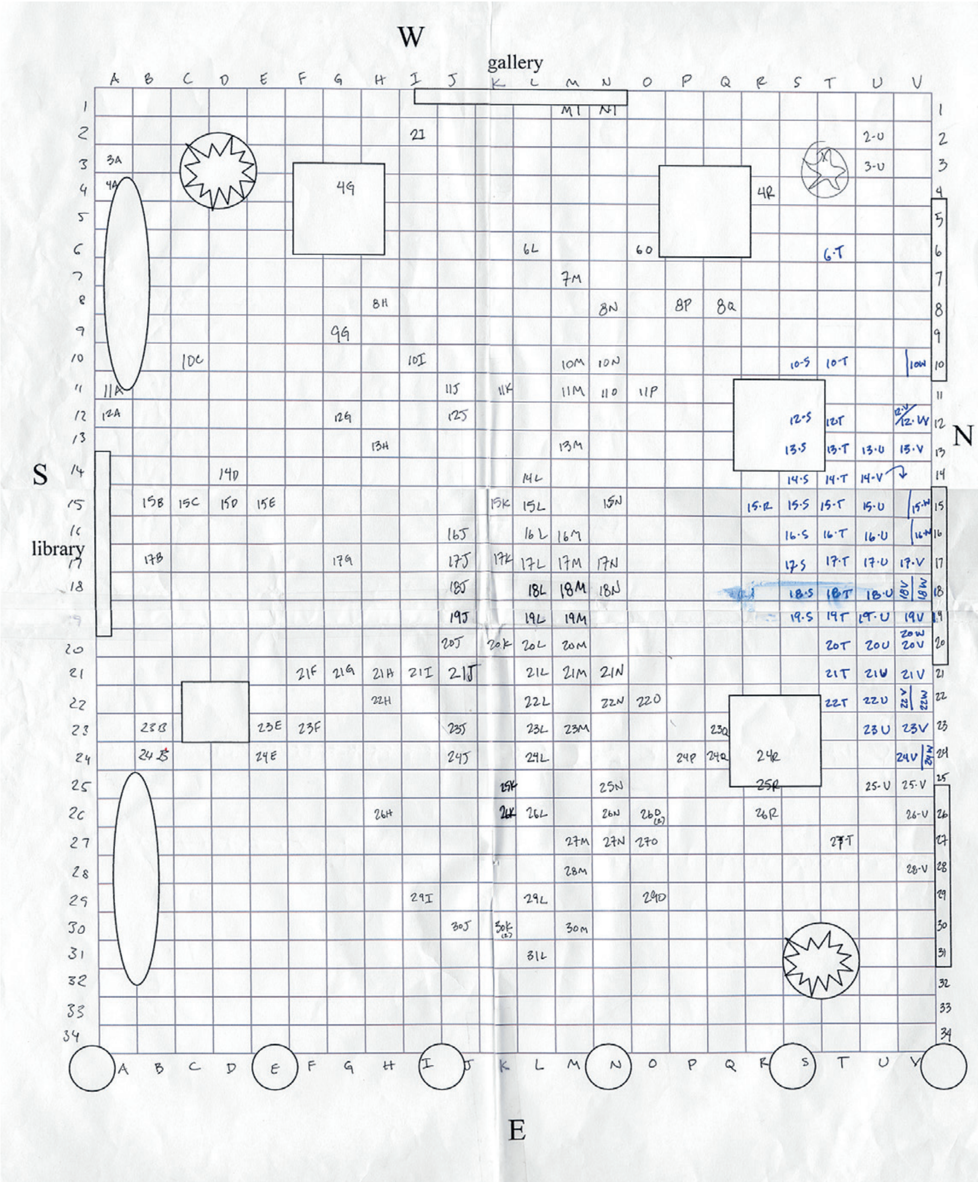
This article describes the innovative treatment of *Adam*, including the use of three-dimensional laser scanning, finite element analysis, materials testing, and empirical studies carried out to determine the optimal adhesives and pinning materials. An explanation is provided about a novel external armature, which minimized the handling of the fragile fracture surfaces of the sculpture. This armature was developed to support the assembled sculpture without adhesive and to serve as the method for clamping the fragments once adhesive was applied. Drilling and pinning techniques are described, as are the challenges related to cleaning the sculpture's surface and to filling losses. The article closes with a summary of lessons learned and conclusions drawn from this extensive multidisciplinary project.

## CONDITION OF THE SCULPTURE

To evaluate the condition of the sculpture following the accident, we first had to retrieve systematically and document the fragments and then characterize them so we could determine their location on the sculpture. We sought to understand the nature of the marble and the structural characteristics of the fractures before we began investigation into appropriate adhesives and pinning materials. Knowledge of the marble's properties and of potential stresses on the fractures also helped in the design of an external armature that protected and supported the fragments during our work. We also conducted a surface examination of the sculpture to find evidence of tool marks and surface decoration that would help us gain insight into Tullio Lombardo's carving techniques.

### Recovery, Documentation, and Characterization

The sculpture landed on its right side, and the force of the impact on the stone floor was so great that fragments were thrown considerable distances, some stopped only by the patio walls. They ranged in size from the intact torso including the right thigh, measuring approximately 44 inches (112 cm) in length, to small but identifiable pieces, such as a branch of the tree trunk measuring 1¾ inches (4.5 cm) in length, to hundreds of smaller fragments. Because we hoped that the pattern of their scatter on the floor might help point to their location on the sculpture, we developed a systematic mapping and retrieval system to document the position of every fragment. The patio's rectangular floor tiles were the basis of grid locations. Each tile was given a letter and number designation, and each unit of the grid containing even the smallest fragment was marked according to its coordinates (Figure 1). Next, the grid units were photographed (Figures 2a, b). Only then were the fragments collected. They were subsequently laid out on tables in a temporary studio space so they could be studied (Figure 3).




1. Map of the Vélez Blanco Patio indicating the locations of the fragments. The tile pattern of the patio floor was used to create a grid. Tiles were designated “A” through “V” on the horizontal axis, and 1 through 34 on the vertical axis; then each fragment was assigned a letter and number according to its location on the grid. The square elements indicate the location of sculpture pedestals in the gallery. *Adam* was located on the pedestal closest to the northeast corner. Diagrams of Figures 1; 5a–d; 6; 16b; 17a–c; 37; 41; and 58a–c: Carolyn Riccardelli


2a,b. Photographic documentation. To record the scattering of the fragments, each floor tile was individually photographed. Left: the base with fragments of the left leg and upper right arm. Right: fragments of the tree trunk and the right forearm. Photographs of Figures 2a,b; 3; 4; 5a–d; 7; 9; 18; 24; 32; 36; 39; 40; 42; 43b; 44–48; 49a,b; 50–55; 57; 61; 62; 64–75; 77; 78a,b; 79–82; 84 and 85: Carolyn Riccardelli

3. Some of the major fragments arranged on a table in the Tullio studio

Once the Tullio team was fully assembled, we began examining the fragments and planning their reconstruction. It was at this point that the full nature and extent of the damage became clear (see Figure 8). The sculpture's integral base broke away from the legs at the ankles as well as at the base of the tree trunk. We speculated that the primary point of impact for the sculpture was the rear corner of the base just under the tree trunk. This area suffered extensive damage, breaking into dozens of fragments and crushing the marble, causing large areas of loss. This and other direct impact points appear as flattened, burnished areas on the surface that are more opaque than the surrounding stone due to crushing of the marble crystals, or grains. Wherever these points of impact occurred on *Adam*, there was associated pulverization and loss to the marble.

The tree trunk broke into three major fragments, with the base of its branch and the bird carved in relief receiving the most damage. The branch broke into four major pieces and many smaller fragments, a dozen of which were identified and subsequently reattached. A small strut connects the top of the tree trunk to *Adam*'s right hip; this roughly carved block of marble suffered internal pulverization while the surface shattered into many pieces, twenty-five of which were reattached.

4. A sample of small fragments with exterior surfaces. These fragments, which would be used in the reassembly of *Adam,* were placed in protective plastic bags labeled with their original patio number. They were later sorted by color, shape, and tool mark characteristics to locate their position on the sculpture.

The right lower leg broke into two large fragments, one from just below the knee to the middle of the calf and one from the middle of the calf to just below the ankle. The left leg broke into five large fragments with only minor areas of loss, most notably at the top of the knee where there was an impact point with associated crushing of the marble. One of the left leg fragments was a wedge-shaped piece at the knee that was, at its widest, 5 inches (12.7 cm), tapering down to just 1½ inches (3.8 cm) on the inside of the leg. The shape and location of this fragment made it one of the most difficult to manage during reassembly of the sculpture.

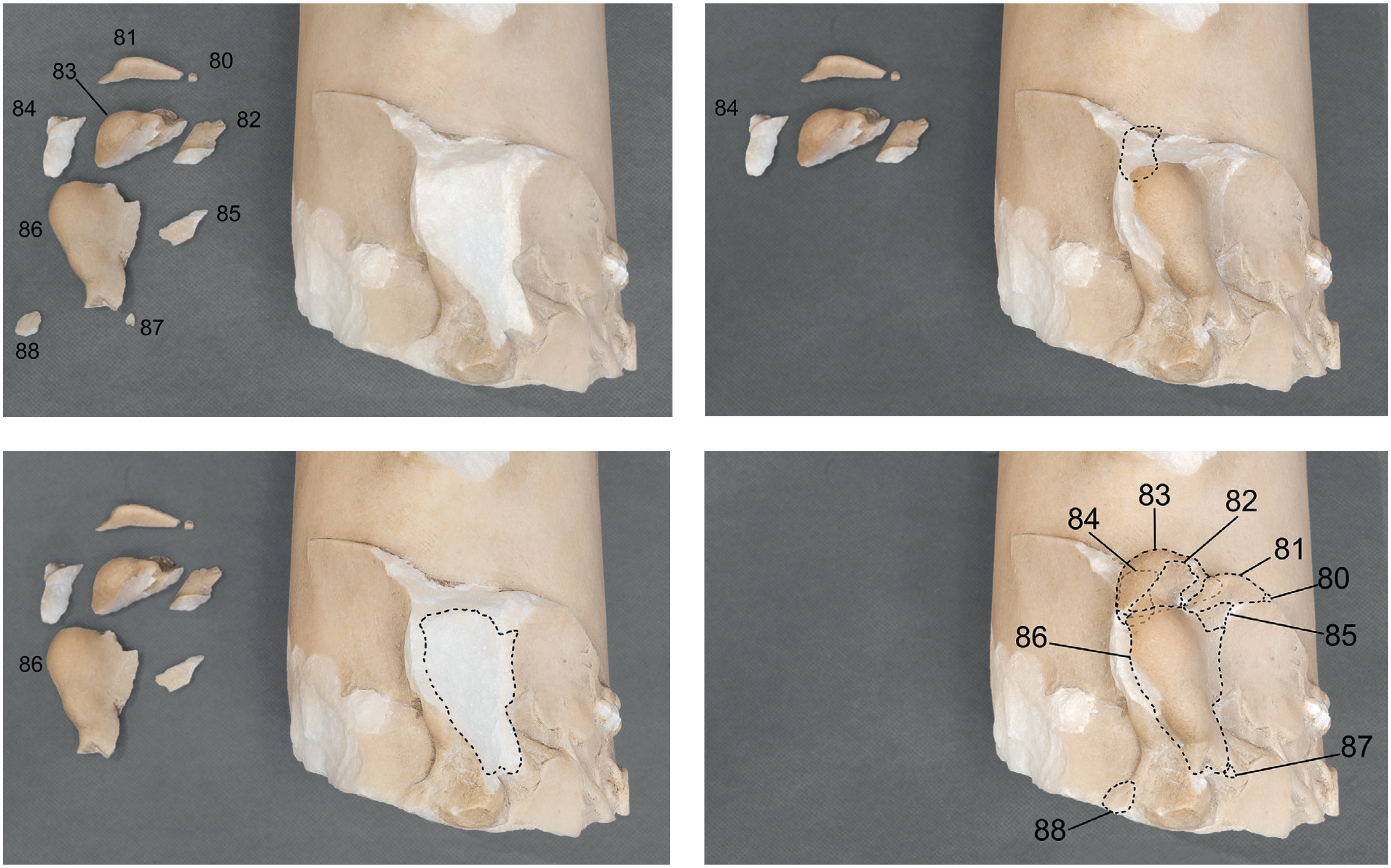
*Adam*'s right arm was among the most seriously shattered areas, breaking into eight major fragments and dozens of minor ones, many of which were not reattachable because the damage to the forearm was substantial. Extensive loss where the arm broke away from the torso in the bicep area indicated that this was another point of impact. The right hand sustained damage from impact, shattering the little finger and adjacent palm, which broke into more than twelve pieces.

The left arm broke from the torso at a nearly vertical angle across the bicep, separating as one large fragment. The left hand broke off as one large piece. However, the upper portion of its little finger was lost to pulverization, and the rest of the digit shattered into many small fragments, eleven of which were reattached.

The head broke away from the torso at the base of the neck. The damage to the head was miraculously limited to a shallow loss along the left side of the nose as well as an impact point in the hair on the right side of the head.

Throughout the reconstruction process, we sorted hundreds of tiny fragments created by the accident, a task that continued until the sculpture was fully assembled in 2013. The initial step was to separate out internal fragments, as they were unlikely to be reused. We recognized that incorporating internal fragments would have produced misalignments on the exterior joins, while any gaps caused by their absence could be filled with an appropriate conservation-grade material. Moreover, lacking any external surface, they gave few if any clues about their original location on the sculpture. In contrast, the alignment of the external fragments was of paramount importance, and so we concentrated on locating those pieces.

The process was painstaking. Through patient examination over a period of years, we took note of the external shape, color, three-dimensional form, inclusions or veining,

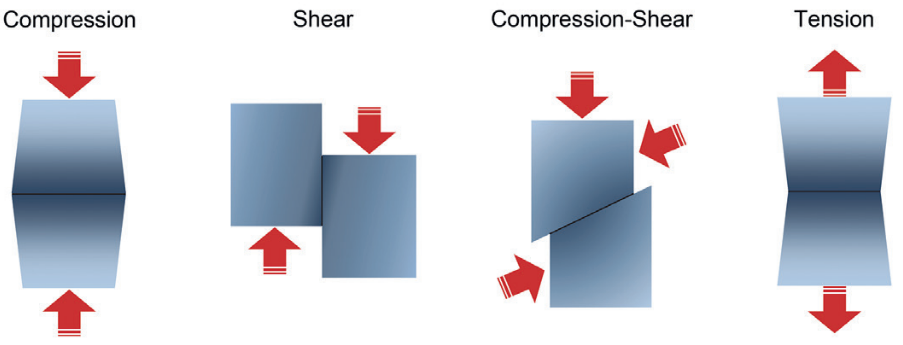


5a–d. Reassembly documentation for small fragments. As the fragments were relocated on the sculpture, their patio numbers were replaced with consecutive numbers. A sequence of annotated photographs was produced to document the location of each small fragment as well as to assist in correctly placing the fragments when it was time to attach them.

and tool marks of hundreds of fragments (Figure 4). As connecting fragments were not found in any particular order, it often took years to fill in any one area of damage with its components. The complex nature of the sculpture's breaks deterred us from adhering fragments in place as soon as we found them. We also recognized that if we joined fragments too soon, we ran the risk of locking out an adjacent fragment that might be found in the future. Although the adhesive we chose for the project is reversible with solvents, we wanted to avoid any unnecessary reversing of joins, as this action can wear on the edges of the stone, especially on tiny, delicate flakes of marble.

It became immediately clear that managing all of the individual pieces would require a custom-tailored method of record keeping and documentation. As the interlocking puzzle of particular areas was solved, the fragments were assigned new, consecutive numbers, while the original patio grid numbers were preserved in a database created for the project. Once an area of loss began to fill in sufficiently, a detailed sequence of photographs was taken and annotated to facilitate reconstruction when the time came to attach the fragments with adhesive, which in most cases was several years later (Figures 5a–d).

Understanding the nature of the forces acting upon the major fragments of the assembled sculpture was a central concern, as it would influence the choice of adhesives, the need for and locations of pins, and the design of the external treatment armature. Compressive forces exist in locations on the sculpture where a bonded fracture, or join, is perpendicular to the forces of gravity, as can be observed when books are stacked flat on a desk. In the stack, the "joins" between the books stay put. But if the books are turned upright, as on a bookshelf, the joins between the books experience shear, or a "slipping" force. Tilt the shelf off level, and the instability due to shear force is clearly evident. In several locations on *Adam*, specifically where the fractures were neither perfectly vertical nor horizontal, we recognized that the fragments would experience a combination of two primary forces, described as "compression-shear." Tensile forces, on the other hand, are those that pull away in opposing directions, as would a sculpture's arm hanging at its side. See Figure 6 for a diagram of these forces.




6. Types of structural forces present in *Adam*. Compression occurs when directly opposing forces are pushing toward one another. Shear, or sliding, forces are opposite one another but parallel to the surface acted upon. Compression-shear is a combination of the previous two forces. Tension is the opposite of compression, and occurs when opposing forces are pulling away from one another.

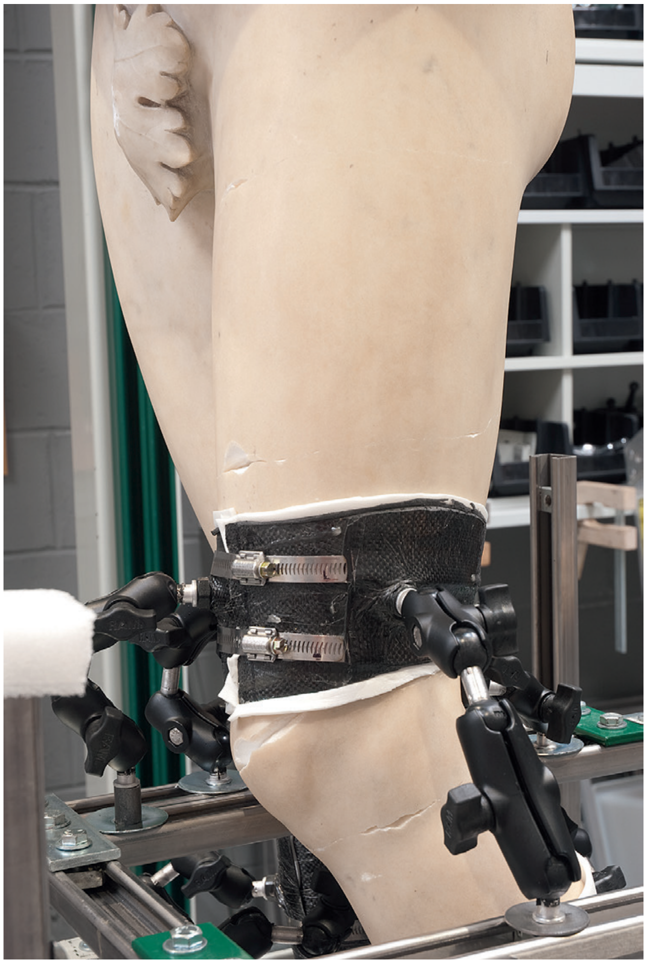
Many of the fractures in the tree trunk and *Adam*'s legs were essentially horizontal, and thus perpendicular to the force of gravity. When set in place, these fragments would experience compressive loading as the primary force; therefore we knew they could safely be stacked on top of one another during reassembly. Technically, however, each join in *Adam* would ultimately experience some combination of compressive, shear, and/or tensile forces, to a greater or lesser degree. In a few critical locations, the assembled fragments would be under various combinations of forces, experiencing the more unstable shear and/or tensile forces to a significantly greater degree than the rest of the sculpture. The most vulnerable of these fractures occurred at each of the ankles, where the weight of nearly the entire sculpture—that is, 85–90 percent of the sculpture's total weight of 770 pounds (349.3 kg)—rests on what is the smallest surface area.[1] Both of *Adam*'s ankles fractured at acute angles, so the break surfaces that needed joining would be dominated by a combination of shear (slipping) and compressive (pushing) forces from the weight of the sculpture resting on them. Another fracture in which the assembled fragments would be under this combination of forces was the left knee, where the wedge-shaped fragment bridged the calf and the thigh.

The fractures in compression-shear prompted much of the materials research directed at the choice of adhesive and application technique, and at the need for, size of, and orientation of pins. In the end, the joins in compression-shear were the only places where pins were used in the sculpture's reconstruction. Such minimal pinning marks a major break with the prevailing methods for large-scale marble sculpture conservation and was decided upon only after a thorough investigation into the forces that would be at work on the reconstructed breaks.

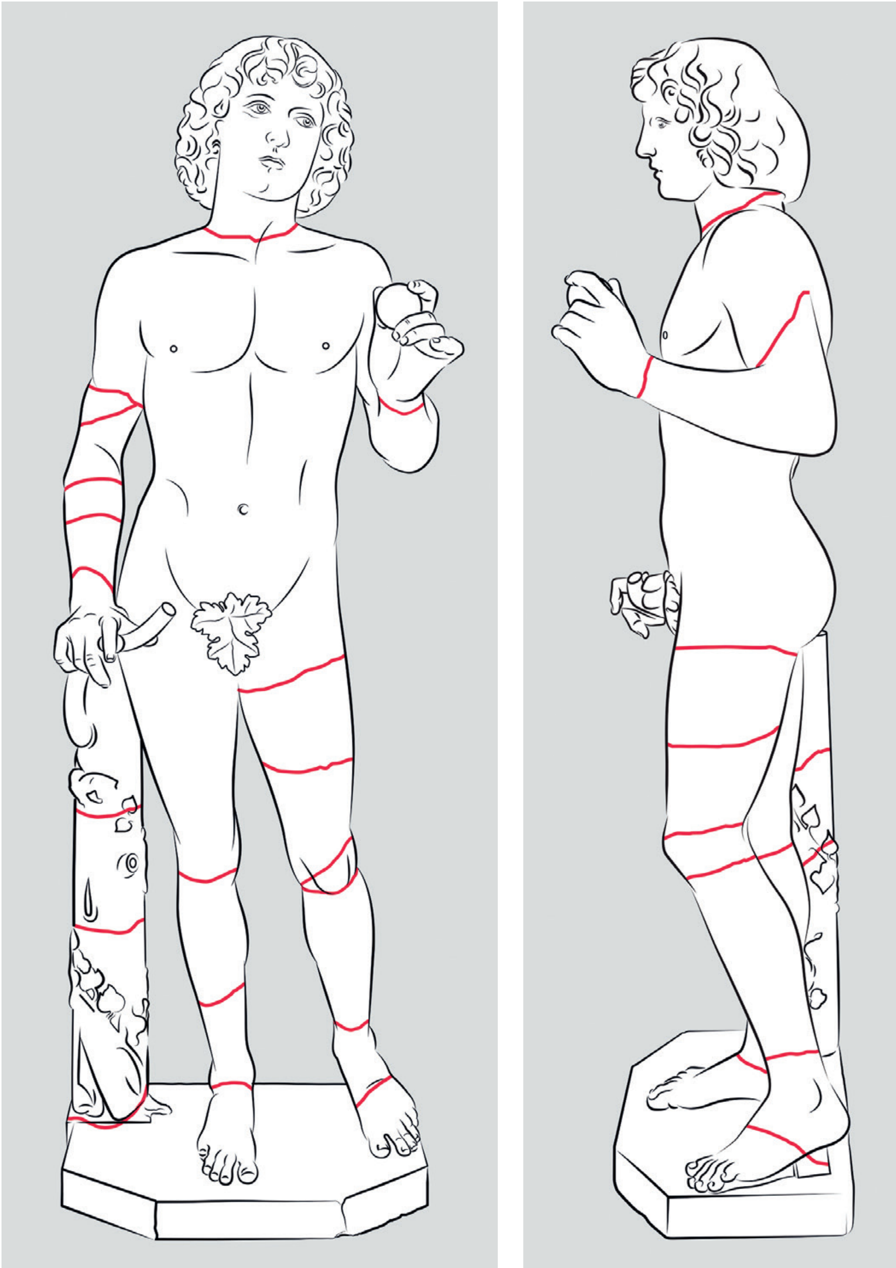
Fractures in the neck and the tree trunk were oriented in such a way that, once repaired, those areas would be subject mostly to compressive stress. However, both of the joins connecting the arms to the torso would be mostly in tension (pulling), with the exception of the left wrist, which has a vertically oriented fracture that would have to withstand primarily shear force. The reattachment of the right arm was to be particularly complicated because the arm connects to the torso in two places. The join at the bicep would be in tension, while that between the right hand and hip would be mostly in shear.

By studying the location and position of the breaks, we quickly understood that varied and complex forces would act on each of the joins of the major fragments. It also became clear that finding a way to connect them while applying the compressive force or clamping action required for good adhesion necessitated the development of a custom treatment armature. Finally, addressing the variety of forces present in each join needed to be balanced with an assessment of the physical and aesthetic requirements for assembling the sculpture as a whole. Our task could be accomplished only by entirely rethinking traditional methods of reassembling sculpture.

We also had to rethink the nature of the adhesives we would use in the joins. The high quality of Carrara marble that Tullio used meant that *Adam*'s clean breaks fit together tightly (Figure 7). Therefore the bond line—the space occupied by adhesive at each join—had the potential to cause



7. Joins in the upper left thigh. Where the break edges joined together very tightly, as in this thigh, preservation of the edges was of utmost importance. In this photograph, the leg fragments are supported in the external armature without the use of adhesive.



8. Diagram showing the sculpture's major fractures. Note particularly the asymmetry of the leg breaks; there are twice as many joins in the left leg as in the right. Displacement by adhesives in these joins was a concern addressed in adhesive testing. Diagram: Douglas Malicki

9. Fracture surface of the left calf fragment. This view of the interior surface illustrates the high quality of the Carrara marble, its pure white internal color, and its uniformity. The crisp break edge is in evidence, as well as past surface applications of fats that have penetrated the marble, visible as yellowing along the perimeter of the fragment.

displacement, and so it was a primary consideration in the choice of adhesives and the development of joining techniques. A particular concern was the fact that the right leg had broken into two pieces between the torso and the base, while the left leg had broken into five pieces (Figure 8). Displacement along joins in each leg would be additive, risking a misalignment at the final connections because of the unequal number of joins in the legs. For this reason, adhesive bond thickness was a key element in the materials testing and selection of potential adhesives.

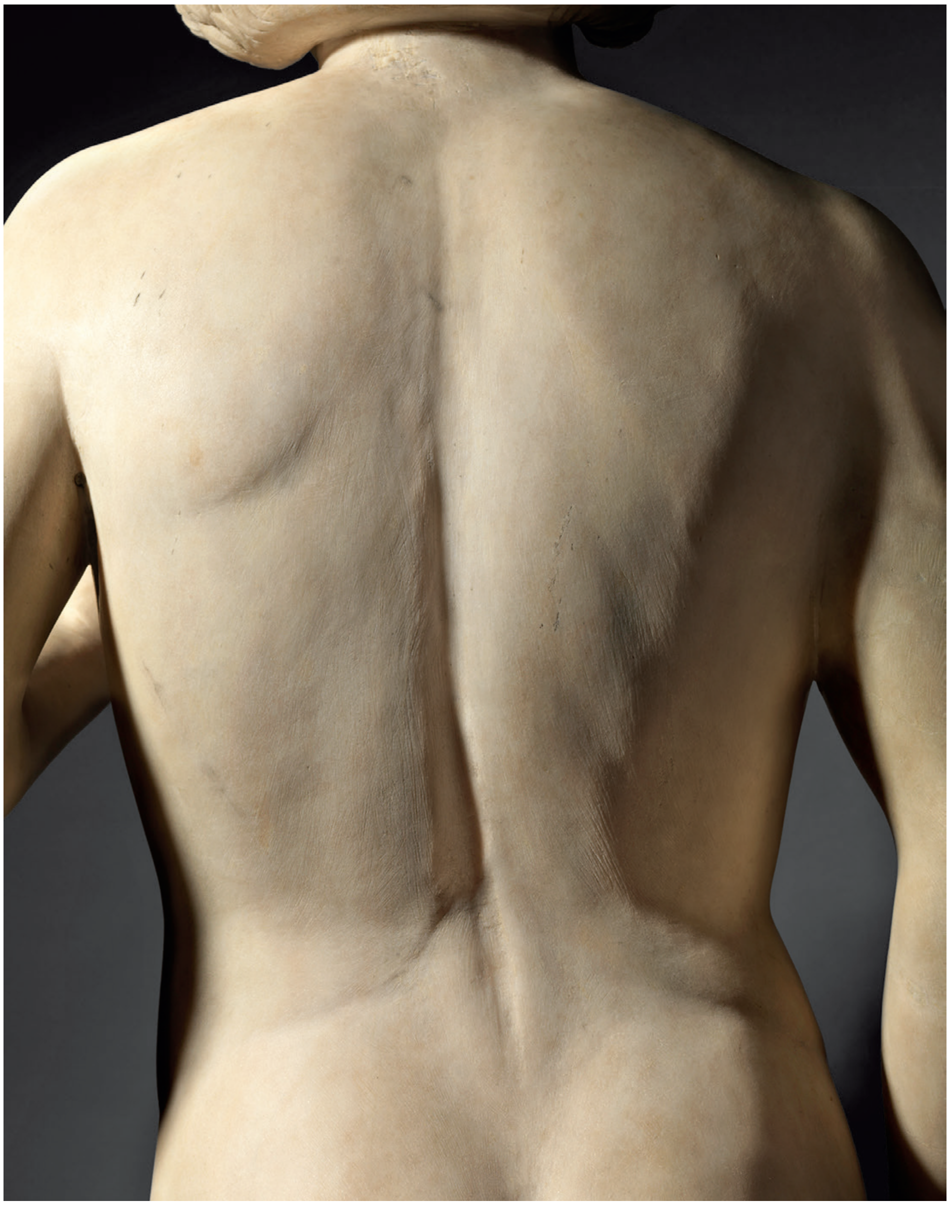
**Petrographic Study and Surface Examination**

In addition to studying the results of the fall, we undertook a detailed examination of the properties of Carrara marble as well as of Tullio's carving techniques to understand both sculpture and sculptor. Prior to the accident, the sculpture had sustained no fractures and virtually no loss to the carved surface in more than five centuries. The absence of original joins on *Adam* was known, and it indicated that the sculpture was carved from a single block of Carrara marble. Of the three main quarrying districts in Carrara, Italy—Colonnata, Miseglia, and Torano—a petrographic study of a sample of *Adam* suggested that the marble derived from Torano, perhaps the extraction site of Polvaccio, which has the reputation of having the marble of the highest quality, the so-called statuario marble.[2] The astonishing whiteness and homogeneity of the marble used for *Adam* was visible in the fresh breaks exposed by the fall (see Figure 9).

*Adam* does not retain the abundance of point or flat chisel marks characteristic of many of the figures remaining

10. Tullio Lombardo. *Adam*, ca. 1490–95. Carrara marble, H. 78¼ in. (191.8 cm). The Metropolitan Museum of Art, Fletcher Fund, 1936 (36.163). Detail of hair after cleaning and before filling. Drill holes of varying size define *Adam*'s curls. Photographs of Figures 10, 11, 22: Peter Zeray, The Photograph Studio, MMA

11. *Adam*'s hair, left side, after cleaning. The transition from unarticulated hair at the back of the head to fully carved curls around the face is evident.



12. Detail of the back, after assembly and cleaning using raking illumination. Deep rasp marks define the upper back, spine, and lower back, revealing how the front of the sculpture appeared prior to finish. The shoulder blades are more highly finished than the lower back and have been modeled with a fine file. The rasp marks articulate the back muscles in a manner not dissimilar to the shading lines of a draftsman. Photographs of Figures 12–15, 21, 94a–d: Joseph Coscia Jr., The Photograph Studio, MMA

on Tullio's Vendramin monument (ca. 1490–95), from which the sculpture originates and which is now in Santi Giovanni e Paolo in Venice.[3] The hair is fully defined at the front of the head, with tightly wound curls. Tullio employed drills of varying sizes to define the center of each ringlet and gave further definition to the depths of the hair by drilling a sequence of small holes adjacent to one another.[4] In the most completely finished curls, the narrow "partitions" of marble between them had been removed with a tiny chisel (Figure 10). On the back of *Adam*'s head, however, there are no curls; instead, there is a very broadly defined mass of marble for the hair, resembling a snood (see Figure 13). This area has some rudimentary tool work to give the general form but none of the drill holes or blocking out that would indicate the early stages of design transfer. Moving from the back of the head toward the face, there is a transitional area where Tullio drilled holes plotting out the centers of the curls as well as some shallow arcs created with a flat chisel. These curls are superficial, but they begin to take shape as they progress toward the front, with deeper carving and more definition. At the front, a deeply incised outline separates the hair from the face, and both ears are covered by well-defined curls. It is in this sequence from back to front that the roughed-out volumes slowly progress from a flat description of curls to a fully realized form (Figure 11).

The front surfaces of the figure were never highly polished, but thin, faint lines from an abrasive stone or fine file

13. Detail of the back of the head and neck, after assembly and cleaning. The snood shape of the hair is evident as are two deep chisel marks that remain just beneath the hair.

14. Detail of the left armpit, after assembly and cleaning. Between *Adam*'s left arm and torso two drill holes remain, as well as a deeply cut area that may have been a place where the early removal of the stone proceeded too far.

are in evidence. The decision not to polish may relate to the surface appearance of ancient marbles that Tullio would have studied, which would have lost any original polish they may have possessed from burial. Nonetheless, the transition between sculptural forms on this part of *Adam* is so well and so convincingly integrated that it is difficult to see the evidence of earlier carving or rasp work. Denoting the sculpture's intended location within a niche, the back is not as highly finished or as completely articulated as the front, and it is therefore in these dorsal areas that Tullio's carving method becomes more apparent. Deep rasp marks define the upper back, spine, and lower back to the buttocks, and these marks must surely reflect how the front of the sculpture appeared before being taken to its final level of finish (Figure 12). Rasp marks articulate the back muscles in a manner not dissimilar to the shading lines used by draftsmen to indicate shadow and light.

Several chisel marks at the back of the neck remain, just beneath the hair, indicating that earlier in his carving process Tullio used chisels to model larger, broader areas (Figure 13). He followed this chisel work by employing a series of rasps, ranging from coarse to fine, to delineate the muscles. The shoulder blades are more highly finished and protrude from the back, shaped with a very fine rasp that has left faint lines. The deeper recesses of the spine and muscular lower back retain marks of a coarser rasp. Between *Adam*'s left arm and torso two drill holes remain, as well as a deeply cut area that may be evidence that in the initial stages too much marble was removed (Figure 14). Most parts of the hands are carved in great detail, yet some parts remain undescribed. For example, the thumbs, which are mainly hidden from view, have not been articulated to the same degree as the rest of the fingers. They lack thumbnails and are taken no further than summarily formed silhouettes, demonstrating Tullio's economy in carving the less visible areas of the sculpture.

The upper surface of the base displays irregularities in the carving that may simply be unfinished or may represent an attempt at verisimilitude. For example, the tree trunk is finely articulated, but a raised area of point chisel work is clearly defined at its base (Figure 15). Does this area signal lack of completion, or could it be a simulation of a natural form, perhaps moss? It is worth noting that the same point chisel work is found in the hollows of the tree trunk where moss might also logically be located.

15. Detail of the base of the tree trunk, after reassembly and cleaning. At the base of the trunk is a raised area of point chisel work. Directly in front of the tree trunk, an ambiguous square-shaped tooled area sits slightly proud of the surface.

16a,b. Tool marks on the underside of *Adam*'s integral base. Top: RTI capture in the coefficient unsharp mask rendering mode. Bottom: the same RTI capture with the incised lines highlighted in red. RTI: Winifred Murray and Carolyn Riccardelli

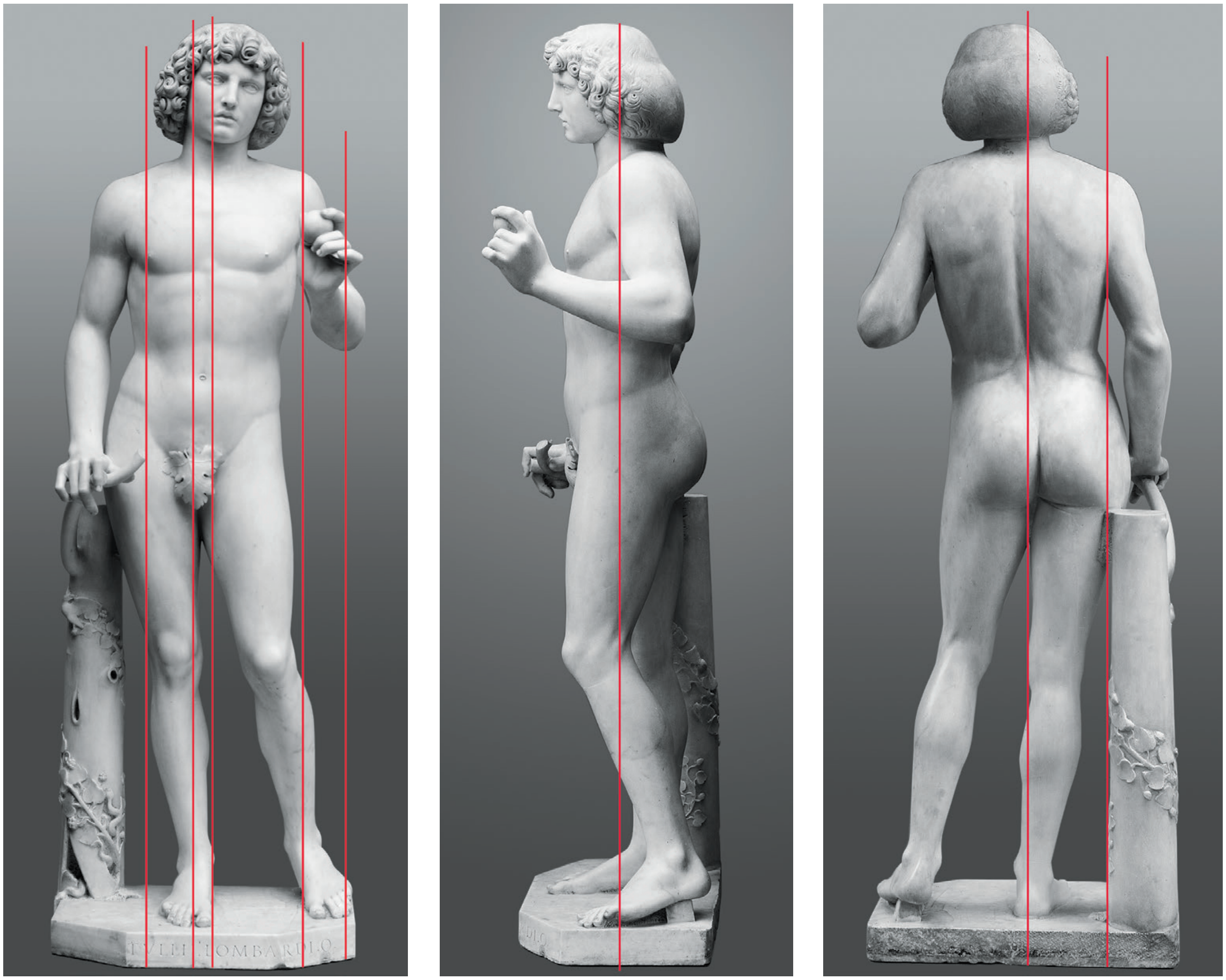
Directly in front of the tree trunk, a faint, square-shaped tooled area is raised slightly above the surface (see Figure 15). It most likely reflects a late change of mind on the part of the sculptor, but a change from what? For structural reasons, and based on tool marks found on the underside of the base, it does not seem to indicate a first placement of the supporting tree trunk, but it might be the remains of an extension of the "moss" that appears at the base of the trunk. Also on the upper surface of the integral base, flat planes carved at varied levels, particularly in the area between the feet, may simulate stone paving or rocks that *Adam* stands on, as has been suggested.[5] These planes or stonelike features were carved with a flat chisel.

Marks from the point chisel and a remnant of flat chisel work are found under the arch of *Adam*'s left foot. The surfaces of the feet, with curiously low arches, are carefully finished using fine abrasive stones or files. There is a suggestion of *Adam*'s weight being pressed down on the right foot, as the big toe widens and flattens. Between the first and second toes of both feet are small, raised remnants of unfinished stone.

The underside of the sculpture's integral base—not easily accessible and therefore previously unstudied—is covered with intersecting tool marks that are difficult to read or record in normal light. To capture them digitally for further study of the subtle variations in surface texture, we used an examination technique called reflectance transformation imaging (RTI).[6] With the RTI capture, it was possible to enhance digitally the tool marks, helping us to confirm that the underside of the base was part of the exterior surface of the original dressed block of marble (Figures 16a,b). Perfectly straight lines were cut with a point chisel at right angles to each other across the surface, indicating the center of the block; it is possible that these lines were intended to demarcate the sculpture's proportions. Two circles, offset from one another, inscribed in the lower left corner denote the diameter and location of the tree trunk. The surface also features a faint, grooved pattern along the edges made with a thin, curved chisel, or roundel. These grooves are the intended perimeter lines for the bottom of the base as laid out on the quarried block. Once those lines were established, the central section of the bottom of the block could be carved into plane. This phase was accomplished with a toothed chisel, which prepared the flat surface under the sculpture.

The rear face of the plinth—the area that would be situated against the back of the niche—is also unfinished and thus may be a remnant of the original block. This surface was flattened with a tooth chisel and is marked with two vertical incised lines, one of which connects at a right angle to one of the lines on the underside of the base. These incised lines (both on the underside and on the back of the base), if projected up the height of the figure, correspond to its center of gravity, and they apparently indicate the position of the hands, which are also the outermost reaches of the sculpture (Figures 17a–c). Visualizing the shape of the block of marble in this way allowed us to deduce the care with which the sculpture had been laid out on the exterior, which was almost certainly marked with many other incised lines and marks.

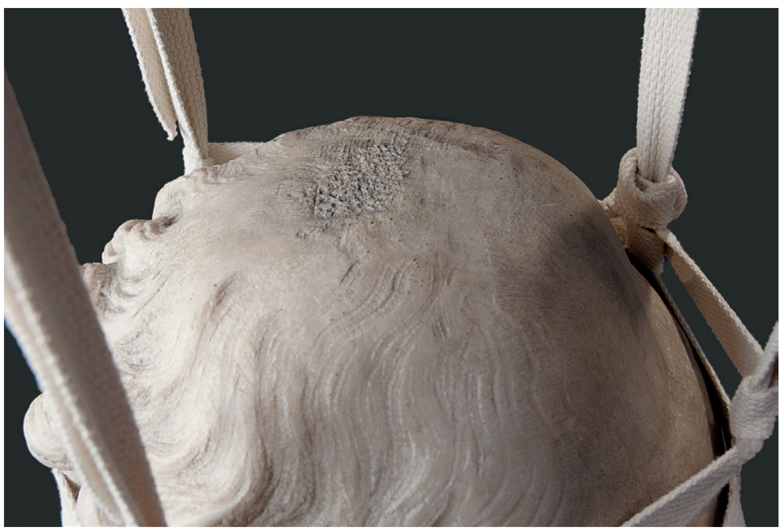
Tool marks on the top of *Adam*'s head seem to correspond to the toothed chisel marks on the underside of the base. Viewed with raking illumination, these marks are visible within a flattened square area (Figure 18). There are also intersecting lines within this tooled square that appear



17a–c. Diagrams showing vertical extensions of the lines on the underside of the base. Those lines as well as others may have been incised on the marble block before it was carved.

to define the center of the block and are analogous to those found on the underside of the base. It is therefore likely that these lines, made like those under the base on the surface of the dressed block, were maintained by the artist as points of reference throughout the entire carving process. That this center mark remains in place suggests that Tullio carved his figure with the minimum of marble wastage, fitting *Adam* very precisely within the original block. Such economy is achievable only through careful planning.

We also sought to determine whether the marble had ever received any applied decoration. It is known, for example, that the tree trunk and sling in Michelangelo's (1475–1564) *David* were gilded, as was a garland that was made for the statue but may never have adorned it.[7] Similarly, the architectural decoration of Desiderio da Settignano's (ca. 1429–1464) mid-fifteenth-century marble tomb of Carlo Marsuppini in the Basilica of Santa Croce, Florence, was polychromed, and its figures were at least partially gilded.[8] During a recent examination of the



18. Top of *Adam*'s head, photographed with raking illumination. There is a small square of tool marks identical to ones found on the underside of the base. It is possible that these tool marks are the remains of the top of the original dressed block.

19. Vendramin monument, coffered arch. This area, with the kneeling doge, shows gilded decoration. Blue paint is found in the background of the rosettes in the coffers. Photographs of Figures 19, 20: Anne Markham Schulz and Mauro Magliani, 2012

20. Vendramin monument, tondo with Christ Child showing gilded decoration

21. Traces of azurite pigment in the hollows of *Adam*'s tree trunk

22. *Adam*'s left hand. Traces of clay minerals remain on the fruit between the index and middle fingers, which may indicate the presence of a bole used for gilding.

19

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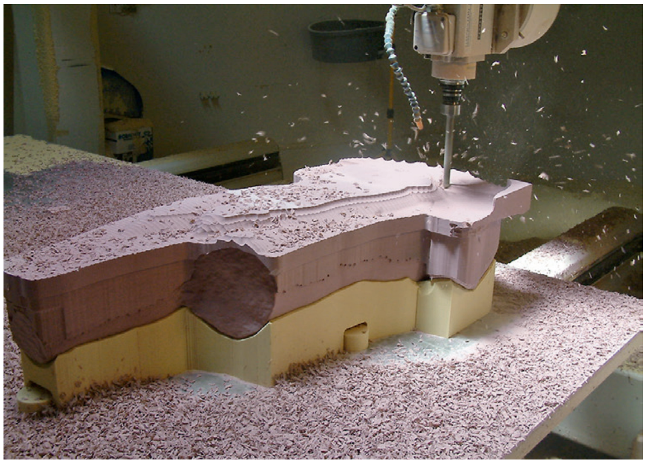
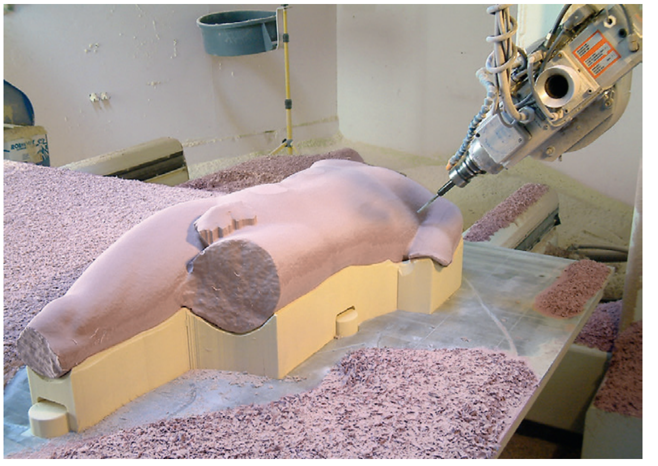
22

Vendramin monument, we observed blue paint and gilding on the coffered arch above the kneeling figures of the doge and a youth, although it is possible that these were added or renewed later (Figure 19).[9] On the uppermost register of the monument, the gilding appears to be original on the hair, wings, and tails of the sirens and on the tondo containing the Christ Child (Figure 20).

Traces of similar bluish-green paint were found in the hollows of the tree trunk supporting *Adam* (Figure 21). An analysis of the pigment showed it to be azurite.[10] While no gilding is discernible to the naked eye, traces of a reddish-brown material consistent with bole, a preparation for gilding, were found on the fruit held in *Adam*'s left hand (Figure 22),[11] an indication that it was probably highlighted in gold. Significantly, the Christ Child in the tondo at the top of the Vendramin monument holds a gilded orb in a pose that is similar to *Adam*'s, creating a symbolic link between the two figures.

23a,b. Full-scale model of *Adam*'s torso being fabricated in dense polyurethane foam by a computer numerically controlled (CNC) milling machine. This model was used as a mock-up to design the external armature as well as to formulate and rehearse assembly methods. Photographs: Ronald Street

## RESEARCH

A guiding principle for the engineering studies and materials testing supporting *Adam*'s conservation was to explore, and indeed challenge, traditional methods for stone sculpture reconstruction. Surprisingly, in making a critical assessment of existing practices, we found few fundamental studies evaluating the properties and performances of adhesives and pinning materials that related to our project. Our general goals, consistent with established principles of conservation theory and practice, were *minimal intervention* and *reversibility*: do only what is necessary and make sure what you do can be undone. Specifically, we wanted to select methods and materials that would allow us to achieve these goals in light of a full understanding of the sculpture as a material and a structural entity.

The sections that follow describe the arc of our research, which was to move from theory to practice, from what is most desirable to what is doable. Going from desirable to doable required that we: (1) achieve a full material and structural understanding of the sculpture; (2) test the specific materials and methods; and (3) evaluate the feasibility and advisability of implementing the outcomes from parts 1 and 2. Accordingly, our team collaborated with imaging specialists, mechanical engineers, material scientists, and conservation scientists throughout our research, but when moving from desirable to doable, we all recognized that the conservators who would perform the treatment would ultimately have responsibility for the reconstruction of the sculpture. Thus the research phase of our project also included empirical research, carried out by the conservators as an application of findings from engineering studies and materials research to the condition of the broken sculpture and the conditions under which it would be reassembled.

For part 1, scanning and imaging specialists along with mechanical engineers used laser scans of the fragments to create virtual models that could be subjected to structural analysis in order to locate, characterize, and quantify existing forces acting throughout the sculpture.[12] For part 2, material scientists provided the guidance to design and interpret experiments to determine the specific properties of adhesives and pinning materials. As described in detail below, we were particularly interested in the strengths of both thermoplastic (reversible) and thermosetting (nonreversible) adhesives, their stability over time (tendency to creep), and displacement of joins (bond-line thickness). For pinning materials, we had concerns from the beginning of the project that the commonly used stainless steel pins were much too stiff to be used for reconstructing Carrara marble. Experiments were designed to test a wide range of pinning materials for their stiffness and modes of failure.

For part 3, to test the results of parts 1 and 2, we used stone specimens designed to mimic the critical joins in the sculpture. These tests provided valuable information not necessarily evident from the earlier testing programs, especially regarding the degree to which drilling pinholes weakens the marble surrounding the join and the need to provide adequate pressure on the join to minimize the bond line. This information was critical for deciding whether pinning should be employed at any join.

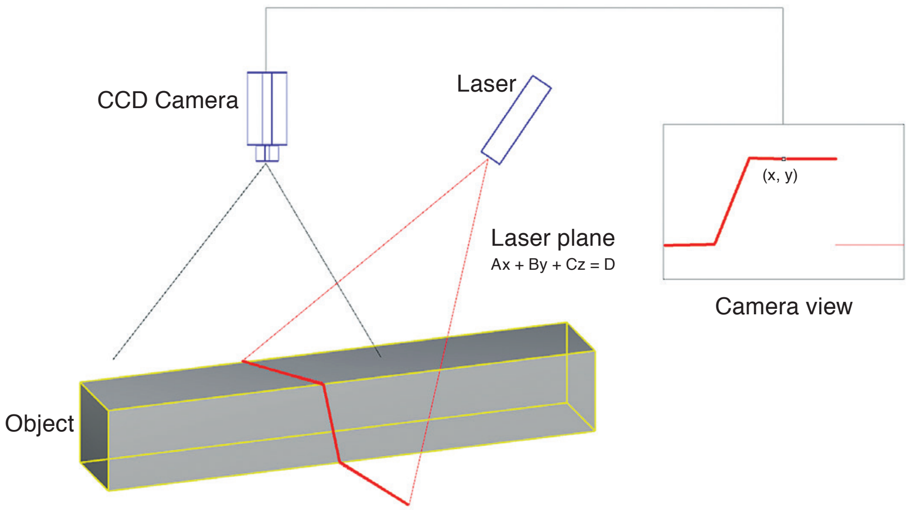
The research that went into planning the reconstruction of *Adam* was long, intensive, and complex because it involved several disciplines. Like many projects—not just conservation projects—this one progressed from thinking about what to do to actual implementation, from a hands-off approach to a hands-on approach, and from virtual reality to material reality.

### Engineering Studies

As an early step in preparation for conservation treatment, the Museum undertook a complete three-dimensional (3D) laser scanning of the major fragments. Among other uses,

24. One-fifth-scale epoxy model of *Adam* created from laser scans and 3D printing. The 16-inch (40.6 cm) tall model was easily held in the hand. Model: Ronald Street

25. Diagram showing principles of laser triangulation system. A laser projects a line of light onto the object; the camera sensor detects the shape of the reflected laser light; and 3D point positions are computed by intersecting the line through the sensor pixel location with the known plane of laser light. Diagrams of Figures 25; 28; 31; 56; 60a,b; and 63: Ronald Street



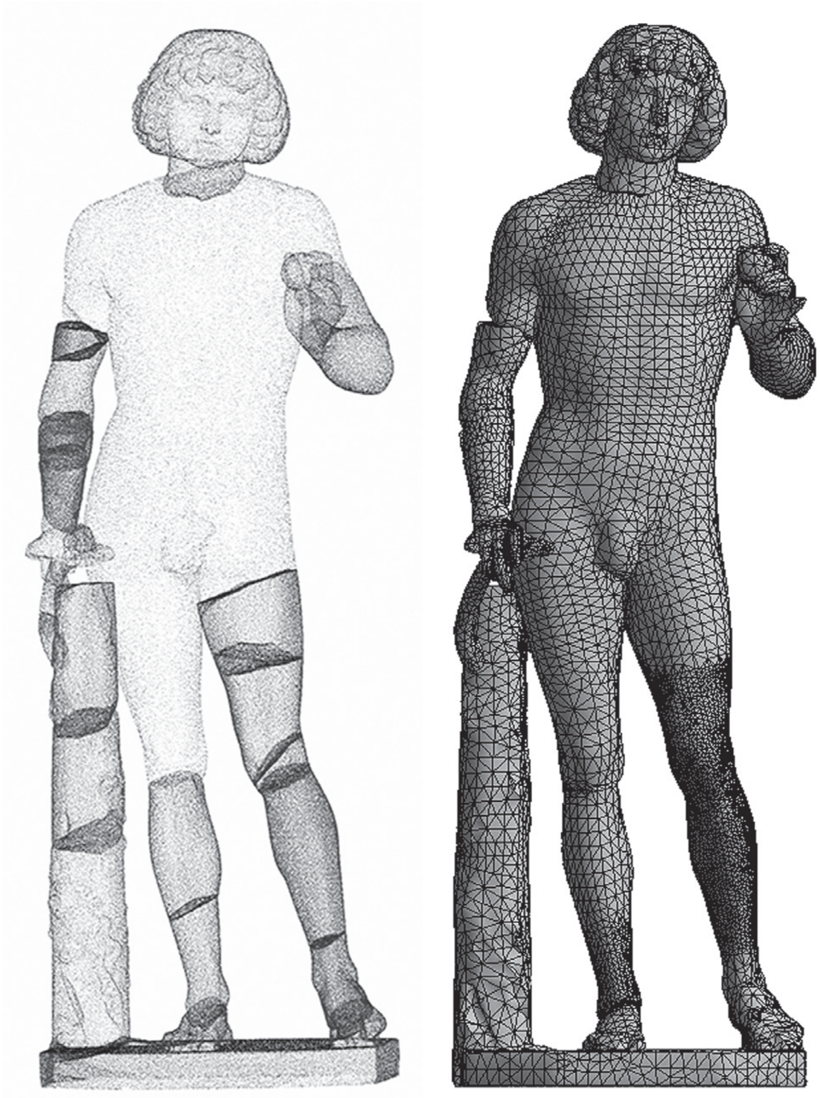

the scanning and the resulting data allowed the team to use computer programs to reconstruct what had become an unwieldy collection of fragments. From this 3D virtual model,[13] several avenues of research could be pursued, the results of which could contribute to decisions about the nature of interventions to be carried out. Not only could a range of computer-based visualizations be performed, but the laser-scan data also made it possible to produce full-scale physical models of each of the major fragments milled out of dense polyurethane foam (Figures 23a,b).[14] In addition, we were able to create a one-fifth-scale epoxy model of the assembled sculpture that could be easily handled and consulted throughout the treatment (Figure 24).[15] These models proved invaluable in planning conservation treatments.

Finally, and perhaps most critically, the virtual models could be used to perform a type of structural analysis known as finite element analysis (FEA), a technique involving computational evaluation and analysis of the responses of materials and structures to applied loads. Our goal for the FEA was to determine the nature and estimate the magnitude of the loads carried across the fracture surfaces in the sculpture. This information would help determine the adhesive strength required for each join and help clarify whether pins would be necessary to stabilize them further.

### *3D Laser Scanning*

Laser scanning is the process of directing a structured laser line over the surface of an object. The surface data are captured by a camera sensor mounted in the laser scanner, which records and positions points in a 3D space (Figures 25, 26a). Three-dimensional imaging of sculpture was initially developed in the 1980s as a form of digital photogrammetry.[16] As recently as 2000, accurate and cost-effective 3D imaging methods were limited; thus it was not easy to record accurate geometric measurements of large objects with a high degree of morphological complexity.[17] In the early 2000s, 3D scanning methods began to be used for problem-solving in art conservation.[18] In recent years, portable sensors and efficient algorithms have been developed, complemented by increased computational power. These advances now permit cost-effective, accurate measurements and high-resolution documentation of objects.[19] However, even taking into consideration recent advances in imaging technology, accurate 3D digital documentation of large, complex objects is far from a simple matter.

A high-speed portable laser-scanning system was used to scan each major fragment of *Adam* from different views. Overlapping scans ensured complete capture of the form and aided in the alignment of the scans.[20] Once the major fragments were digitally rendered, they were then aligned to adjoining fragments using software algorithms and



26a,b. Virtual models originating from the 3D laser scans and finite element analysis. Left: results of laser scanning in the form of a "point cloud." Right: finite element model showing mesh distribution. The density of the mesh in the left leg has been increased in preparation for submodeling pins in the knee. Models: Ronald Street

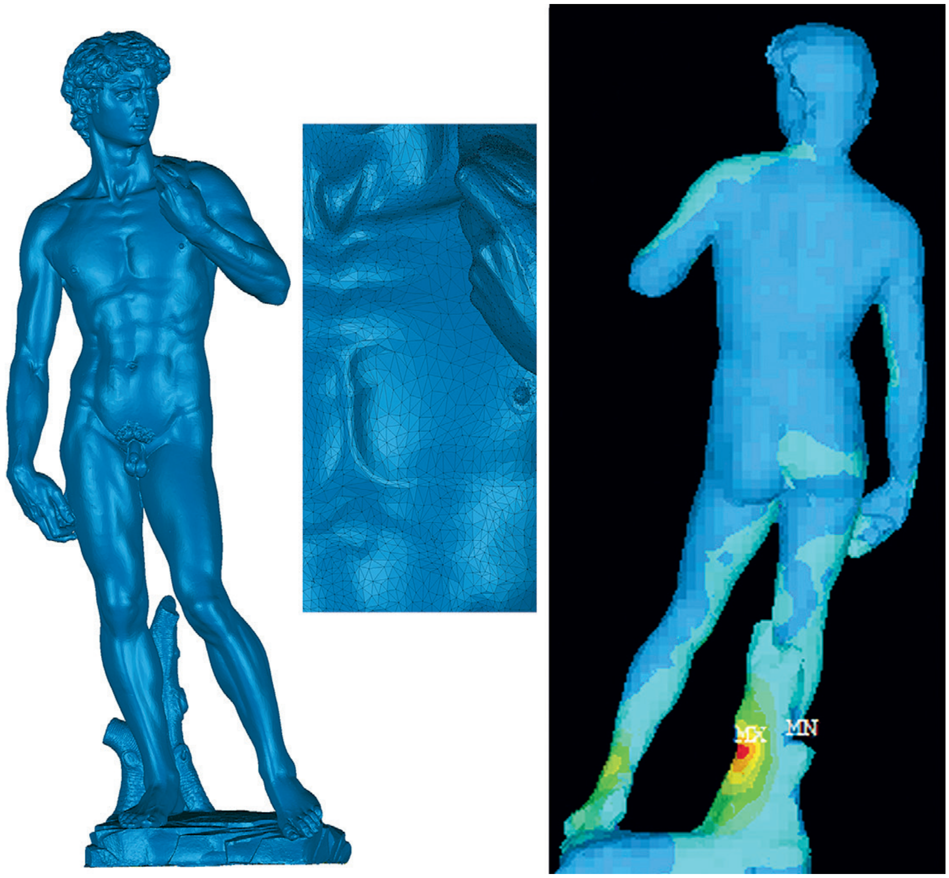
manual adjustments, creating a fully assembled sculpture in 3D virtual space.[21]

***Finite Element Analysis***

Finite element analysis is a technique used in the engineering field to determine the distribution of deflections, stresses, and strains in a structure—factors that define structural integrity. Finite element modeling is a computer simulation procedure that uses 3D computer-aided design (CAD) geometry, which is broken up into hundreds of thousands of small pieces, called finite elements. Each individual finite element is connected to its neighbors in a "mesh" that makes it possible for the program to determine the distribution of force through the entire structure. The finite element method also calculates the deformation of each of the elements, which is used to calculate the resulting strain and stress in the structure due to the externally applied forces (see Figure 26b).[22]

Using the 3D models derived from the laser scans of the major fragments of *Adam*, an initial finite element model was constructed of the assembled sculpture. The team hoped to use the model to derive both a *qualitative* description of the forces transmitted across the fracture surfaces (described as compressive, shear, and tensile forces) and a *quantification* of the stresses that would be present in the entire sculpture.

Scholarly literature existing at the time we scanned *Adam* offered few references relating to the application of finite element analysis to art conservation. The only published work on the use of this technique in sculpture conservation relied entirely on hand-calculations and described a more generalized method in which discrete areas of a sculpture were modeled.[23] We recognized that manual finite element computations would prove unworkable when applied to the complexities of our fragmented sculpture.




27a–c. Digital model of Michelangelo's *David*. Left: laser-scanned polygon model. Center: detail of the polygon mesh. Right: proof of concept study showing overall stresses. Digital model: Marc Levoy; FEA model: Ronald Street

Lacking prior examples of scanned and digitally reassembled sculptures of *Adam*'s complexity, we undertook a proof of concept study that utilized a dataset taken from a digital model of Michelangelo's *David* to determine whether the laser-scanned data could be organized for finite element study (Figure 27a–c).[24] Indeed, this study proved that individually scanned fragments could be assembled into a virtual model that could then be used to perform finite element analysis. Additionally, the proof of concept study provided a foundation for understanding the complexities of such an operation.

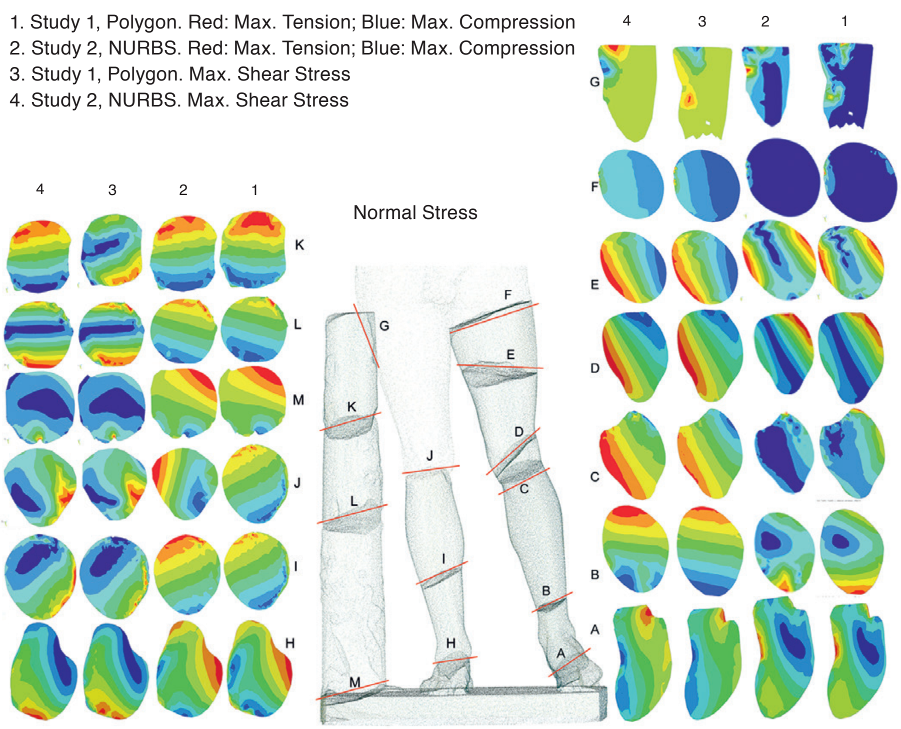
Once we knew we could use the virtual model of *Adam* to perform an engineering analysis of the damaged sculpture, the Museum partnered with Computer Aided Engineering Associates, Inc. (CAE Associates), of Middlebury, Connecticut, to locate and calculate the compressive, shear, and tensile forces transmitted across the fracture surfaces.[25] To get more detailed results, the material characteristics of marble were applied to the model. Because the effectiveness of FEA from a virtual model assembled from individual fragments had never been tested, the analysis was carried out in three phases to determine which type of model would produce the most accurate results.

### *Study 1: Faceted Model*

Study 1 utilized data directly from the laser-scanning process, which produced data in the form of stereolithography (STL) files.[26] This computer file format approximates 3D surfaces with triangular facets, resulting in a series of planes that create a jagged surface when representing curved forms. The analytical model does not represent the true curvature of the original surface and can lead to errors where contact forces and stresses are calculated, such as in the joins of the damaged sculpture.

For Study 1, all the fragments were assembled and virtually bonded together. This approach essentially "healed" the fractures in the sculpture, allowing the maximum load to be distributed throughout the sculpture. Then, to obtain the most accurate numbers from the FEA, predefined material characteristics of Carrara marble, such as density and stiffness (also called "elastic modulus"), were entered into the calculations.[27]

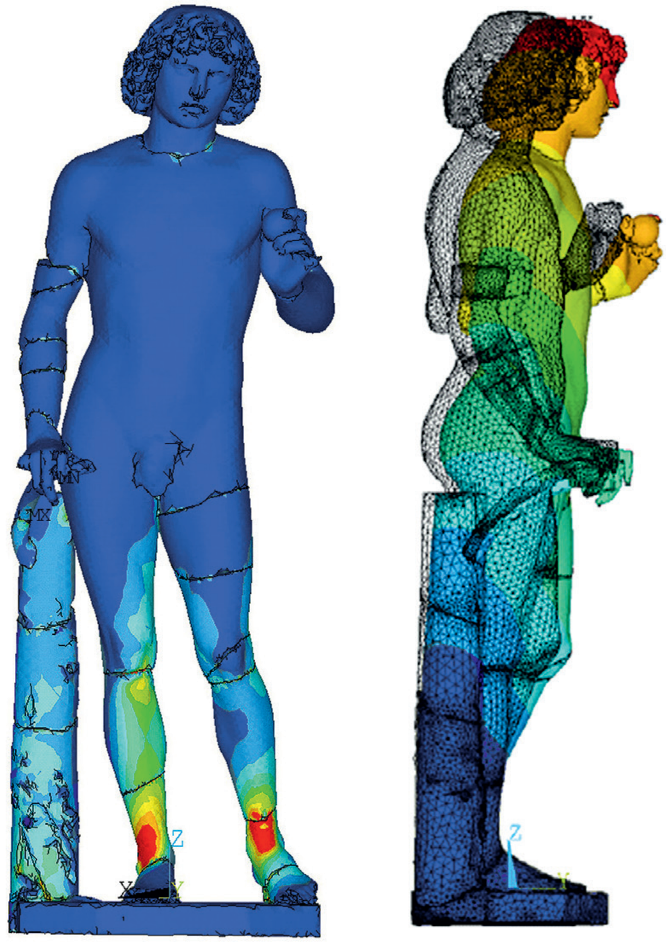
After the FEA model was completed, it was possible to look at a graphical representation of the magnitude and




28. Graphical representation of the results from finite element Studies 1 and 2. Stress plots are represented in columns 1, 2, 3, and 4. The colored bands represent degrees of stress. The plots, or slices, in columns 1 and 2 illustrate compressive (represented by blue and green) and tensile (represented by orange and red) stresses. Columns 3 and 4 illustrate shear forces: here red areas indicate maximum shear stress, decreasing down to blue, which represents the minimum for the slice.

nature of the forces at the location of each break in the sculpture. These FEA diagrams, or "stress plots," illustrate compressive, shear, and tensile loads with their magnitudes represented as colored bands across each fracture. Stress plots are essentially slices taken through the model to allow detailed examination of the forces acting on that cross section. Because the joins were bonded in the Study 1 model, virtual slices were taken just above or below the actual fracture locations as a way to determine approximate forces on each break. The results for Study 1 are graphically represented in columns 1 and 3 of Figure 28. The information gained from these stress plots helped us quantify the forces present in the damaged sculpture and was used to plan adhesive and pinning research.

Study 1 also allowed us to look at how the overall sculpture reacts to gravitational force (Figures 29a,b). This portion of the study showed us that the sculpture has a slight tendency to lean forward and twist about its vertical axis. The twisting is such that the left shoulder rotates toward the right shoulder in a clockwise fashion. The fact that the sculpture twists indicates that the legs experience a slight twisting or shearing deformation under gravity's influence. This study provides some insight into the sculptor's challenges when designing and carving a figure in contrapposto. Considering the tendency of a figure in this position to twist and lean, as well as the vast open spaces between the legs and the right leg and the tree trunk, one must marvel at Tullio's masterful achievement in finding the balance between aesthetic concerns and structural necessities.



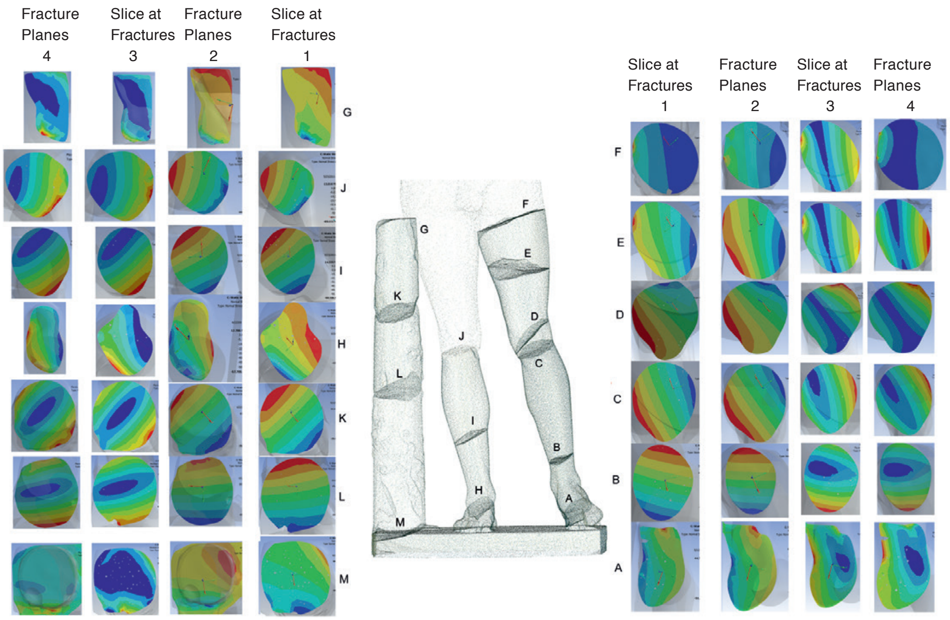
29a,b. Results of Study 1. Left: finite element model showing overall forces. Right: finite element model showing an exaggeration of the natural clockwise twist present in the sculpture. FEA models of Figures 29, 30: Ronald Street and CAE Associates

*Study 2: Smooth Model*

In addition to estimating forces, we also hoped to use the engineering study to develop a model that could be employed to examine the need for pins, their sizes, locations, orientations, and the methods of their insertion. This kind of modeling is not possible with the faceted model created in Study 1, and so a smooth model, or nonuniform rational basis spline (NURBS)–based model, was produced.[28] This format creates a model with smooth surfaces that can more accurately represent curved forms, allowing for subsequent finite element models that can focus in on specific areas of interest (Figure 30a).

The resulting smooth NURBS model represented the sculpture in reassembled condition and was analyzed using

30a–c. Results of Studies 2 and 3. Left: from Study 2, an assembled virtual model in the smooth NURBS format. Center: from Study 3, a continuous NURBS model with bonded contacts. Right: from Study 3, the hybrid model showing imported surfaces from one side of the fracture interface generated from the fragment boundaries of the laser-scanned model, which was utilized to represent fracture surfaces. The imported surfaces look like ruffles extending from the legs.




31. Graphical representation of the results from finite element Study 3. Stress plots are represented in columns 1, 2, 3, and 4. The colored bands represent degrees of stress. The plots, or slices, in columns 1 and 2 illustrate compressive (represented by blue and green) and tensile (represented by orange and red) stresses. Columns 3 and 4 illustrate shear stresses: here red areas indicate maximum shear stress, decreasing down to blue, which represents the minimum for the slice.

the same Carrara marble characteristics as in Study 1.[29] As in the previous study, compressive, shear, and tensile loads across the fracture surfaces were obtained by making virtual slices through the model parallel to and vertically offset from the fracture surfaces. The results of Study 2 agreed well with those calculated in Study 1, indicating that the more functional NURBS format could be used as we began to look more closely at critical sections of the sculpture, in particular the left knee (see Figure 28, columns 2 and 4, for a graphical representation).

*Study 3: Hybrid Model*

Several years after Studies 1 and 2 were completed, a hybrid model study was organized at the request of the conservators, who had begun their treatment of the sculpture and were formulating pinning concepts that they wished to model. In preparation for modeling these pinning scenarios, CAE Associates performed a comparison of the section stresses from the original analysis (Studies 1 and 2) with an updated NURBS model.[30] In Study 2, the breaks in the legs had been virtually bonded, but the shape of the breaks remained intact within the model. In Study 3, the fracture surfaces in the legs were removed and replaced by one continuous surface (see Figure 30b).[31]

A benefit of the new continuous (unbroken) NURBS model was that it permitted a more accurate examination of stress in fracture locations. Next, an innovative method was devised to isolate the rough shape of the broken surfaces in the faceted (STL) model and import them into the smooth, continuous (NURBS) model (see Figure 30c).[32] This clever approach allowed us to take advantage of the benefits of each type of model, combining them to give a more accurate result. Study 3 confirmed that there were only minor differences among stress plot results of all the analytical studies performed. The results of Study 3 are graphically represented in Figure 31. Once this hybrid model was prepared, the analysis continued by exploring various pinning scenarios in the left knee. The results of this focused pinning modeling are discussed in "Pin Testing," pp. 70–74.

*Results of Studies 1, 2, and 3*

The overall trends in the forces acting on each join were found to be consistent in the three analyses. By comparing results of the faceted STL, fractured NURBS-based, and continuous NURBS-based models, we determined that the best representation of the forces on each fracture was achieved by creating a hybrid model that could reproduce the fracture surfaces with complete accuracy. The compressive, shear, and tensile forces on each join in the sculpture, as well as the overall stresses in the sculpture, were successfully calculated. The maximum compressive stress occurring in the sculpture is at the base of the left calf fragment toward the front: 134 pounds per square inch (psi) (0.924 MPa). The maximum tensile stress, 76 psi (0.524 MPa), occurs at the back of this same fracture. Finally, the maximum shear stress on the sculpture, 84 psi (0.579 MPa), occurs at the connection between the hip and the torso. The values reported here were used as the foundation around which we designed and interpreted the extensive materials research that followed this structural analysis.

**Materials Research**

Rods and cramps of lead, copper, iron, and alloys of the latter two metals, anchored with plaster, lead, or natural resins, have been routinely used to attach large fragments of stone sculpture. Current practice favors stainless steel and titanium because of their resistance to corrosion and their thermal expansion coefficients, which are similar to those of the stone. Even with the advent in the twentieth century of structural adhesives, such as epoxy and polyester resins, pinning has remained standard practice. Implicit in this approach is the widespread acceptance that the stabilization imparted by a pin more than compensates for any weakness in the stone created by drilling the holes to insert it. But there are disadvantages. In addition to the effect of removing stone, there is a potential for further damage owing to the fact that steel pins used in combination with epoxy and polyester adhesives are actually much stronger than is required to sustain the loads present in most marble sculptures. So if increased stress is applied later to these joins, failure will occur not at the join line but in the surrounding marble, causing considerably more damage than the original fracture that the pin was intended to repair. Another disadvantage of these traditional stone repair techniques is that they are difficult or practically impossible to reverse without harming the original material. Wishing to take a new approach to the treatment of *Adam* that would help ensure our goal of reversibility, the Tullio team undertook several campaigns of materials testing that covered all aspects of the treatment being considered, from assembly and adhesives to drilling and pinning materials and methods.

#### *Adhesives Testing*

Materials testing commenced with an investigation to determine the best adhesive for reconstructing *Adam*. The goals of the adhesive testing were: (1) to evaluate the adhesive's strength and stability; (2) to determine the degree of displacement caused by the adhesive system; and (3) to test reversibility. The materials chosen for the testing came from two general classes of adhesives: thermosetting and thermoplastic resins.

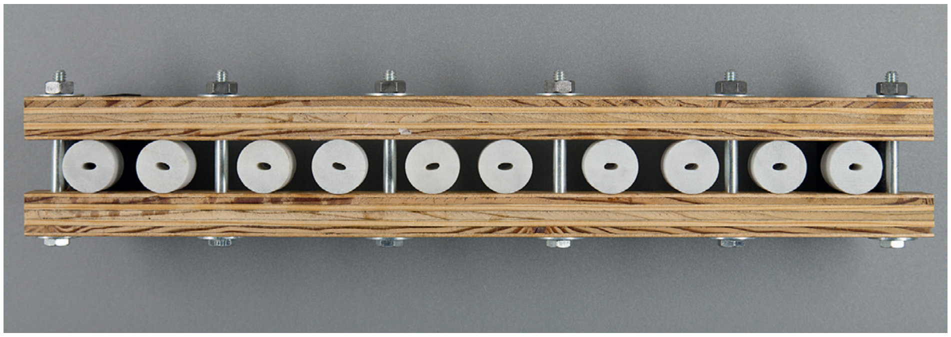
Thermosetting adhesives, which include structural adhesives such as polyester and epoxy resins, cure via a chemical reaction that takes place over a finite period of time; once that reaction has occurred, the molecules are chemically cross-linked and they become insoluble. Hence, thermosetting adhesives are not considered reversible.

Thermoplastic adhesives, on the other hand, include all resins that can be dissolved in organic solvents, such as the acrylic resin-solvent mixtures used in this testing program. They set by the formation of films via solvent evaporation. A drawback of thermoplastics is that solvent evaporation often occurs slowly and is governed by the physical circumstances of its application, such as porosity of the substrate. The result is that residual solvent is retained over an indefinite period of time and, in theory, could have a plasticizing effect on the adhesive. Moreover, for our project, the broad and closely fitting joins in *Adam,* combined with the density of the marble, meant that there would be only small losses at the edge of joins through which solvent could freely evaporate. Nonetheless, the primary benefit of using a thermoplastic adhesive is that the resin remains soluble in organic solvents, making the adhesive and join reversible.

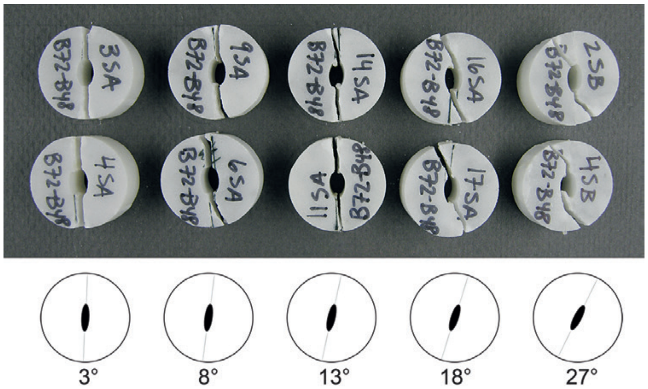
The Tullio team was therefore particularly interested in thermoplastic adhesives, and specifically in the acrylic resin adhesives Paraloids B-72 and B-48N because of their chemical stability and reversibility.[33] Although considerable research has been carried out on the use of B-72 as a consolidant or coating, little has been published on its adhesive properties.[34] Given the tight joins and unequal number of breaks in the sculpture's legs, displacement—the amount of space occupied by an adhesive within a join—was a critical issue. Any significant displacement caused by adhesive would result in uneven lengths of the legs, making it impossible to align the legs and torso properly. Thus measuring the thickness of the adhesive after setting—the bond line—was an integral part of the testing. To ensure that the test conditions matched those of the proposed treatment as closely as possible, Carrara and Vermont marble, with properties roughly similar to those of the marble of *Adam*, were chosen as the stone substrates for the tests.

Conservator Stephen Koob's 1986 article in *Studies in Conservation* was the first significant publication to advocate the use of acrylic resins as adhesives in conservation, and his instructions for preparing B-72 solutions have become standard in the profession.[35] More significant for the Tullio project was an adhesives study carried out jointly by the J. Paul Getty Museum, Los Angeles, California, and the Nelson-Atkins Museum of Art, Kansas City, Missouri. This research investigated the tensile and shear strength of adhesives, and the article Jerry Podany and his coauthors published in 2001 in the *Journal of the American Institute for Conservation* (*JAIC*) concluded that the practice of making epoxy resin joins reversible by applying a layer of B-72 between the marble and epoxy resin did not weaken the join.[36]

Thus, in recent years conservators have continued to rely on epoxy and polyester resins but have made them reversible by applying a thin barrier coating of B-72 directly to the substrate on both sides of a join and allowing it to set fully. They have then used an epoxy or polyester resin as the final structural adhesive. The result might best be described as a B-72–epoxy "sandwich." The acrylic barrier coating can be dissolved with solvents that have little or no swelling effect on the epoxy or polyester resin. While the rationale for coating the stone surfaces with B-72 may be reversibility, the sustainable bond between acrylic resin and stone is essential to the stability of the entire join. As Podany and his coauthors stated, "Given the strength of epoxy and polyester adhesives, the critical link, therefore, is the B-72, and in large part the integrity of the bond depends upon the strength of this material as an adhesive."[37] Indeed, results of tensile testing in their study showed that there was little difference between the strength of joins in marble specimens bonded with B-72 alone and those mended with both epoxy resin plus a B-72 barrier. However, the same study found that in shear tests, B-72 alone did not perform as well as epoxy and polyester resins used either alone or in combination with a B-72 barrier layer. The researchers believed that this failure might be attributed to the plasticizing effects of the solvent retention discussed above.[38] Nonetheless, aspects of this research encouraged the Tullio team to evaluate acrylic resins as structural adhesives to be used without an epoxy resin partner. Our concern with epoxy resins was not only their excessive strength and irreversibility, but, crucially, the thickness of the join that would be created by using it in conjunction with a B-72 barrier. A brief summary of the adhesive research is presented here; details of the procedure and full observations of all tests performed can



32. Preparation of Brazilian disk sandwiches. A clamping device was designed to mimic the maximum forces found in the sculpture. The specimens were left in the clamps for a minimum of three weeks while the adhesives set or cured.




33. Brazilian disk sandwiches bonded with B-72–B-48N blend after testing. These specimens were used to evaluate interfacial fracture toughness, an indication of adhesive strength. Each marble disk was tested with its elliptical hole oriented at a specified angle. Photograph and diagram: Mersedeh Jorjani and Carolyn Riccardelli

be found in recent publications by Mersedeh Jorjani, Nima Rahbar, Ting Tan, and others.[39]

*Interfacial Fracture Toughness (Strength)*

The goal of the first adhesives study was to find a system strong enough to withstand the forces in the sculpture while not displacing the joins. We collaborated with Columbia and Princeton Universities to carry out an investigation into the interfacial fracture toughness—or strength—of several established conservation adhesives.[40] In practice, there are two ways of characterizing adhesion. The first is to quantify it by ‘‘strength’’ based on stress analysis. The second is to quantify it by “fracture toughness,” which describes the ability of a material containing a crack to resist fracture. Although the strength measurement is simpler to carry out, it is well accepted among mechanical engineers that interfacial fracture toughness is a more accurate, quantitative, and reliable measure of adhesion.[41] Significantly, this experiment marks the first time the fracture toughness technique has been used in an art conservation study.[42]

Nine adhesive systems were tested on samples made of Carrara marble, consisting of small disks pierced with an elliptical hole in the center (referred to as “Brazilian disks”), then cut or broken in half.[43] Two categories of sample sets were prepared: one with smooth joining surfaces, and another with fractured surfaces. Joined together with the adhesives under evaluation to create “Brazilian disk sandwiches” (Figure 32), each marble disk was tested with its elliptical hole oriented at a specified angle and stressed to failure with a mechanical analyzer (Figure 33).[44]

This type of testing produces graphs that describe the interfacial fracture toughness of the adhesive and marble interfaces.[45] The graphs of each adhesive system and sample type were compared with those of the control sample set: unbroken marble Brazilian disks tested in the same manner. If the graph, or “energy trend,” for a bonded sample set closely matches the control set, then the adhesive has strength compatible to the intrinsic strength of unbroken marble.

The best-performing adhesive was a blend of 3 parts Paraloid B-72 and 1 part Paraloid B-48N, each made first as a 40 percent solution in acetone and ethanol and then combined by volume.[46] This 3:1 blend displayed an energy trend close to that of unbroken Carrara marble. Moreover, although the fracture energy of the B-72–B-48N blend was shown to be slightly lower than that of marble alone, most of these specimens fractured within the marble and not in the adhesive itself. Similar fracture patterns were reported in the study by Podany and coauthors mentioned earlier.[47]

The overall performance of the nine adhesive systems tested, the thermoplastics, including the conservators’ favored adhesive, B-72, were found to be nearly as strong as thermosetting adhesives. All 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.

*Bond-Line Thickness*

The examination of bond-line thickness—the thickness created by adhesive used to attach two fragments of marble—was an essential aspect of our testing. In the process of preparing the Brazilian disk sandwiches for the fracture toughness tests, waferlike sections of stone were left over, and they were used to measure the bond-line dimensions for each adhesive. Measurements were performed under magnification using a process that allowed many measurements along the join, so that an average bond-line thickness and average deviation could be calculated.[48]

In earlier conservation literature, bond-line thickness studies were carried out by bonding smooth surfaces.[49] Our work revealed that specimens with smooth joining surfaces do not give an accurate indication of an expected bond-line thickness for the fractured-surface joins normally encountered when repairing marble. Our bond-line thickness study was the first to employ sample sets of both smooth and fractured surfaces. It revealed that the specimens with smooth joining surfaces resulted in thinner bond lines than those with fractured joining surfaces.

The thickest bond line in our study was 58 microns for the fractured specimen joined with the B-72–epoxy resin sandwich (epoxy resin coupled with two B-72 barrier coatings).[50] Our preferred adhesive based on the interfacial fracture toughness testing described above, the B-72–B-48N blend, was found to have a bond thickness of only 41 microns, falling in the middle of the range of bond-line thicknesses (Figures 34a,b). Fortunately, the dimensions of the bond lines overall were much smaller than previous literature had led us to anticipate.[51] Indeed, this study showed that the use of any of the adhesives for an object with numerous fractures would not likely result in any perceptible displacement of the joins.[52]

*Creep Testing*

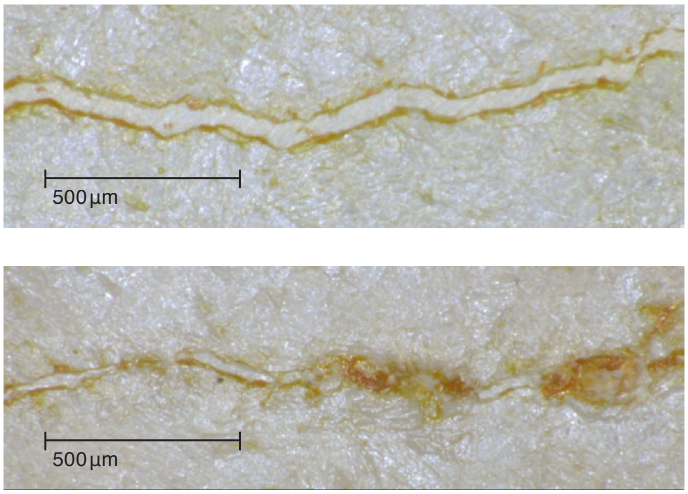
We also examined the long-term stability of the adhesives, specifically, the effects of creep. "Creep" is the term used to describe the permanent mechanical deformation of an adhesive when placed under a load over time. Again collaborating with Columbia and Princeton Universities, we developed a study to look at the creep behavior of various adhesives.[53] This research marked the first time a scientific study of creep was carried out on these conservation materials.[54]

Creep testing was performed using marble Brazilian disk sandwiches prepared in the same way as those used for the fracture toughness study.[55] Again, two sample sets were prepared for each adhesive, one with smooth join surfaces and one with fractured surfaces. The testing setup, in which a sensitive foil gauge was attached to the specimen and the marble disks were stressed in a mechanical analyzer, can be seen in Figure 35.[56] The resulting data were then subjected to mathematical calculations designed to extrapolate short-term laboratory results into predictions of long-term creep life.[57]

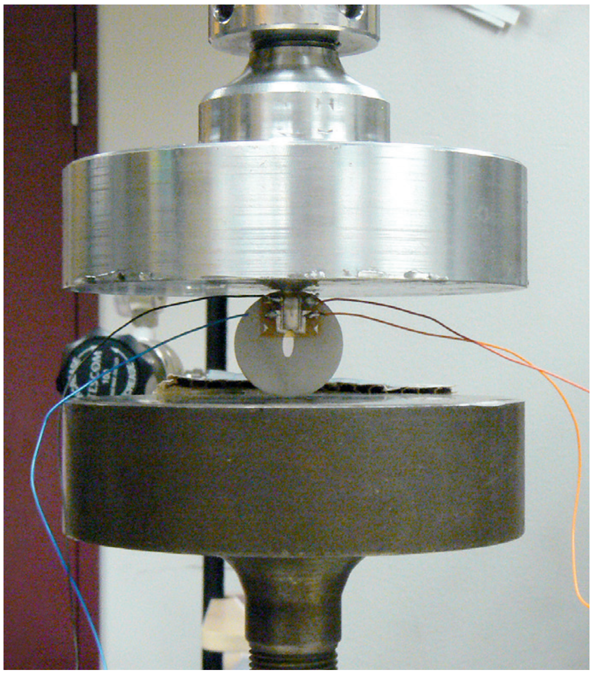
Thermoplastic acrylic resins (B-72, B-48N, and the blend of the two) performed as well as the thermosetting adhesives. The results indicated a very long-term gestation period for adhesive failure caused by creep in both categories of adhesives.[58] This unexpected conclusion goes against the common belief among conservators that thermoplastics have the potential to creep when used as structural adhesives, even at room temperature.

Specimens with the B-72–epoxy resin sandwich performed best in the calculated predictions, with a projected service life of more than 10,000 years. Our calculations predicted several thousands of years of service life for the B-72–B-48N blend, ranking it a close second behind specimens made with a B-72–epoxy resin sandwich. Analysis of the results suggests that the addition of B-48N to a B-72 adhesive may help prevent long-term creep.[59]

In all cases, the smooth specimens outperformed the fractured ones. When we started our testing we anticipated the opposite, thinking the rough surface might provide a greater frictional coefficient, or "tooth," to the join. These studies helped us understand the nature of failure, however, and how it might begin with flaws that exist on a microscopic level. A roughly fractured marble surface has many locations, termed "microvoids," at which failure can start, whereas it is possible to achieve a much more consistent




34a,b. Comparison of bond-line thickness. Top: fractured Brazilian disk sandwich bonded with B-72–epoxy sandwich. Bottom: fractured Brazilian disk sandwich bonded with B-72-B–48N blend. The specimen surfaces were etched and stained with an alizarin-HCl solution to improve contrast. Photographs: Mersedeh Jorjani



35. Creep testing setup. A foil gauge was applied to each specimen and then connected to a voltage meter that could detect small amounts of deformation. The load on the specimen was increased in stages until deformation was detected. Photograph: Andrea Buono

adhesive film on a specimen with a smooth surface with fewer flaws, resulting in a longer predicted service life. This reasoning also highlights the importance of adhesive application techniques, confirming that a continuous, consistent film is critical to a join's strength.[60]

*Summary of Adhesive Testing Results*

For the treatment of *Adam*, we chose a 3:1 blend of B-72 and B-48N because this system is reversible, has adequate strength without creep, produced a minimal bond line, and has excellent aging characteristics. This adhesive sets by solvent evaporation, and we anticipated that it would require at least four weeks of setting time to reach optimal strength. The matter of solvent retention was further investigated by the Tullio team and is discussed in "Adhesive and Solvent Retention Experiments," pp. 74–77. The combination of these results proved to us that reversible acrylic resins can indeed be trusted as structural adhesives provided certain working techniques are followed. The broader value of these results is that they will inform the conservation community about these familiar adhesives and encourage conservators to use them in new ways.

***Pin Testing***

Pinning has long been a practice in large-scale sculpture restoration. Certainly it seems to be a technique used ever since the first person joined pieces of stone in antiquity. However, there is little in the conservation literature devoted to the use of pins in sculpture. At the time of our study, the insertion of rigid pins into stone had yet to be thoroughly studied; the most closely relevant studies were related to rebar in reinforced concrete or to pinning blocks of architectural stone.[61] Inserting a pin into a marble sculpture is an entirely different operation, as it involves drilling and thus the removal of original material. In keeping with the goal of minimal intervention, we therefore undertook several studies in collaboration with Columbia and Princeton Universities to examine pinning materials and methods.[62]

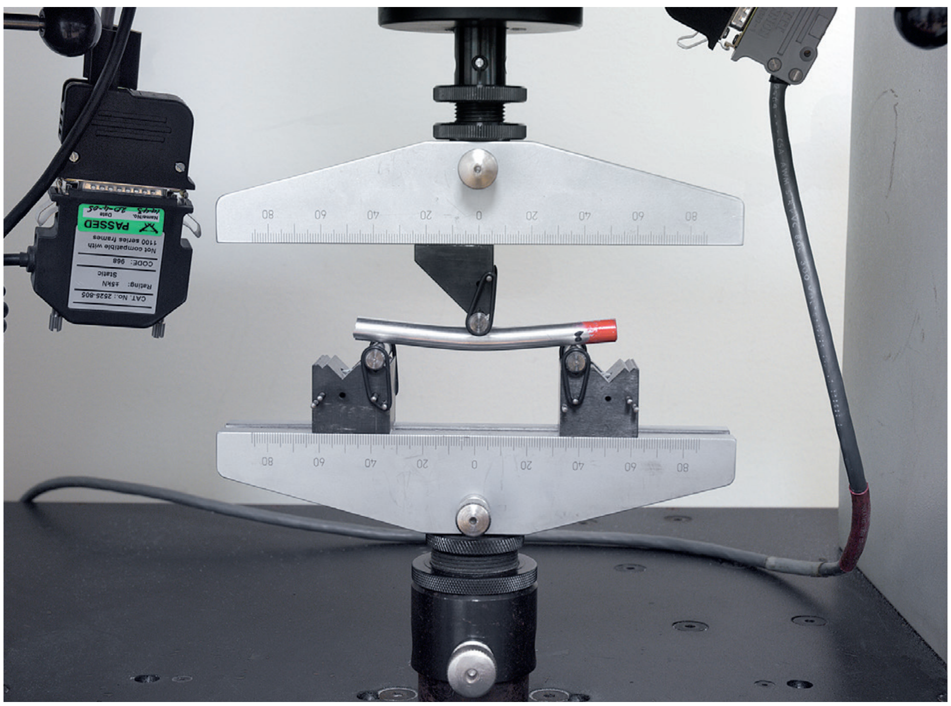
Our research centered on the effects of a pin inserted into marble, and specifically on the stiffness of the pin in relation to the surrounding stone. Different pinning materials were tested to gain a better understanding of how they deformed under stress. The ideal pinning material helps to create a join with mechanical properties similar to those of the material being joined. Making the join stronger than the surrounding material runs the risk of further damaging the stone under new or increased stresses.

The hole drilled to accommodate the pin became another focus of testing. Irrespective of a pin's material, a pinhole is essentially a flaw and therefore a weakness in the marble, a site where new breakage can originate. We sought to gain a better understanding of how much a drilled hole might compromise the stone. A more immediate objective of the pinning research was to determine the number and size of the pins needed for *Adam*. We were aiming for minimal quantity and minimum size of drill holes. A brief summary of pin testing is presented here; details of the testing procedures and results can be found in a recent publication by Carolyn Riccardelli and others.[63]

*Standardization of the Stiffness Value*

The research on pinning began with basic modulus testing. The modulus of elasticity is a measure of the stiffness of a material: higher values indicate stiffer materials. Testing materials were chosen based on their published modulus values ranging from very flexible (Teflon) to very stiff (stainless steel). For most materials, moduli reported in the literature are determined by placing the material under compressive or tensile loading.[64] The assessment of the sculpture's stresses in the finite element analysis showed us that, in *Adam*'s case, *bending* stresses are most critical in relation to pins. Thus, a testing protocol known as the three-point bend was chosen to evaluate these stresses in pinning materials (Figure 36).[65] The results of these tests are plotted on a graph that conveys two essential pieces of information about the pinning materials: the elastic modulus of a material (its stiffness) and its mode of failure.[66]

The moduli obtained through our tests differed considerably from those reported in the literature or by manufacturers. For example, beginning with the stone itself, a set of ¼ inch (0.64 cm) diameter Carrara marble rods was prepared and tested, producing a modulus value several orders of magnitude lower than that normally reported in the geology literature.[67] This higher reported value is commonly



36. Three-point bend testing setup used for determining the flexure modulus of pinning materials. The mechanical analyzer applied downward force until the specimen deformed or failed.

considered the standard modulus for marble, but it is actually the elastic modulus in *compression*—describing the stone's ability to withstand downward force such as that experienced by an architectural column. The compressive modulus does not describe the lesser ability of marble to resist bending forces and therefore does not represent the way in which a sculpture actually fractures. Our new, lower modulus value for marble proved to be important to integrate into our analysis focusing specifically on *Adam*'s left knee; see "Additional Finite Element Modeling," pp. 83–85.

Also tested was carbon fiber rod, a composite material made of graphite fibers embedded in resin (vinyl ester). As the reported modulus is significantly higher than the numbers obtained in our tests, we consulted the manufacturer and learned that this modulus is taken from the tensile strength of the fibers themselves and does not reflect the ability of the composite material to resist bending.

We tested another composite material—fiberglass rod, which is made of glass fibers embedded in polyester resin. Our tests determined that its elastic modulus is about twice that of Carrara marble; even so, it represented the closest match. Notably, both composite materials tested have a characteristic kinking behavior upon failure, as distinct from metal pins, which bend due to their ductility. This kinking behavior—a local delamination and buckling process in which the stiff resin component of the composite fails but the fibers remain intact—could potentially be beneficial if the sculpture were ever subjected to a future impact. Because fiberglass rods were determined to have the elastic modulus and failure mode most compatible with Carrara marble, fiberglass became a leading candidate for use in pinning joins in *Adam,* and careful attention was given to its performance in further pinning studies.

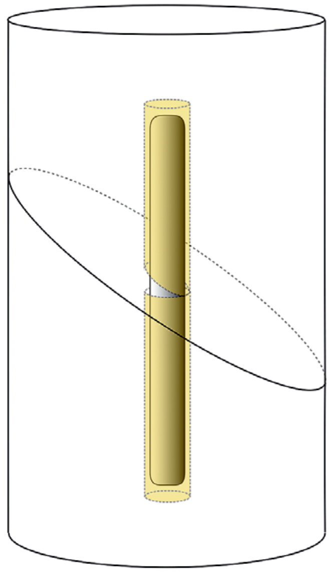
*Smooth-Surface Specimens*

Following the stiffness tests, we examined the structural behavior of pins when set into marble cylinders. Samples were prepared with the full range of pinning materials and were designed to be representative of the critical shear joins in the *Adam* sculpture.[68] We started by looking at the pin itself and designed a testing sample that would isolate the behavior of the pin without any additional interference from the surface of the join. To this end, this first phase of research looked at how marble behaves when it is joined by a pin set into epoxy resin but without adhesive on the interfacial surfaces.

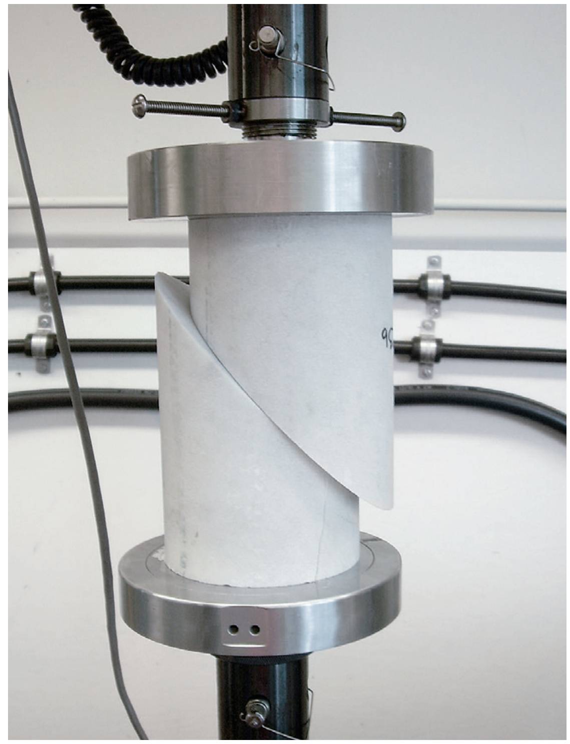
The specimens were made of 8 inch (20.3 cm) tall, 4 inch (10.2 cm) diameter Carrara marble cylinders, each cut at a 45-degree angle across its center to mimic the shear joins of *Adam*'s ankles and left knee. The angled join surface was sanded smooth to minimize friction between the upper and lower halves, focusing force on the pin alone. For this sample set, the pins were approximately 4 inches (10.2 cm) long, and ½ inch (1.3 cm) in diameter, as recommended by our colleagues at Princeton University, who suggested a length-to-diameter ratio of 8:1 based on their collective experience in fracture mechanics. The rationale was that this ratio would produce an ideal pin that would not be so long as to create focused stress points at its ends but still long enough to ensure an effective mechanical connection between two fragments. When the pins were set into the marble cylinders, the epoxy resin adhesive was restricted to the pinholes and was not permitted to extrude onto the smooth, angled "mating" surfaces of the marble (Figure 37).

Six different materials were tested, including stainless steel, fiberglass, and titanium. Each prepared cylinder was placed in a mechanical analyzer and subjected to gradually increasing compressive force until either the pin or the marble cylinder failed (Figure 38).[69] The downward force combined with the specimens' 45-degree-angle join created an overall compressive-shear loading scenario that reflected the critical breaks in the sculpture. The result of this testing is a stress-strain diagram that describes the maximum load at the moment of failure as well as the mode of failure.[70] The results of two representative sample sets are given here to illustrate the range of our results.

The marble cylinders prepared with steel pins fractured severely during the test, leaving the pin seemingly unaffected (Figure 39). While the force required to reach failure



37. Diagram of smooth-surface specimen. Carrara marble cores were cut at a 45-degree angle to mimic the shear joins of *Adam*'s left knee and both ankles. The pin was affixed in the marble with epoxy, but the join surface was not bonded.



38. Testing setup for smooth-surface cylinders. The 8-inch-tall assembled specimens were subjected to gradually increasing downward force until there was failure of the pin or the marble. Photograph: Christina Muir

39. Three smooth-surface marble cylinders with stainless steel pins after testing. This kind of Y-shaped failure was typical for specimens pinned with stainless steel and titanium.

40. Upper and lower sections of three smooth-surface marble cylinders with fiberglass pins after testing. The marble was undamaged when the fiberglass pins were pushed to failure.

in this test[71] was much higher than internal forces within *Adam*, and indeed within most marble sculptures, these results are an indication of what might happen if a sudden impact or a fall were to occur in the future.

On the other hand, when the fiberglass-pinned specimens were pushed to failure, there was no damage to any of the marble cylinders, and all the pins broke cleanly through (Figure 40).[72] As previously stated, the modulus testing showed that fiberglass rods have a flexure elastic modulus about twice that of marble, and the results of the smooth-surface tests confirmed that there is good compatibility between the two materials.

In summary, the smooth-surface testing set showed that the average maximum load trends correspond well to those of the tested moduli of the pinning materials. Metal pins (titanium and stainless steel) with their high elastic moduli proved too stiff, as they caused the marble cylinders to break apart. Plastic pins (polycarbonate, Teflon, and acrylic) with very low elastic moduli did not cause damage to the marble cylinders but failed at loads lower than the internal forces determined to be within the *Adam* sculpture.

Fiber-based composite pins (fiberglass and carbon fiber) failed at relatively high applied loads without damaging the marble cylinders. The carbon fiber pins, which have a much higher elastic modulus than fiberglass pins, failed at a higher load than the fiberglass pins. The smooth-surface testing results indicated that both of these materials would be able to withstand the forces in the *Adam* sculpture without causing damage to the stone in case of impact. The kinking behavior of fiberglass pins that was observed in the modulus testing contributed to this positive result. Rather than failing by deforming and remaining in place, as would a ductile metal, composite pins kink and then break, allowing separation of the join before further damage is done to the marble.

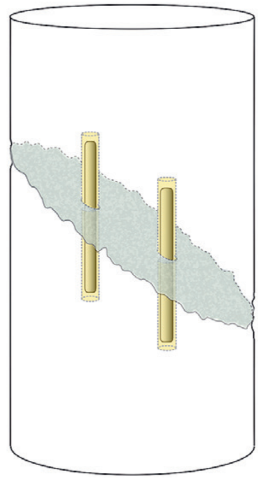
*Fractured-Surface Specimens*

The next round of samples was designed as mock-ups of *Adam*'s ankle joins, matching them in both size and theoretical mending technique. Based on the results of the smooth-surface tests, we chose titanium, carbon fiber, and fiberglass for the fractured-surface mock-ups.[73] Rather than cutting the cylinders as in the smooth-surface specimens, this sample set was fractured at a 45-degree angle to create a more realistic join. These cylinders were 5½ inches (13.9 cm) tall and 2½ inches (6.4 cm) in diameter, and made of Vermont marble because it is easier to obtain and more affordable than Carrara marble. Two small pins, 2 inches (5.1 cm) long and ¼ inch (0.64 cm) in diameter (thus the same 8:1 ratio), were set into the cylinders using epoxy resin; the fractured surfaces were joined with the B-72–B-48N blend we had already chosen for the treatment of *Adam* (Figure 41).[74] The fractured cylinders were then tested in the same manner as the smooth-surface set.

As was observed in the smooth-surface set, titanium pins caused damage to the fractured-surface marble cylinders (Figure 42). All three specimens were severely fragmented, while the titanium pin inside the sample was only slightly deformed under the relatively high maximum applied load.[75] The carbon fiber pins performed well, but damaged one of the three specimens in the set.

Once again, fiberglass pins performed best, causing no damage to the marble cylinders (Figures 43a,b). In each specimen, both the acrylic resin adhesive blend on the join and the fiberglass pins failed before there was any damage to the marble cylinder, creating an ideal pinning system.[76] All specimens tested in the fractured-surface set showed join-strength several orders of magnitude greater than the loads determined by FEA to be present the sculpture.

Finally, a set of cylinders fractured at the 45-degree angle, but without pins or pinholes, was repaired with the B-72–B-48N blend. This unpinned sample set served as a control of sorts. During testing, the specimens failed along the adhesive join with no consequential damage to the marble. In fact, the average maximum load was slightly *higher* than the fractured-surface sample set made with fiberglass pins.[77] While the difference is not statistically significant, this result affected the way we pondered the necessity of pinning each join, a process described in detail in “The Problem of the Left Knee,” pp. 83–86.



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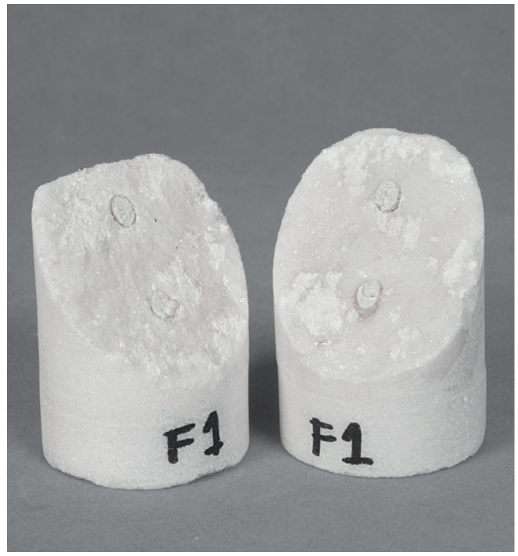
43a




43b

*Summary and Discussion of Pin-Testing Results*
With such compelling results on which to base our decision, we chose fiberglass rods to be the pinning material for *Adam*'s reconstruction. Carbon fiber rods had promising characteristics during testing but proved to be much stiffer than the marble, cracking one of the testing specimens. Fiberglass was determined to have a modulus (stiffness) more compatible with marble, and testing showed that it would not cause damage in case the sculpture were subjected to an impact. Conventional wisdom suggests that repair materials such as pins or adhesives should have properties, such as strength and modulus, similar to the substrate. Yet stainless steel, with a much higher elastic modulus than that of marble, continues to be the most commonly used conservation pinning material. We believe that our testing results will prompt conservators to consider a wider range of effective pinning materials. For the repair of sculpture that will remain in a controlled museum environment, the reasons for choosing stainless steel—corrosion resistance, coefficient of thermal expansion—become less important. Our testing established that fiber-based composite rods such as fiberglass and carbon fiber outperformed both stainless steel and titanium in that they were of sufficient strength to withstand the maximum static forces of the sculpture and did not damage the marble cylinder before pin failure.

Throughout all our pinning studies, we became keenly aware that the process of drilling into marble introduces a flaw, thereby potentially weakening the stone. And, while we agreed that we had found in fiberglass an ideal pinning material, we had not yet addressed our objective to minimize the number of pins we would ultimately use in repairing the sculpture. Therefore, it was particularly significant that the unpinned fractured-surface cylinders outperformed the sample set prepared with fiberglass rods. These results had profound implications for the eventual selection of which joins in *Adam* we would pin.

*Pins and Reversibility*
While the final decision on the number and location of pins was still pending, we agreed that *Adam*'s ankles should be pinned, and so we developed a protocol for inserting the pins in a reversible manner. Historically, pins have been set into stone using plaster, shellac, hide glue, or even molten lead. More recently, epoxy or polyester resin adhesives have been used as a way to embed and secure pins. These techniques are difficult to reverse, however, and they typically lead to some kind of damage or risk to the object during the process of removal. Although reversibility can be achieved by the use of acrylic resin adhesives thickened with bulking agents, such as glass microballoons,[78] when setting pins into stone, the depth of the pinhole at the center of a marble join makes for slow solvent evaporation. Judging exactly how long it would take for that adhesive to set before it would be safe to place a load on the join would be problematic.

Epoxy resin adhesives, on the other hand, have a known cure time, and when used in the pinhole can lock a pin in place, making it simple to know exactly when a join is capable of carrying a load. But such joins are very difficult to reverse. So to take advantage of the curing benefits of epoxy but still create a reversible join, conservators in recent years have elected to use a sleeve system in which the pin is set into the stone by mechanical means, either by inserting a metal sleeve or by creating a sleeve with epoxy.

The epoxy sleeve has gained popularity because of its reversibility.[79] By placing a release agent on the pin prior to

41. Diagram of fractured-surface specimen. Vermont marble cylinders were fractured at a 45-degree angle to mimic the shear joins of *Adam*'s ankles. The pin was affixed with epoxy resin and the fractured join surface was bonded with the B-72–B-48N blend.

42. Fractured-surface cylinder with titanium pins after testing. The marble was badly damaged after the specimen was subjected to compressive force. This kind of damage was typical when the stiffness of the pinning material far exceeded that of the marble.

43a,b. Fractured-surface cylinder with fiberglass pins after testing. Left: assembled. Right: separated. The fiberglass pins failed without damaging the marble.

44. Sichuan marble *David* that was used as a mock-up for assembling *Adam*. The replica was also used for testing and in the development of an external treatment armature. The overhead bridge crane can also be seen in this photograph.

inserting it into liquid epoxy, a cast-in sleeve achieves a snug fit between pin and sleeve. The result is not only effective but also prevents focused stress points that can arise from poor conformation between pin and sleeve. Metal sleeves are also reversible, but thin-walled, snug-fitting sleeve-and-pin combinations are not readily available, and therefore it is more difficult to achieve the same excellent conformation with metal sleeves. A further drawback of metal sleeves is that they require a larger pinhole to accommodate both the sleeve and the epoxy resin that holds it in place.

A common alternative to a fully sleeved pin is one that is bonded at one end and sleeved at the other, sometimes referred to as a "potted pin." We used finite element modeling to compare the benefits and drawbacks of both fully sleeved and potted pins (discussed in "Additional Finite Element Modeling," pp. 83–85), and the analysis showed that fully sleeved pins distribute stress across a join more equally than potted pins. Also, because sleeved pins do not create a solid structure inside the pinhole, they would be released from the marble in the event of a further impact or fall. After taking all of these factors into consideration, we decided to create full epoxy sleeves in *Adam*'s pinholes; when paired with the B-72–B-48N blend on the fracture surfaces, we were confident that we would create fully reversible joins. The technique devised for inserting the pins is outlined in "Inserting Pins," p. 92.

**Empirical Research**

In addition to the studies described above, the Tullio team carried out a series of experiments aimed at evaluating the influence of several parameters purposefully eliminated from the design of the earlier research. Scientific studies yield reliable quantitative results; empirical experiments, on the other hand, offer practical results that can be described as qualitative. The set of experiments related below was designed to incorporate conditions closer to those that exist in the *Adam* sculpture, for example, the additive dimensional effect of stacking fragments of broken stone and the time it might take for sufficient solvent to evaporate from adhesive in a tight marble join before the adhesive reaches full strength. Indeed, these studies were approached systematically, but they also incorporated the working style of the conservator and made accommodation for the inevitable errors or variables that occur in reality and which scientific studies are designed to avoid. The results of such explorations indicate a trend or a relative magnitude and thus contribute to the success of a project by helping conservators build confidence and familiarity with materials and treatment protocols.

***Adhesive and Solvent Retention Experiments***

Several practical experiments were carried out to explore the concepts of solvent retention in acrylic adhesives. Because thermoplastic adhesives set by a process of solvent evaporation rather than curing by chemical reaction, it is difficult to predict exactly when the solvent will have sufficiently evaporated from the system. Solvent retained during the setting process can act as a plasticizer, keeping the adhesive film soft for a period of time and potentially leading to creep or even join failure. The experiments described below attempted to predict how long it might take an acrylic film to pass beyond the point of any potential creep during setting.

*Acrylic Resin Adhesive Experiment: Trial Join*

The Tullio team purchased a modern marble replica of Michelangelo's *David*, in a scale similar in size to *Adam*, specifically for the purpose of breaking the stone figure so that it could serve as a mock-up.[80] There were several benefits to having an alternative broken sculpture on hand. It helped us plan the external armature, practice safe methods for handling and orienting large, heavy masses of fragile stone, and test various adhesive and pinning scenarios. The 70-inch (178 cm) tall replica was carved from Sichuan marble, a white stone with gray veining (Figure 44). This marble proved to be less fine and compact than Carrara marble, and it fractured with a granular texture. However, for experimental purposes its properties were close enough to Carrara marble. Moreover, the composition of *David* provided a figure standing in contrapposto position as well as the scale and mass required to be an accurate experimental stand-in for *Adam*.

We used the *David* replica in our consideration of adhesive-only joining options. Our experiment focused on the connection between *Adam*'s left arm and torso because the size and configuration of the proposed external support armature required that this join be one of the first affixed. *Adam*'s left arm had broken off at an almost vertical angle, resulting in a join that would be subjected to a combination of compressive, shear, and tensile forces. The damage and orientation of the fracture along this join caused the team to be hesitant about drilling and pinning in the upper arm.

While considering various adhesive-only joining options, we tested an acrylic resin adhesive join on the *David* replica's left arm. Using feathers and wedges, traditional stone-splitting tools employed by stonemasons, we broke the replica's left arm at an angle similar to the break in *Adam*'s left arm (see "Marble Replica of Michelangelo's *David*," p. 78). The break was not as crisp and clean as that on *Adam*, however, as the use of feathers and wedges necessitated drilling several holes across the join. The fracture was bonded with the B-72–B-48N blend, applied generously, then clamped and allowed to set under pressure for three months. It was thought that this period would provide sufficient setting time for the adhesive, allowing the acetone and ethanol solvents in the adhesive to volatilize fully. The *David* replica's torso with the attached arm was then placed upright and suspended from an external armature support. Next, a 17-pound (7.7 kg) weight was hung from the arm, located away from the join, near the wrist. About a week later the join appeared to be separating on the inside of the break; strings of adhesive were visible in the depths of the fracture, indicating that the film of acrylic resin was stretching apart (Figure 45). After observing this separation, we wanted to see if we could force the join to fail, and three months later the weight was doubled. One month after that, the join failed completely (Figure 46).

Failure of the *David* replica's arm join occurred more quickly than we anticipated, and we agreed that the failure was likely due to solvent retention in the adhesive film, but we also suspected that the adhesive had been applied too thickly. The exposed adhesive on the broken arm join was stretched and stringy, signifying that the film, although well adhered to the marble, had failed cohesively, or within the adhesive layer (Figure 47). Three months had seemed a sufficient time for the adhesive to set fully, but clearly that was not the case with the *David* replica's arm. The results of this experiment confirmed that a thin continuous film of adhesive is far more effective than an overly thick one and

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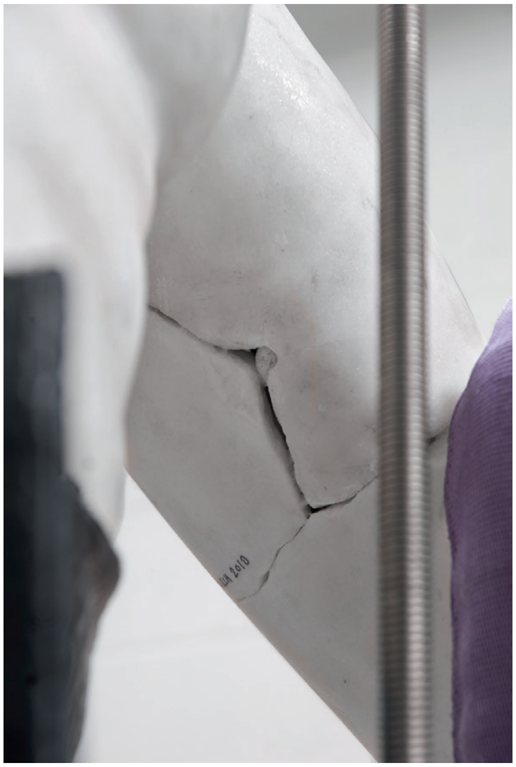


45. Trial join in progress on the *David* replica. The left arm was attached to the torso using acrylic resin adhesives and then allowed to set for three months before a weight was suspended from the arm. One week after the weight was applied, the join began to separate.

46

46. Torso of the *David* replica, photographed after the left arm join failed. The arm is floating by a catch-strap created to prevent it from falling to the floor.

47. Torso of the *David* replica, showing the failed adhesive. Note the stringy, rough nature of the adhesive film, indicating that the overly thick layer had not fully set.

demonstrated that clamping and tightness of a join have a major effect on its ability to hold. The results also suggested that a pin might be needed in shear joins to counteract the short-term risk of creep during setting.

### *Solvent Evaporation Rate Experiment*

Another, more systematic experiment was required to better comprehend the length of time the marble sculpture fragments should remain clamped and supported following attachment. Experience had shown us that, when using a thermoplastic adhesive to repair large stone sculptures, fragments need to be immobilized within an external structural support until the adhesive, through solvent evaporation, reaches sufficient strength to support the marble's weight. The objective of this experiment was to determine the rate of solvent evaporation of the adhesive through a porous substrate such as marble.

For this experiment, a set of Carrara marble disks was fractured across their 2-inch (5.1 cm) diameter and then weighed.[81] Each disk was then mended using the B-72–B-48N blend and weighed immediately after adhesion. Weighing continued at frequent intervals during the initial days of the experiment. As weight changes diminished, measurements were made each week and, finally, after one year.[82] It was not possible to measure the amount of resin and the amount of solvent applied to each specimen, so the weighing actually tracked the change in weight of the adhesive rather than a specific solvent percentage loss.

Each specimen lost approximately 30 percent of its adhesive weight within the first 3 hours. By the end of the first 24-hour period, each had lost an additional 25 percent of its initial adhesive weight. At 54 hours, solvent evaporation began to plateau, averaging a loss of 48 percent of initial adhesive weight.[83] After the first week, evaporation was slow, steady, and continual. A year later, specimen weights had changed only slightly, signifying that only a small amount of detectable solvent had continued to evaporate from the samples. The results of this experiment were enlightening, as the solvent evaporation occurred much faster in the marble disks than was indicated by the trial join experiment. In the end, however, the limitations of the experiment did not enable us to predict more accurately how long it would take a large join to reach full strength.

### *Creep Experiment: Carrara Cylinder*

One final experiment pertained to solvent retention and potential creep. On the same day that we bonded the small, wedge-shaped fragment in *Adam*'s left knee to the adjacent lower left thigh (see "Left Knee Wedge Join," p. 97), we also joined two parts of a similarly sized fractured Carrara test cylinder. This cylinder had been split along its vertical axis so that the fragments could be attached using the B-72–B-48N blend. The intention was to monitor the strength and creep behavior of the experimental join in the cylinder as a stand-in for the newly bonded fragments on the sculpture.

After the marble cylinder's adhesive had set under pressure for three weeks, shear force was applied to the join to try to instigate creep. The test cylinder was arranged in an armature so that downward pressure was directed at only one side of the vertical join, placing the adhesive in shear. A gauge, the same as that used in the creep testing, was attached across the join to detect movement, and then dead weights were applied, subjecting the join to approximately 30 psi (0.207 MPa) of shear stress.[84] This amount of weight was chosen because it reflected the maximum shear force that our analysis determined would be experienced along the top of the left knee wedge in the assembled sculpture. The experiment continued for several months, but no movement was detected along the join.

### *Discussion of Adhesive and Solvent Retention Experiments*

The vastly different results between the *David* replica arm experiment and the Carrara cylinder experiment can be attributed primarily to working technique, and they highlight the value of these additional studies. The interfaces of the replica's arm join mated poorly due to preparation of the fracture and the quality of the Sichuan marble. The thick layer of adhesive applied to the join increased its susceptibility to creep and failed when weights were suspended from the arm. The Carrara marble cylinder fragments, on the other hand, were bonded using a thinner layer of adhesive on cleanly fractured, tightly fitting interfaces and did not experience creep when weight was applied. These results are reflected in a creep experiment carried out by colleagues at the J. Paul Getty Museum, who also found that a thick layer of adhesive tended to creep, while a thin layer underwent very little movement or creep.[85] Podany and his coauthors explained this effect in their 2001 article: "Thicker bond lines increase the dependency upon the cohesive strength of the adhesive, which is often weaker than its adhesive strength and may be insufficient for the stresses placed on the bond by shear loads."[86]

While the solvent evaporation rate experiment indicated that solvent evaporation has the potential to occur significantly faster than had been suggested by the experiment on the *David* replica's arm, the experiment was limited in that it did not provide a means for translating the solvent evaporation performance of small specimens to the large surface area of *Adam*'s legs. Clearly, a large join would take longer to set than a small one. The weight loss in this experiment measured the evaporation of solvent that is free to move out of the adhesive and through the stone. Without knowing the exact amount of solvent that is able to leave the system, it is difficult to guess the endpoint of the experiment.[87] Other studies and our results show that after the initial, easily measurable loss of solvent, what remains is very tightly locked inside the polymer structure.[88] It is this residual solvent that could potentially plasticize the adhesive.[89]

Regardless of the long-term solvent retention issues, the fact remains that acrylic resin adhesives cannot properly sustain a significant load until many weeks after application. Thus the critical role of the proposed external armature was clear, as was the wisdom of the decision to pin *Adam*'s ankles, since pins would counteract potential creep while the adhesive set in the areas where the full weight of the sculpture would be concentrated.

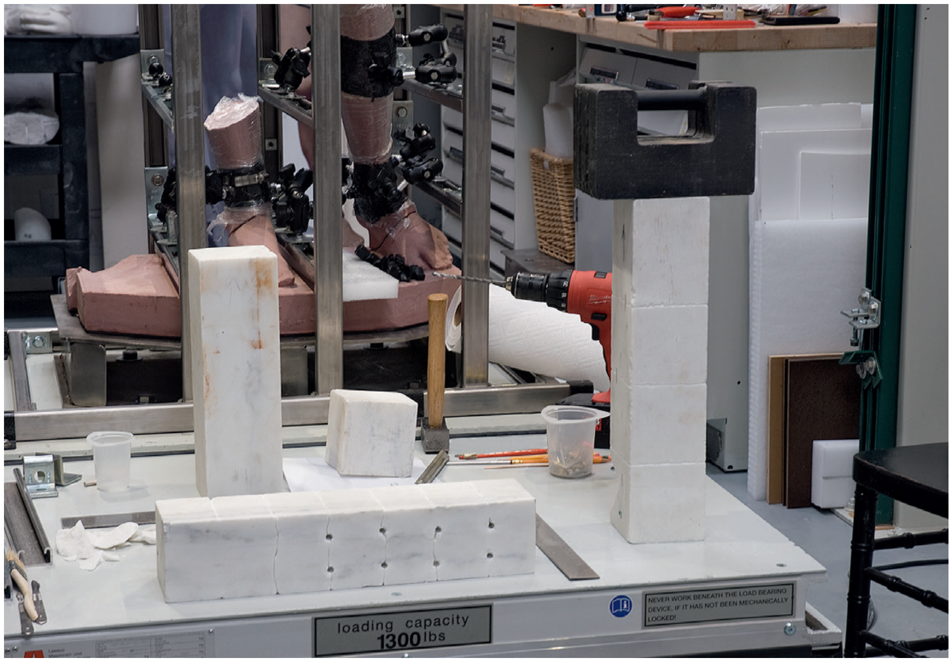
### *Bond-Line Thickness Experiment: Marble Blocks*

Because bond-line thickness was such a critical component of the adhesives we were studying, we carried out an empirical experiment to look at the displacement of the joins due to the addition of adhesive. Three blocks of Vermont marble, approximately 4 inches (10.2 cm) square and 14 inches (35.6 cm) long, were precisely measured.[90] With feathers and wedges, the blocks were then broken at between four and six locations (reflecting the number of breaks in *Adam*'s left leg), reassembled without adhesive, and then measured a second time.

The process of fracturing marble invariably leads to a displacement of grains along the fracture that can prevent the tightest possible fit between fragments. To improve the fit, we carefully cleaned away loose grains of marble from the fracture surfaces before the blocks were reassembled and measured for the third time. Finally, the blocks were mended using the B-72–B-48N blend, clamped under the mass of a 50-pound (22.7 kg) weight, and allowed to set for several weeks (Figure 48). One month later, the blocks were measured for the fourth and final time.

The measurements indicated that the length of the blocks increased not only due to the addition of adhesive (as expected) but also merely from the process of fracturing the stone and putting it back together. Removal of loose grains from the fracture surfaces had a positive effect, reducing increased length. Dividing the change in length of each adhered block by the number of joins provided an average bond-line thickness of 150–200 microns per join, about the thickness of an index card. It was therefore established that even within the tightest join, there was space for adhesive to occupy without causing significant displacement.

Our previous bond-line thickness study with Brazilian disk sandwiches produced even thinner bond lines because the clamping pressure achieved during their fabrication was greater than that of the marble block experiment. These differing results indicate that there is a direct relationship between bond-line thickness and clamping pressure. The amount of clamping pressure applied to the Brazilian disk sandwiches was based directly on the actual pressures present in the sculpture. Therefore, we can infer that the bond-line thicknesses realized in the assembly of the sculpture are closer to those achieved in the Brazilian disk sandwiches than to those in the empirical bond-line experiment.




48. Bond-line thickness experiment in progress. Each marble block was measured, broken into several parts, reassembled without adhesive, and measured again. The block was then bonded together and measured a final time.

## PLANNING THE TREATMENT

As we moved from the research phase of the project to planning the treatment—that is, to the implementation of the understandings we had gained—we knew that we would need to design specialized equipment to meet our treatment goals of minimal intervention and of reversibility. And while we had determined to pin the ankles, we had yet to reach a final decision regarding the join at the left knee. Even as we furnished the Tullio studio with equipment that would facilitate the reassembly of *Adam* with minimal handling, we addressed the left knee join through additional research and discussion, and this process is described in detail as a case study in decision making for complex conservation projects.

### Specialized Equipment

Taking into consideration the contours, weight, and number of fragments, we knew it would be impossible to use a traditional clamping system to hold fragments of the sculpture in place while the adhesive set. Thus, early in the project, it was proposed that we use the sculpture as its own clamp, assembling it fully every time a major join was made. In this way, the full weight of the sculpture would be brought to bear on each join, providing the clamping pressure required during adhesion. Assembling the full sculpture after each join would have the added benefit of allowing conservators to monitor the alignment of the fragments as the treatment proceeded. Finally, this "self-clamping" method—that is, clamping by using the weight of the sculpture itself—addressed the need to apply sufficient compressive force on the joins to form a thin film of adhesive between the fragments. We knew from our research that the compressive pressure achieved during adhesive setting was directly related to bond-line thickness, and therefore vital to the success of the reconstruction.

The self-clamping method had many benefits, but one potential liability of repeated assembly and disassembly of the sculpture was harming the break edges of the fragments, which were brittle and readily damaged on contact. We needed to minimize handling of the marble to preserve these edges, as they would ensure the ultimate tightness of the joins. The solution was an external armature capable of positioning and precisely aligning the unadhered fragments during repeated assembly and disassembly of the sculpture. Ultimately including carbon fiber straps, ball joints, and a rigid support structure made of metal framing stock, the armature was used in combination with an overhead bridge crane and a custom-designed lift table. Working in concert, the innovative armature and rigging equipment provided an ideal workspace in which to assemble the sculpture. The development of this armature, which was accomplished by utilizing two different full-scale sculpture mock-ups, was probably the most time-consuming part of planning the treatment, and required substantial research and engineering.

The armature proved to be critical to another step in planning the treatment. Following discussions with colleagues at the J. Paul Getty Museum who have extensive experience in the reassembly of large-scale stone sculpture, we determined to undertake a "dry run." Fully assembling the sculpture without adhesive would allow us to find strategic points at which fragments could be bonded together in groups rather than proceeding one join at a time. The dry run gave us the first opportunity to examine the sculpture for any troubling misalignments that had resulted from the damage caused by the accident. Following the dry run, the assembly of the actual sculpture proceeded relatively rapidly.

***Mock-ups***

We knew we needed mock-ups to design the external armature, and we needed them in any case to plan the treatment of *Adam*. Rather than carry out a variety of theoretical treatment techniques on an original work of art, conservators regularly turn to small-scale, focused mock-ups to gain familiarity with methods and materials. In our case, however, the scale of the *Adam* sculpture and the nature of the damage warranted a commensurate increase in the scale of the mock-up. For many conservation projects, full-scale mock-ups are not feasible due to limited resources, but the potential benefits in our case justified the approach.

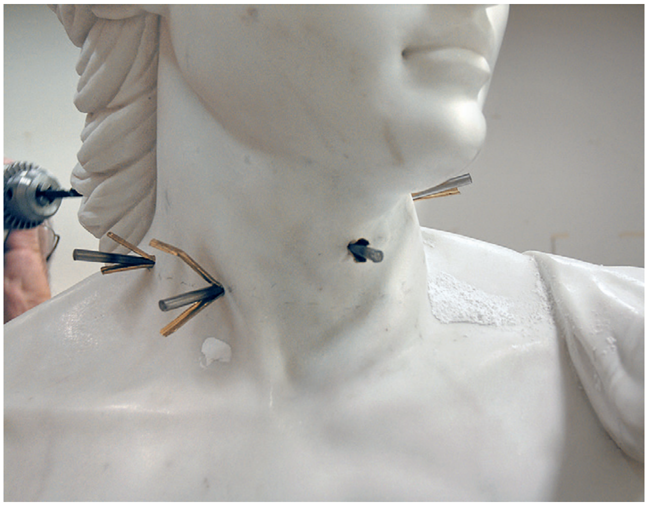
Our full-scale mock-ups enabled the conservators to formulate and rehearse assembly methods using the models rather than the sculpture itself. And by substituting the model for the original work, the conservators were also able to design and fabricate supporting armatures for the sculpture that would hold and steady each of the major fragments while they were being joined and allow extremely accurate manipulation and placement of the heavy fragments. In addition, we anticipated that the armature fabrication would involve materials and handling that could potentially soil the surface of the fragments. Using the mock-ups as part of an indirect method thus had the benefit of preventing soilage as well as damage.

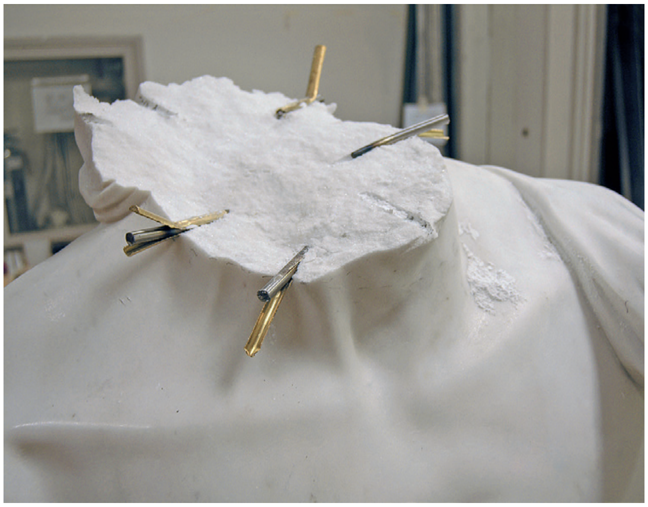
*Marble Replica of Michelangelo's* David

The replica of *David,* described above, served as a mock-up for testing as well as a working model for designing the external support armature. As we had in our trial join of *David*'s left arm and torso (see "Acrylic Resin Adhesive Experiment: Trial Join," pp. 74–76), we used feathers and wedges (Figures 49a,b) to break the marble replica (Figure 50) in the same pattern as the *Adam* sculpture. Some additional modifications were required, specifically the removal of the tree trunk behind David's right leg, to make the mock-up more similar to *Adam*'s stance.[91] With the *David* replica prepared, the goals of the armature needed further definition. Was it required solely to keep the sculpture from falling, and/or to aid in lifting the heavy fragments, and/or for positioning the fragments? These questions were addressed as the replica was put to use.

*Full-Scale Milled Model of* Adam

As previously mentioned, one of the benefits of the laser scanning was that it allowed us to produce a full-size 3D model of *Adam* by means of a computer numerically controlled (CNC) milling machine (see Figures 23a,b). This machined, or "milled," model was made of dense polyurethane foam that did not replicate the weight of the marble but had mass significant enough to serve as a suitable stand-in. Each of the major fragments except the head and the tree trunk was fabricated. Because the milled *Adam* was identical in form and scale to the marble *Adam*, it could be used to fabricate the components of the external armature that would ultimately support the actual sculpture. The milled model was also used to conceptualize and design the intricate drilling rigs used later in the project. The importance of





49a,b. Preparation of the *David* replica. Feathers and wedges were used to break the replica. This ancient method utilizes a series of drilled holes along the desired break line. Two "feathers" are placed into the holes, and then a metal wedge is inserted between the feathers. To break the stone, the wedges are tapped with a mallet so that a crack is propagated.

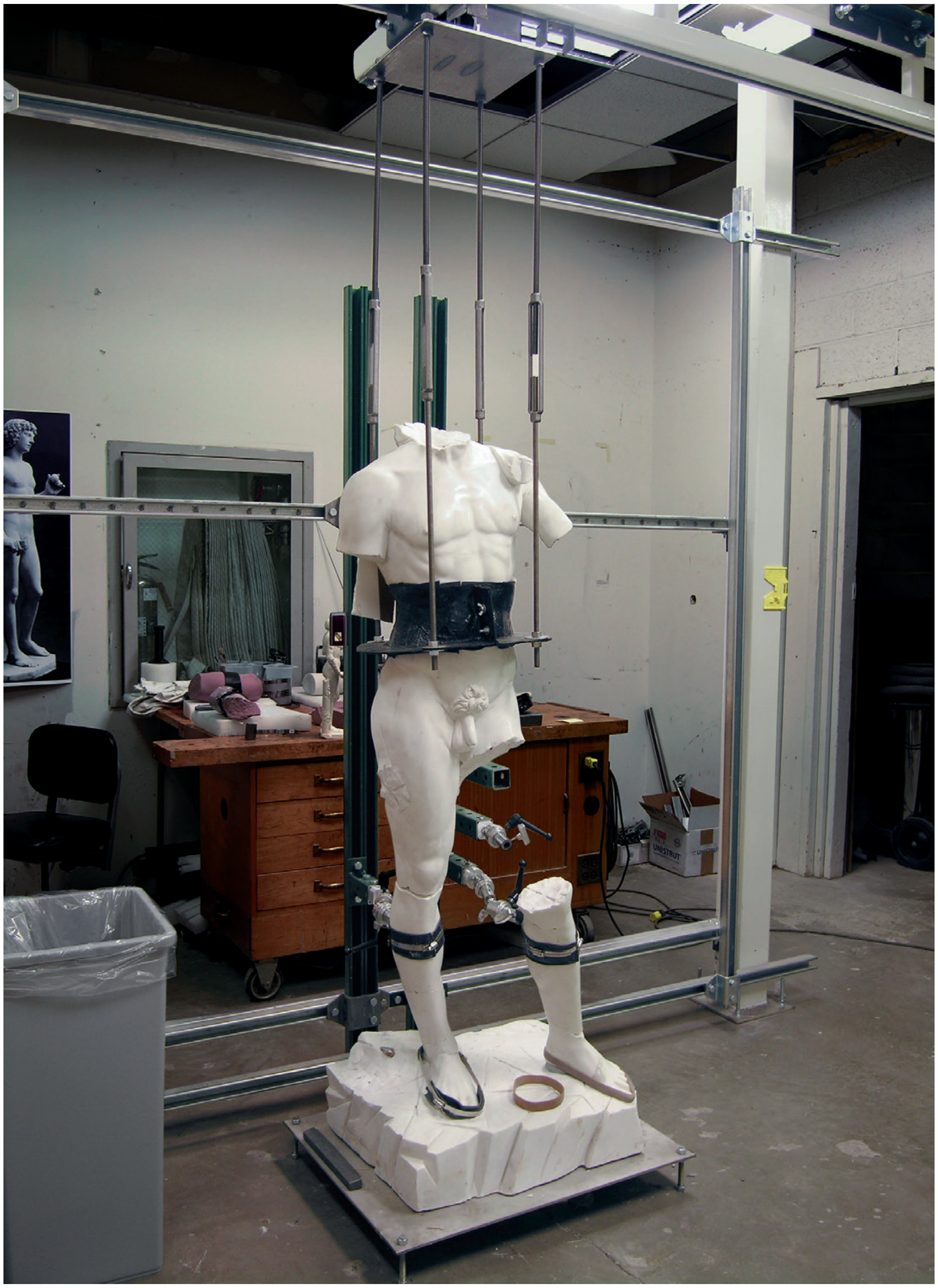
50. The *David* replica's torso, after the figure was strategically broken to match the breaks on *Adam*. This marble figure served as a stand-in for *Adam* as the treatment armature was developed.

this full-scale milled model to the many complex aspects of the project cannot be overstated.

***External Armature***

The goal of safe assembly was met by the development of an innovative external armature, a kind of "exoskeleton." It needed to be strong, be capable of holding the fragments in precise orientations for long periods of time, and allow for macro- and micro-scale adjustability along the vertical plane while the leg fragments and the torso were stacked upon each other. The design also had to allow the pitch, or angle, of each fragment to be adjusted with great precision. Finally, the armature needed to be designed with the capacity to open and close joins without disturbing the relative positions of fragments one to another or causing abrasion or other damage to the fracture surfaces in the process.

Having decided to work indirectly on mock-ups rather than the sculpture itself, we used the *David* replica to explore our early armature concepts. We knew that a key component of the armature would be devices that could securely grasp each individual fragment. After initially attempting to fabricate steel fittings to hold the fragments, we turned to a new material, laminated carbon fiber fabric, to create customized removable straps—collars that were molded and tailored to hold each major marble fragment. Fabricated from layers of carbon fiber cloth laminated with epoxy, this material can be made to conform to any shape.[92] Moreover, it is as strong as steel but one-third the weight. To



51. The *David* replica's torso enveloped in a "corset" designed to suspend it over the legs. The support was made of laminated carbon fiber fabric. We used the *David* replica as a test case for developing the armature for *Adam*.

52. Carbon fiber straps on fragments from the milled model of *Adam*. Hose clamp closures were incorporated around the circumference of the straps, and ball joint fixtures were used to attach the straps to a surrounding rigid support.

gain experience, we fabricated these straps around the *David* replica's fragments, each going through many design iterations before the final format was realized.

One of our main concerns was how to hold the largest and heaviest fragment, *Adam*'s 380-pound (172.4 kg) torso, securely in a fixed position while also providing for the ability to adjust the moment, or angle, with precision. The standard rigging method for handling such large fragments of stone sculpture is to use nylon lifting straps "choked," or tied off from the front and back, to provide an even distribution of weight and a balanced pickup (see Figure 50). While endless nylon slings[93] were useful for moving the torsos of mock-up sculptures and of *Adam* itself, the choked lifting strap method did not produce the refined and accurate movements necessary to put this particular sculpture back together. Our project needed a more adjustable system that would allow us to change the position of the sculpture more subtly.

Ultimately, a lifting armature was designed that would provide full flexibility in moving the torso as it was positioned over the legs. The concept was to have a rigid "corset" around the waist with a flat, shelflike flange extending outward and encircling the torso. The corset would be suspended from an overhead rail by means of threaded rods extending from holes in the flange. To test the concept, we made a two-piece removable carbon fiber version of the corset for the *David* replica's torso (Figure 51). The direct molding process provided a close fit. The corset held the torso at its waist, preventing any movement of the heavy fragment, but could easily be removed by unfastening the bolts that secured its two pieces together. The trial on the *David* replica allowed us to work out issues of the scale and shape of the corset, and the overall methodology of putting *Adam* together.

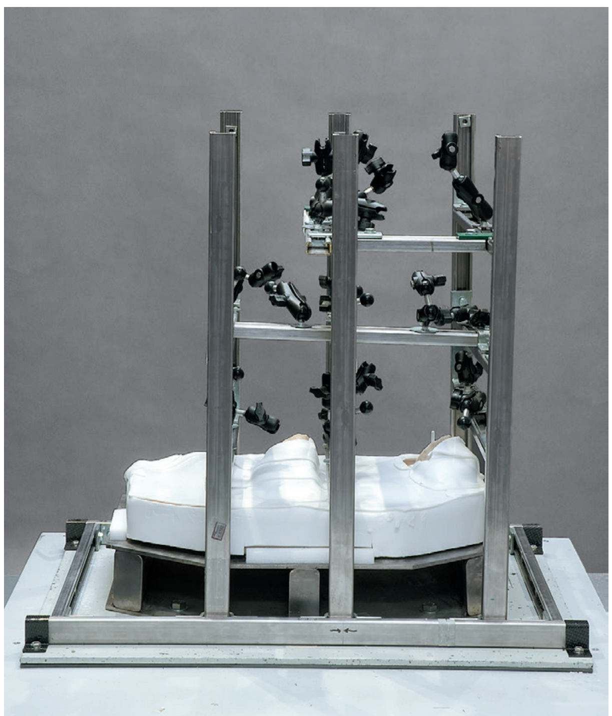
Once the armature design was more fully evolved, the full-scale milled model of *Adam* was substituted for the *David* replica. Because the milled model was 1:1 in scale, we could use it to fabricate the final armature that would be used with the sculpture itself, thereby minimizing handling of the *Adam* fragments and preventing damage to the fracture surfaces. Once the straps were fabricated on the milled fragments, they could be transferred directly to the sculpture.

To make the armature straps, the milled fragments were wrapped with a layer of thin foam, followed by a protective layer of plastic wrap. Then several layers of carbon fiber fabric were placed over one another, using epoxy as the laminating medium. After the rough strap had cured, it was cut off the model, further refined, and furnished with an internal layer of thin foam as well as an external hose strap for tightening onto the fragment. Finally, several nuts were affixed around the circumference of the strap, providing points of attachment by means of ball joint fixtures to the rigid framework (Figure 52).[94] The process of laminating carbon fiber fabric and cutting the cured strap off the model was dirty and messy, highlighting for us another benefit of working indirectly using a mock-up rather than on the *Adam* sculpture itself, which was thus protected from both handling and potential soiling.

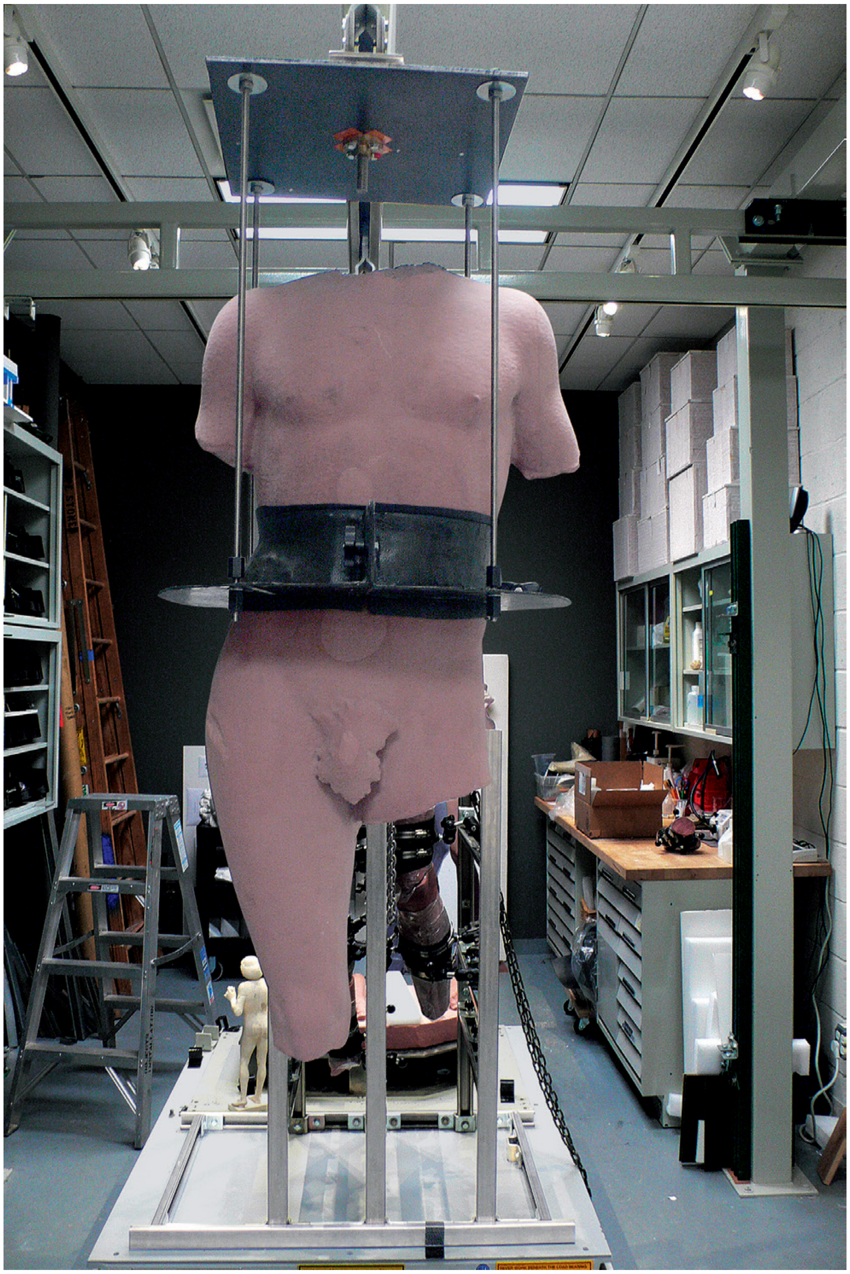
A rigid, cagelike system was developed to support the leg fragments and their associated carbon fiber straps from all angles. This support structure was made of lengths of stainless steel Unistrut channel, a commercially available modular framing system that provides infinitely adjustable points of attachment along the length of the channel.[95] Each strap had at least four points of connection to the framework by means of ball joints that could be loosened to allow flexibility in positioning and could be tightened to secure the fragments rigidly in place (Figures 53, 54).

The milled *Adam* also served as the form on which the corset was fabricated before it was transferred to the marble torso. Like the corset developed on the *David* replica, the one created for *Adam* was a robust carbon fiber strap composed of two halves fastened with bolts at the front and back. Additionally, there was a wide flange extending perpendicularly from the corset through which threaded rods

53. The full-scale milled model of *Adam*'s torso suspended over the left leg during armature development. The left leg is supported by carbon fiber straps and ball joints. The rigid support is constructed of metal strut channel framing stock.



54. The completed rigid framework of the armature. The Unistrut channel framing system allows flexibility of design and infinite points of attachment.



55. Completed torso corset for *Adam*. The torso was suspended by threaded rods from the overhead plate. Coupling nuts were turned to adjust the pitch of the torso. Adjustability was also designed into the suspension system, allowing fine pivot adjustments of the 380-pound fragment.

56. Freestanding bridge crane. An object can be positioned anywhere within the supports of the structure by means of the movable beam (highlighted in yellow). See also Figure 44.

were inserted. These rods extended vertically to an overhead hanging plate, allowing adjustment of the pitch and pivot of the torso by turning the coupling nuts that held the rods in place (Figure 55). This steel plate hung from the crossbeam of an overhead rail system (see "Bridge Crane and Lift Table"), which allowed the torso to be maneuvered away from the legs when necessary.

A stainless steel pallet, referred to as the "working base," was the foundation of the external armature used to support the sculpture throughout the treatment. Because it could accommodate the prongs of a forklift, it also provided the means to move the sculpture within the Museum as necessary. The pallet was designed to conform to the footprint of *Adam*'s integral base so that ultimately it could be incorporated into the design for the new gallery pedestal (see Figure 77). Two identical bases were fabricated so that one would be available for design, mock-ups, and testing while the other remained under the sculpture to provide support and facilitate its movement. The sculpture simply rests on a conformable lead sheet between it and the working base; no mechanical attachment was used.

### *Bridge Crane and Lift Table*

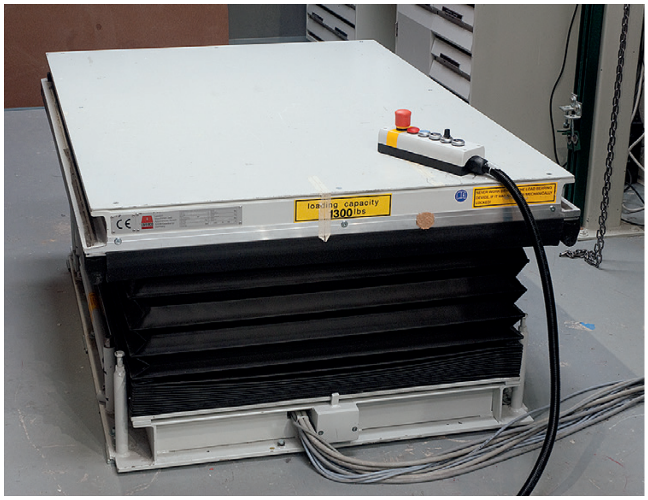
The armature served as the direct support for each of the sculpture's fragments, but rigging equipment was also needed to manage the overall support and movement of the heavy fragments. As the armature concepts evolved, we realized that a standard lifting gantry would not meet our needs. Instead, a more versatile, freestanding bridge crane was used for the overhead lifting (Figure 56). This structure was extremely stable and equipped with a movable rail, or bridge, from which chain hoists could be attached. From this bridge, the torso hung in its corset assembly, allowing us to position this heavy fragment anywhere within the four supporting posts of the structure and providing the flexibility required for refining the armature functions. Further modifications and additions enabled us to lock the moving parts in place when required.

With the torso hanging securely within its corset and attached to the overhead hanging plate, which was in turn attached to the movable bridge, we needed a precise way to bring the legs—supported in a separate armature—up to meet the torso. We investigated a number of commercially available lift table designs, but none proved adequate. The table we required had to provide a smooth and controlled transition from stationary to moving, with no jerky starts and stops. It also had to have the capacity for slow and precise height adjustment. Moreover, the lift table would have to hold a fixed position for extended periods of time while supporting a load, thus ruling out hydraulic or pneumatic lifting devices, which could potentially leak or drift downward over time. After considering options, we selected a table that lifts by means of a mechanical stacking chain that locks as it builds a stable vertical column under the table deck.

Laweco, a manufacturer of specialized lift systems, designed and fabricated a lift table that met all of our requirements, customizing the electronics to create the smoothest possible lifting action.[96] The table was equipped with a remote control box with a swivel controller for fine speed adjustment (Figure 57). With such a controller, the table could be moved slowly when needed, and stopped accurately and precisely.

### The Problem of the Left Knee

As the organization of the armature and equipment in the Tullio studio came together, the focus of attention shifted to the closer investigation of those joins of the sculpture where pins would be required and the precise method of insertion to be used in each case. During the early phases of the project, the Tullio team had agreed to pin both ankles and *Adam*'s left knee, where shear forces acted on the top of the small, wedge-shaped fragment. But as research into adhesives and pinning progressed, and with a clearer understanding of how pinholes weaken stone, we began to ask if it would be necessary to pin the knee, which required a longer pinhole through a fragment that had sustained a direct impact. To investigate pinning options in this key area, we undertook additional engineering studies.




57. Lift table. This custom-designed piece of equipment was instrumental to the successful assembly of the sculpture. A remote controller allowed fine adjustments to the rate of the table's speed.

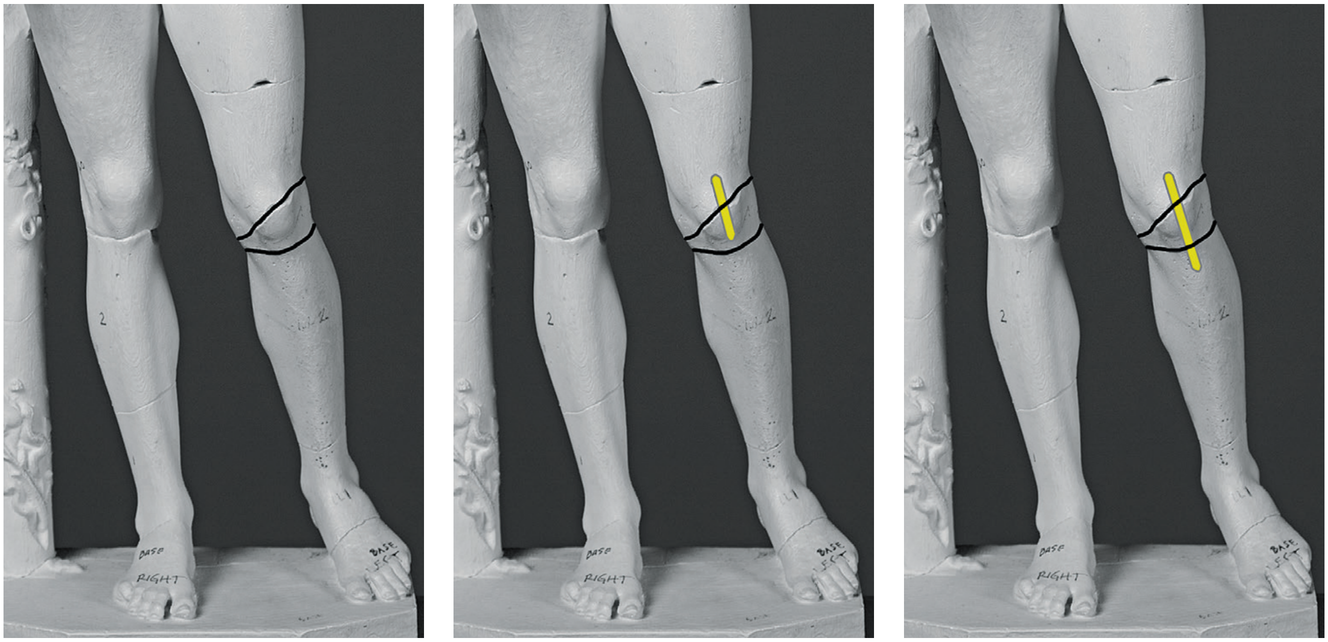
### *Additional Finite Element Modeling*

In addition to determining the general stresses and strains on a structure, the finite element method can be used to test concepts in a specific region of a virtual model. For example, different types of loading scenarios can be introduced into the model, or, as we did with *Adam*, the effects of pins inserted into specific locations on the sculpture can be studied. The virtual model can thus gauge the structure's response to various circumstances, helping to answer questions that might be time-consuming or complicated to answer in a traditional testing protocol.[97]

To help resolve pinning questions, the Tullio team, CAE Associates, the materials scientists at Princeton University, and Simpson Gumpertz & Heger (SGH), an additional engineering firm, collaborated to develop the most comprehensive and thoughtful approach. CAE Associates continued with finite element modeling work it had already started; the Princeton participants performed a peer review role; and SGH provided an overriding organizational and advisory role.[98]

The goal of the study was to answer whether the shear forces present in the sculpture were high enough to warrant a pin in the left knee and, if so, by modeling pins in the virtual representation of the sculpture, to help determine ideal dimensions and position. In addition, because the initial finite element analysis (Studies 1 and 2) had used techniques that were new at the time, the engineers wanted to improve on those models. This reexamination of the virtual model and the forces present on the joins is described in "Study 3: Hybrid Model," p. 66.

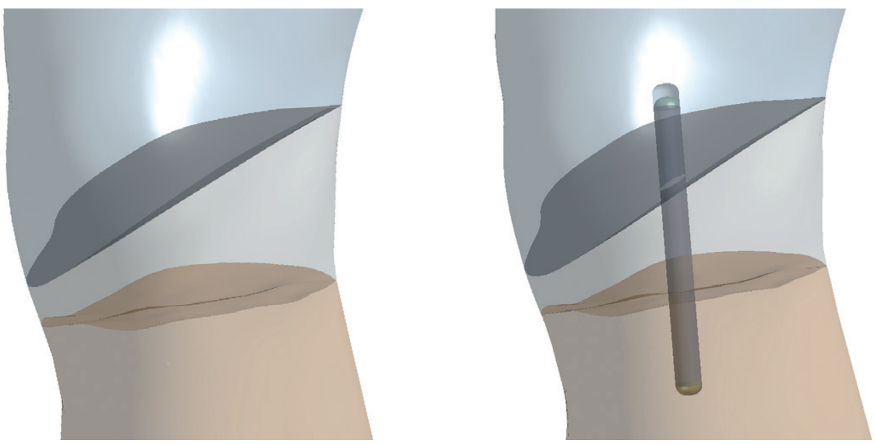
Following preparation of the hybrid model, different joining scenarios were modeled to find the least invasive and stress-inducing method of repairing the vulnerable left knee join. Possible options included: adhesive only; adhesive plus a pin connecting the thigh and the wedge fragment (thus counteracting the shear condition of the fracture); and



58a–c. Three proposed joining techniques for *Adam*'s left knee examined with finite element modeling. Left: adhesive only. Center: pin from thigh to wedge. Right: pin from thigh, through wedge, to calf

adhesive plus pin starting in the thigh, passing through the wedge, and ending in the calf fragment (Figures 58a–c). In this last scenario, the pin would theoretically transfer the sculpture's load directly from the left thigh to the left calf, preventing additional stress on the wedge-shaped knee fragment. But we needed to know if introducing a pin at this juncture would distribute and/or relieve the stress on the fracture.

Beginning with the existing model from Studies 1 and 2, CAE Associates recommended performing a force distribution study to determine the static load on each leg and on the tree trunk. In "Standardization of the Stiffness Value" (pp. 70–71), we explained that flexure elastic modulus of the marble was determined and that this value differed substantially from the reported elastic modulus of marble in compression. Because the reported value had been incorporated into the models in Studies 1 and 2, and because the newly determined flexure modulus was determined to be a better indication of failure in the sculpture, it was proposed that the results of the modulus as well as the materials testing on the Brazilian disk specimens be integrated into the finite element model.[99]



59a,b. Examples of finite element submodels of left knee. Left: adhesive-only join. Right: fiberglass pin from thigh, through wedge, to calf. The pin in this model is larger than the one ultimately used in the sculpture. Diagram: CAE Associates

Once the new marble characteristics were satisfactorily incorporated into the model, the next step was to create a model specifically of the knee, known as a submodel, which could be used to try out various pinning and adhesive options. Finally, the results of the submodel testing were applied to the complete model, thereby predicting the sculpture's response to a pinned knee. The hybrid model previously described (see "Study 3: Hybrid Model," p. 66) was developed specifically for this purpose.

CAE Associates performed several analyses to compare the stresses between a pinned join and one joined with adhesive only (Figures 59a,b). Several models were created to determine which portion of the join is most critical in the knee section: the upper wedge to lower thigh fragment connection or the lower wedge to calf fragment connection. This analysis was performed to determine which of the three aforementioned proposed joining scenarios would be most effective. In addition, the pin was modeled with a low-friction surface to emulate a sleeved pin (see "Pins and Reversibility," pp. 73–74). Running through multiple scenarios helped to build a mathematical model that could gauge a pin's response should either of the joins have a cracked interface and clarify how a crack in the knee would affect the remainder of the structure. What, for example, would happen if the bond should fail between the lower thigh and the wedge? Would the pin safely carry the load? What if there were no pin?

This analysis revealed that failure of the adhesive bond on the upper surface of the wedge would present a far more serious problem than losing cohesion on the lower surface of the wedge. A failure in the lower wedge surface would cause some redistribution of force, but much of the stress could be carried safely within the knee. Significantly, a loss of cohesion on the upper wedge join would produce a spike in the stress at the tree trunk–hip connection. In other words, the model showed that if there were no pin to hold the knee join in place during such a hypothetical adhesive failure, the hip section would become vulnerable. It was clear that the upper wedge join was one of the most critical in the sculpture and that a pin in this location could safely carry some of the resulting load due to adhesive failure, while the remainder would be distributed evenly throughout the sculpture.

***Was a Pin Necessary?***

Every engineering project requires the assessment of different goals, a kind of balancing act. In our case we had a new understanding that drilling for the insertion of pins could potentially weaken the marble, an understanding we needed to balance against the knowledge that pins would reduce or eliminate creep while the adhesive sets. These understandings address failure modes at two different stages in the life of the join: the former in the longer-term life of sculpture after conservation, and the latter during the conservation process itself. While the analysis had provided many possible scenarios, the final decision would need to incorporate the accumulated experience and expertise of the conservators as well as the input of our consulting engineers.

The method of pinning under discussion called for a ¼ inch (0.64 cm) diameter fiberglass pin to be inserted into a hole drilled into the thigh fragment, through a hole in the knee wedge, and terminating at a hole in the calf fragment. The exact length of the pin was based on the suggested 8:1 length-to-diameter ratio, but with extra length added to accommodate the insertion through the wedge fragment, yielding a total length of 4 inches (10.2 cm). The proposed join would use the reversible B-72–B-48N blend on the fracture surfaces and cast-in epoxy resin sleeves within the drilled holes.

When the sculpture was first placed in the armature, we had difficulty stabilizing the knee's complicated shear join, and the need for a pin seemed obvious. However, when the time came to make a decision on pinning the knee, the conservators had refined the armature in this area so that it was well stabilized (see "Left Knee Armature Modification," p. 96). Several concerns were then debated. Was a pin necessary to counteract adhesive creep in the initial stages of the joining process? Or would the armature provide sufficient support while the adhesive reached full strength? And would the adhesive alone be sufficiently strong to stabilize the join over the long term? If pins were to be used, it was agreed that fiberglass would have a major advantage over stainless steel if the sculpture should ever encounter another impact. However, the flaw introduced by drilling pinholes was judged to be a serious enough problem to make us reconsider our strategy. Should pinholes be avoided altogether? So important was this decision that in the section that follows we present both sides of the argument—to pin or not to pin—to illuminate the decision-making process and the complexities occasionally encountered during a conservation treatment.

*The Arguments for an Adhesive-Only Join*

The primary argument against pinning was that the forces acting on the left knee were not substantial enough to justify weakening the marble by drilling holes in it. The maximum shear stress on the wedge fragment's upper surface was determined in the finite element analysis to be approximately 30 psi (0.207 MPa), focused specifically on the rightmost portion of the wedge. The left leg is not an isolated element, but one of a series of interconnected forms that reinforce each other, aided by the two other members (right leg and tree trunk) supporting the weight of the sculpture. For the left knee to creep, the joins on the right leg, hip, *and* tree trunk would also need to creep. It is helpful to imagine *Adam*'s engaged right leg as the anchor of the figure, since it stands within the line of the sculpture's center of gravity. Considering the forces at work in these areas where shear and compressive stress do not exceed 40 psi (0.276 MPa), it seems highly unlikely that any of the adhered joins would fail. Testing had confirmed that the strength of the chosen B-72–B-48N blend would be sufficient under the maximum compressive, shear, and tensile loads present in the sculpture, assuming that the joins were immobilized long enough for sufficient solvent evaporation to occur.

Another argument against pinning concerned reversibility. A drilled hole removes original material that cannot be replaced and thus, by definition, contradicts conservation theory's preference for reversible treatments. Furthermore, introducing a hole in a seriously fractured area like the knee wedge creates risk; it can be considered analogous to the methods of splitting stone. By drilling a hole, one theoretically sets up a condition of infinite stress at the end of the hole; it is this stress that initiates the propagating crack when splitting stone with feathers and wedges. Thus it would not be the presence of the pin that would constitute the risk, but the pinhole itself.

Further supporting the argument against pinning were the good performance of the adhesive-only fractured cylinder specimens, the absence of creep in the Carrara cylinder experiment, and the conservators' judgment, based on trial runs, that the armature would hold the join securely as the acrylic adhesive reached full strength. The conservators' hands-on experience was an important element in weighing the options, since decisions in complex conservation treatments cannot be based solely on numbers, quantification, and engineering, valuable as they are.

### *The Arguments for Pinning the Join*

The argument for pinning rested on a different assessment of the stated risks. As we have seen, the primary argument for inserting a pin was to address the risk of adhesive creep during setting. While some empirical tests showed that the joins were secure after three months, the result of the experiment on the *David* replica's arm proved otherwise. That join had been allowed to set for three months but began to creep almost immediately after a load was placed on it. It is true that this join differed from that in *Adam*'s knee primarily because it had failed in tension, and the forces on *Adam*'s knee would be compressive and shear. Nevertheless, the join had failed, and that result supported the use of a pin.

Additionally, a pin in place would overcome uncertainties about the length of time it would take for the adhesive to set. The solvent evaporation tests remained inexact and were not able to provide precise guidelines for determining when solvent had sufficiently evaporated from the adhesive film for it to be at full strength. We were proposing to set the pins into epoxy resin sleeves and to bond the fracture surfaces with acrylic adhesive. Because epoxy resins have a known cure time, the join is essentially locked in place once the epoxy resin cures inside the pinhole; the pin resting snugly inside its sleeve would then act as a mechanical break against any potential creep during setting. Epoxy's relatively short cure time could thus allow us to move more quickly to the next step in the assembly with the assurance that the join was securely held in place.

Inserting a pin could also address the risk of minor movements within the armature. Although the armature had been modified to hold the knee join in place, it remained a difficult join to assemble securely. The planned sequence of the assembly further suggested that pinning would be prudent. After the legs were fully reconstructed, we planned to attach the arms and head. To do so, the supporting armature and corset would have to be removed and the sculpture would become freestanding. At this point, a pin bridging the join that had been determined by finite element analysis to be one of the most critical in the sculpture would constitute additional insurance against movement.

Drilling a pinhole at the knee was admittedly invasive, but the intervention would be minimal compared to past practice, as the proposed pin would be significantly smaller than those traditionally used, with less stone removed in the drilling. And, unlike the former practice of anchoring pins, the proposed sleeved pinholes provided a measure of reversibility. Hence we could be reassured that any decision to pin had been informed by an exploration of past practices and a mitigation of the problems introduced by traditional methods.

### ***The Decision to Pin the Left Knee***

We ultimately resolved to pin the left knee, a decision that flowed from several conclusions reached during our research. We knew the pin would act as a short-term mechanical lock against creep without introducing stress to the surrounding marble. Comparing the materials research results of the fiberglass fractured cylinders with the results of the adhesive-only specimens, we found no significant difference in their performance. Finally, finite element modeling showed that, in case of adhesive failure, the presence of a pin would help distribute the load throughout the sculpture rather than directing stress toward the already compromised tree trunk–hip connection.

Precedent also mattered. A choice for which there is no precedent, as not pinning would have been, would have added a further layer of risk. So past practice also informed the decision to drill holes and pin the knee. Even including the knee pin, the pins used in *Adam* would number only three—an unusually low number for the reconstruction of a damaged sculpture of this size and stature (Figures 60a,b).

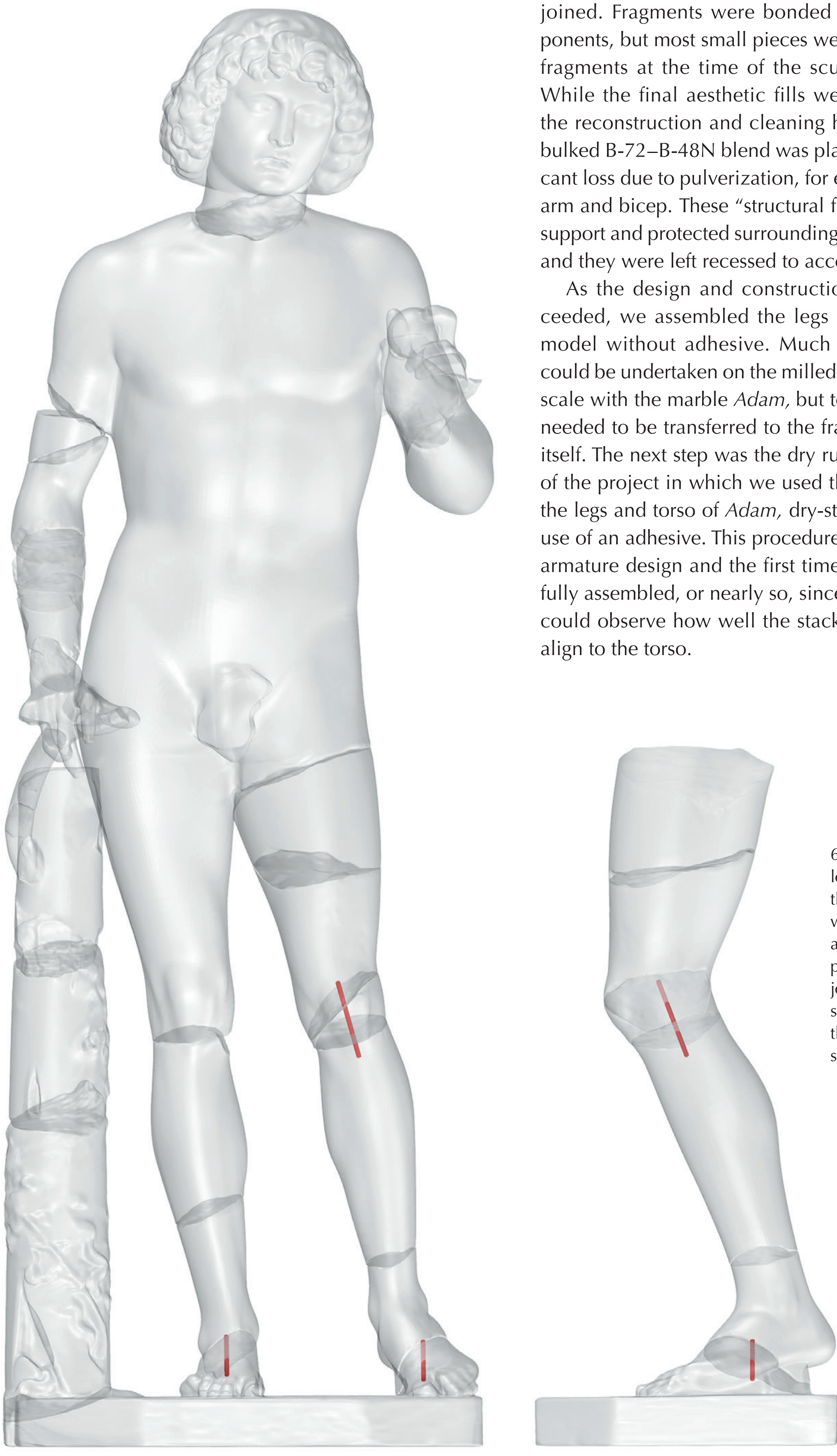
## TREATMENT OF THE SCULPTURE

As decisions were finalized, the treatment of *Adam* could begin. It is important to note, however, that the many processes laid out in linear form in this article were actually occurring simultaneously. Testing and analysis took place even as the armature was being developed. Each process informed the others as we moved forward continuously from theory to practice. The treatment of the sculpture involved two distinct phases: reconstruction of the broken fragments, and surface cleaning and filling. The reconstruction, from assembly of the armature to final placement of *Adam*'s head, is described in detail to illustrate the decisions, complications, and subsequent resolutions as the assembly progressed. The methods and philosophical issues related to the cleaning of the marble and its subsequent filling are also highlighted.

### **Preparation for Assembling the Sculpture**

As small fragments with external surfaces were sorted and their locations on the sculpture identified, some were joined, using the same acrylic resin adhesive blend we would use later to bond the major joins (see Figures 5a–d). For example, once the majority of the fragments for the upper portions of the tree trunk were found, they were joined. Fragments were bonded for other isolated components, but most small pieces were bonded to their major fragments at the time of the sculpture's reconstruction. While the final aesthetic fills were not carried out until the reconstruction and cleaning had been accomplished, bulked B-72–B-48N blend was placed in areas with significant loss due to pulverization, for example in the right forearm and bicep. These "structural fills" provided immediate support and protected surrounding fragments from damage, and they were left recessed to accommodate the final fills.

As the design and construction of the armature proceeded, we assembled the legs and torso of the milled model without adhesive. Much of the armature design could be undertaken on the milled model, which was 1:1 in scale with the marble *Adam,* but to perfect it, the armature needed to be transferred to the fragments of the sculpture itself. The next step was the dry run, one of the milestones of the project in which we used the armature to assemble the legs and torso of *Adam,* dry-stacking them without the use of an adhesive. This procedure was a critical test of the armature design and the first time the sculpture had been fully assembled, or nearly so, since the accident. At last we could observe how well the stacked leg fragments would align to the torso.



60a,b. Diagram showing the location and angles of the three fiberglass pins. One pin was inserted into the left knee, and one in each ankle. The pins were located where the joins were under compressive-shear force. Left: seen from the front. Right: the left leg seen from the side

61. *Adam*'s torso being lifted into its armature for the first time. The corset was used to suspend the torso from the bridge crane. Nylon slings were used to reorient the torso before threaded rods were inserted into the corset flange.

Once the dry run had been successfully executed, we rehearsed the processes of assembly, modifying them as necessary to gain confidence in our approach. It was during this preparation phase that the drilling and pin insertion processes were fully developed.

### *Dry Run: First Trial Assembly*

In preparing the joins for the first dry assembly of the legs and torso, we used small needles and scalpels to remove loose grains on the fractured marble surfaces that might have prevented perfect alignment. Next, the leg fragments were placed in their carbon fiber straps and stacked one by one, using the ball joints to secure them into the armature framework. Meanwhile, using a multistep process in which the torso was maneuvered with nylon slings, we brought the torso from a prone to a vertical position and fit its carbon fiber corset snugly around the waist (Figure 61). It was then suspended from the bridge crane with threaded rods terminating with coupling nuts and positioned out of the way of the stacking process. Once the leg fragments were in the armature, the lift table was lowered, and the torso was safely maneuvered into position (Figure 62).

At this point, the lift table could be raised to bring the break edges close together, making it easier to gauge how to rectify the position of the torso. The adjustability built into the armature proved highly functional, as we were able to change not only the pitch and pivot of the torso but also its position—left and right, forward and back. Within an hour, the torso was adjusted into the correct position over the legs, and the lift table was slowly raised to close the joins. Everything aligned, and the armature provided excellent support for the fragments. We noted several areas, primarily on the left leg, that would need further bracing to counteract the shear and tensile forces acting on the joins (see "Left Knee Armature Modification," p. 96).

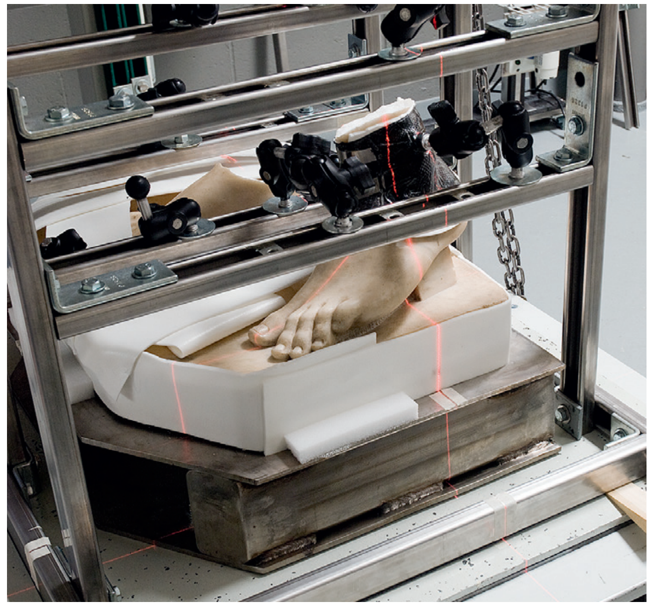
With the alignment perfected, the fine adjustment capability of the lift table could be exploited to raise the legs a bit more so that they would take on most of the weight of the torso and provide the self-clamping action we planned. In this position, the corset only partially supported the weight of the torso. After the completion of the dry run, the leg fragments were then removed from the armature and laid safely aside until we were ready to drill the pinholes for the ankles.

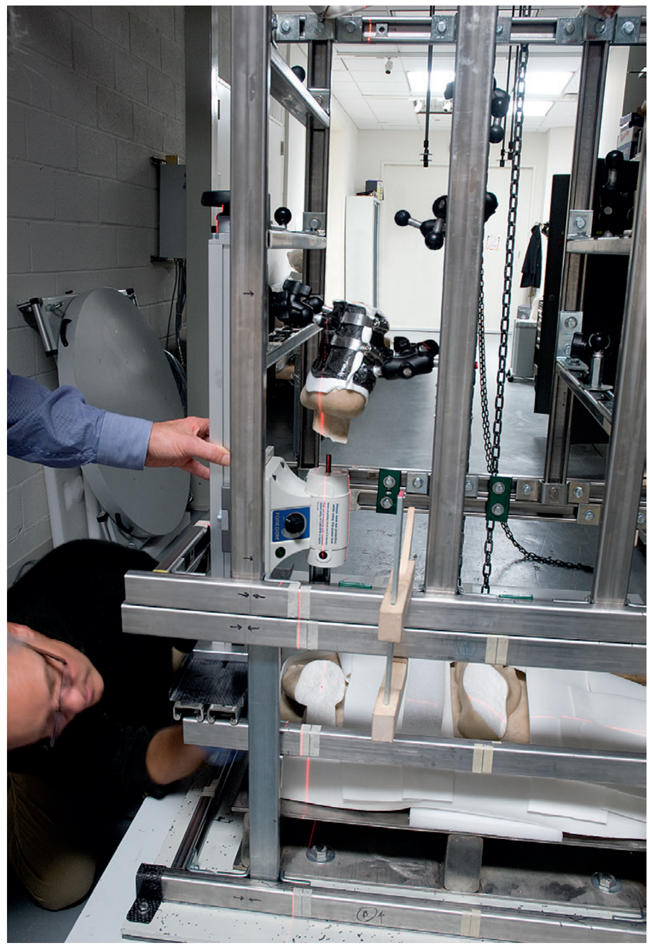
### *Drilling Pinholes*

Drilling into stone at precise angles for the purpose of connecting two fragments is complicated by the difficulty of aligning the pinholes. On an uneven fracture, it is nearly impossible to hold a drill steadily enough in the hand to guarantee that it remains at the correct angle. Furthermore, when drilled by hand, pinholes are rarely successfully aligned on the first try, and it is often necessary to enlarge the holes with repeated drilling until a pin can be inserted into the marble without affecting the alignment of the fragments. To minimize the size of the pinholes and ensure precision in their creation, we developed a special drilling assembly.

62. *Adam* during the dry run. The sculpture was placed into its treatment armature for the first time, making it possible to check the alignment of the stacked leg fragments with the torso. The large torso fragment could be maneuvered to the right or left by means of the overhead rail system to provide better access to the leg assembly. The small-scale model of *Adam* can be seen on the lower right.

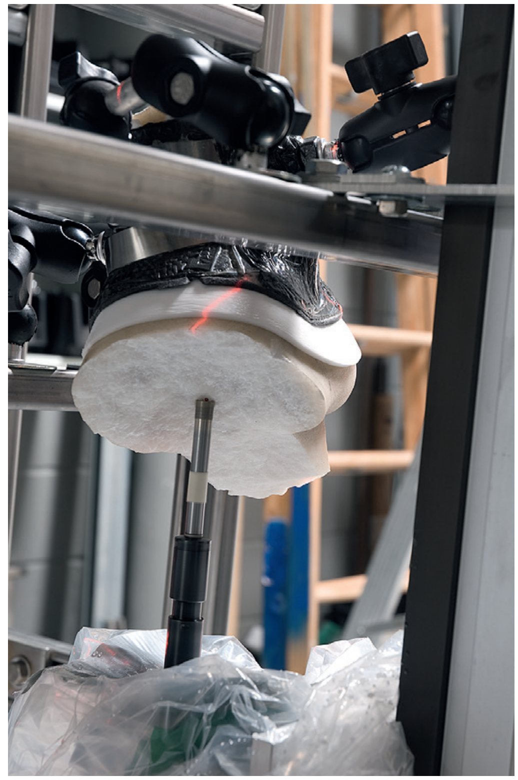

63. Ankle-drilling armature. With the rigid armature resting on the lift table, the ankle fragment was aligned to the base and locked in place with its ball joints. Next, the rigid armature was lifted to allow insertion of the riser (highlighted in yellow), providing space for the drilling assembly (highlighted in tan).





64a,b. Preparing to drill the left ankle. Top: the left ankle fragment rests on the base and the carbon fiber strap has been attached to the rigid framework, locking in its alignment. Bottom: the left ankle fragment is suspended in the armature after insertion of the riser. Red laser lines projected onto the armature were essential to maintain alignment of the fragments.

65. Alignment of the drilling device. Drilling was accomplished with a bench lathe turned on its side and attached to a linear actuator. In this illustration, the drill bit is attached to the lower axle of the bench lathe, prepared to drill downward into the base. The right ankle fragment is suspended above the drilling device.



66a,b. Drilling the left ankle. Left: the pinhole is being drilled down into the base. Right: the corresponding pinhole is being drilled up into the left ankle fragment. Note that the drill is making a hole perpendicular to the base of the sculpture. Water was used to cool the diamond core bit and flush out the marble dust generated during drilling.

*Ankle-Drilling Armature*

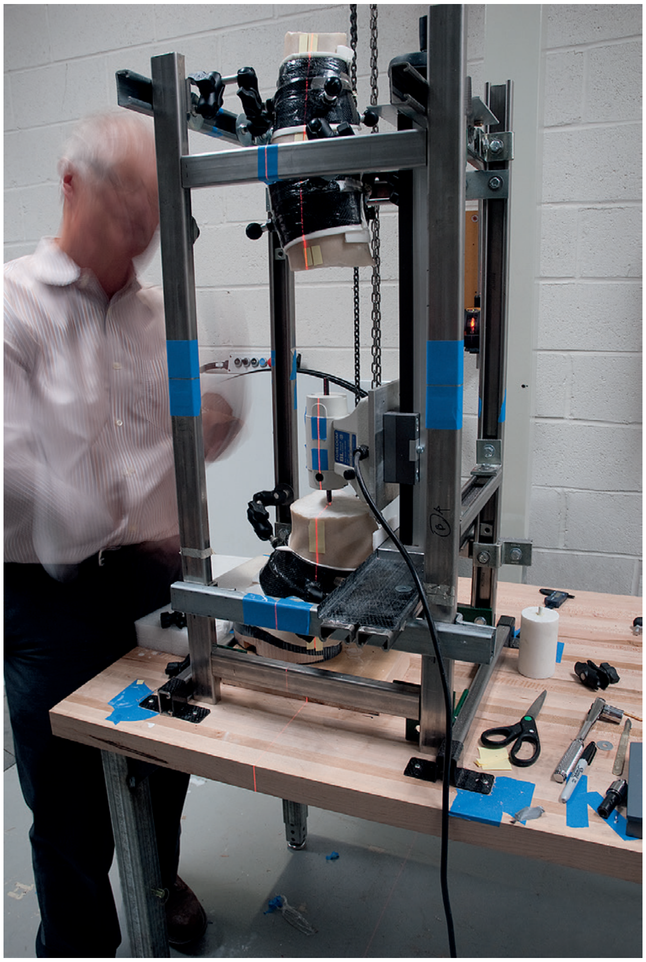
The ankle-drilling armature was designed to take advantage of the existing rigid structure made to support the leg fragments. The insertion of an additional structure beneath it, which acted as a riser, created a space between the ankle and the base while preserving their orientation in relation to each other (Figure 63). With the base and the ankle fragment held apart—immobilized and aligned—a drilling assembly could be inserted between them. The arrangement, which could be used for both the right and left ankles, allowed us to drill up into the fragments and then down into the base without having to realign any of the components. Laser levels capable of projecting plumb lines were critical to the effectiveness of the drilling armature and were used to monitor and maintain the alignment between the ankle and the base, as well as with the drilling armature (Figures 64a,b).

The device used for drilling was a small bench lathe.[100] It proved to be ideal because, when turned on its side, it provided two points of attachment for a drill bit, perfectly aligned along a vertical axis. To convert the bench lathe into a drill press of sorts, it was attached to a linear actuator, a device that creates controlled motion along a fixed axis. By rotating a handle at the top of the device, the external plate holding the bench lathe moved along the length of the unit (Figure 65).[101] In this way, the bench lathe could drill both up and down without the need for flipping or repositioning the device (Figures 66a,b). The armature design ensured that the holes were perfectly aligned within extraordinarily tight tolerances—a clearance of only 1⁄32 inch (0.08 cm) between the 1⁄4 inch (0.64 cm) diameter fiberglass pin and the walls of the drill hole. The drilling itself was accomplished with custom-fabricated diamond core bits, which cut by gently abrading the marble. As drilling progressed, an intermittent stream of water was flowed into the drill hole, cooling the bit and stone while flushing away the marble dust generated during drilling.

*Knee-Drilling Armature*

A separate drilling armature was designed to make the pinhole in the left knee. This pinhole needed to travel from the lower left thigh, through the wedge, and into the calf

67. Knee-drilling armature. This armature placed the fragments of the left knee in an inverted orientation. The bonded thigh-wedge fragment was stabilized on a custom-fit support, and can be seen here resting on the table. The calf fragment is suspended above it, locked into the rigid framework.



fragment. The knee-drilling armature was similar in concept to the one designed for the ankles except that it oriented the knee and calf fragments in an inverted position. Due to *Adam*'s contrapposto stance, his relaxed left leg is bent forward and also leans slightly inward toward the right leg. The angle of this pinhole had to follow this complex three-dimensional line rather than be placed vertically (see Figures 60a,b). Such an alignment was difficult to achieve even with a special drilling armature. The alignment of the hole in the left knee was further complicated by its length (4½ in. [11.4 cm] overall), requiring the same high precision over a relatively long distance.

To simplify the drilling arrangement, the wedge fragment was bonded to the lower left thigh fragment. Once those two fragments were connected, we had only an upper (thigh-wedge) and a lower (calf) fragment to manage. The upper fragment was inverted in the armature, resting on a support, while the lower fragment, also inverted, was oriented above it, suspended in its own armature of rigid Unistrut framework, carbon fiber straps, and ball joints (Figure 67).

As with the ankle armature, the drilling assembly was placed between the fragments, their precise relative positions maintained by laser level lines. This armature enabled us to make two holes in exact alignment through the knee. When the 4 inch (10.2 cm) long, ¼ inch (0.64 cm) diameter pin was inserted into the hole, the fragments aligned perfectly. There was no need to enlarge the holes.

### *Inserting Pins*

Once the holes were successfully drilled, we could turn to the matter of inserting fiberglass pins by means of cast-in epoxy sleeves. We developed a reliable method for making the sleeves by practicing on small mock-ups. Prior to inserting epoxy resin into the sculpture's pinholes, a thin barrier coating of B-72 was applied to the marble inside the pinhole and allowed to set for several days.[102] This step ensured reversibility of the epoxy within the pinhole and has the additional benefit of preventing the adhesive from optically saturating (darkening) the marble. Another important step in creating the cast-in sleeve was to apply a release agent to the pin prior to inserting it into the epoxy resin–filled pinhole, thereby ensuring that the pin could be removed after the epoxy cured.[103]

To create the sleeve, epoxy was bulked with glass microballoons until it formed a workable putty.[104] The bulked epoxy was then placed inside the upper hole to approximately one-third the depth of the hole. The pin with release agent was inserted into the soft epoxy, displacing it so it filled up the hole just shy of the fracture surface, and then the upper fragment was placed onto its mating fragment. This step allowed the exposed portion of the pin to properly align itself into the lower hole (currently empty) while the epoxy in the upper hole cured. The following day, when the pin was pulled out of the epoxy resin, a cast-in, tightly fitting epoxy sleeve remained.[105] This process was repeated for the lower hole once the upper sleeve had fully cured.

When the join was ready to be finalized, the pin was returned to one-half of its sleeve, and the B-72–B-48N blend was used to bond the joining fracture surfaces. We used full-length cast-in epoxy resin sleeves in all three pinning locations, creating a completely reversible pinning setup. If *Adam*'s pinned joins have to be reversed at some time in the future, conservators need only use solvents to dissolve the acrylic resin adhesive blend on the fracture surfaces, and the pin will slide out of its sleeve.

### Assembling the Sculpture

Throughout the project, the logistical plan for assembling the sculpture was intentionally kept fluid. While the overall strategy was to assemble the legs first, then attach the torso, followed by the arms, we reevaluated the proposed order after each join was completed. We expected to start with the ankles, thinking it would be possible to assemble the legs from the feet up to the torso. However, each fragment posed its own complications, modifying our expectations of the joining sequence. Following is a description of the assembly process presented more or less chronologically, noting the challenges and solutions that occurred along the way. All joins were accomplished by at least two conservators working together.

***Tree Trunk: Join 1***

The first adhesive bond of large fragments carried out on the sculpture was on the tree trunk—on September 16, 2010, nearly eight years after the accident. Because it was not possible to affix all three fragments of the tree trunk to one another *and* to the base, the upper and middle fragments on the tree trunk were bonded first. The trunk connects to the torso at the back of the right hip, and as the legs had not yet been assembled, that join could not be accomplished. Instead, we simply joined the top two fragments of the tree trunk to each other by dry-stacking all three tree trunk fragments onto the base and then applying with a brush the B-72–B-48N blend between the top two fragments.

Because the tree trunk terminates midway up the sculpture, the self-clamping method devised for the legs and the torso could not be used. Thus, to hold the join in place while the adhesive set, a long clamp was applied vertically. Some adhesive squeezed out of the join during clamping—a good indication that it was covered with a consistent film of adhesive. The reversible adhesive chosen does not optically saturate, or darken, Carrara marble, and could be simply wiped away with acetone.

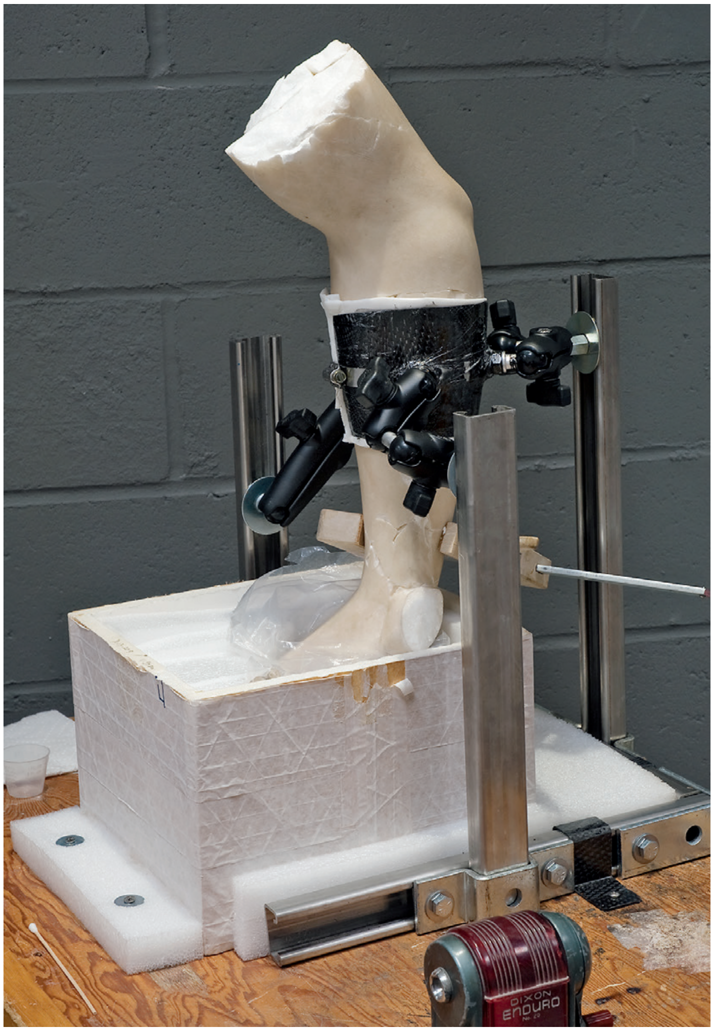
The clamps were removed after one week, but the tree trunk was left assembled on the base for more than a month to allow the adhesive to set fully. At this time, using the acrylic resin adhesive blend, we were also able to attach the many smaller surviving fragments that had come from this upper section of the tree trunk, including those of the bird and at the point of the connection between the now joined parts of the trunk. The joined top two fragments, as well as the lower fragment, were then removed from the base and set aside. The whole tree trunk assembly would have to wait until the trunk could be bonded to both the base and the hip, and that connection could not be made until the leg assembly was completed, two years later (see "Tree Trunk: Joins 2 and 3," p. 99). In short, the reassembly process did not simply start at the bottom of the sculpture and move upward. The progression was complex, needing to account for adhesive setting times, the shapes of the fragments, and the stresses that would be placed on joins as they were accomplished.

***Right Arm and Hand Assembly***

Because of the trajectory of the sculpture's fall from the collapsed base, elements on *Adam*'s right side were the most severely fragmented. The delicate branch extending from the tree trunk to *Adam*'s right hand snapped into several pieces and suffered extensive losses at its base. The right arm was also badly damaged because it took a direct impact with the full force of the fall, as indicated by the break pattern. The arm broke away from the torso just above the bicep, and the forearm split down the middle, suffering pulverizing losses that left a vertical space wide enough for light to pass through (Figure 68). In all, the right arm and hand broke into seven major pieces with dozens of associated small fragments that make up the wrist and little finger, and the location and documentation of these fragments continued even as materials research progressed and the armature was developed.

68. Fragments of *Adam*'s right forearm, vertically oriented and stacked without adhesive

Because of the multitude of fragments and the position of the right arm, we decided to treat it as a discrete zone, fully assembling it apart from the rest of the sculpture. In any case, it could not be attached to the torso until the corset was removed, so we planned on bonding it to the sculpture as a single unit once the legs and torso were fully assembled, freestanding without the armature. There was some risk in this approach, however, as it would not be possible to check the connections between arm and torso until the corset was removed. Moreover, the right arm attaches to the




69. Right arm assembly armature. The right arm was assembled independently of the rest of the sculpture. To attach the assembled arm to its hand, a small armature was designed to hold the arm vertically while the hand was immobilized in a padded box below.

torso at two places—at the shoulder and via a small strut between the wrist and the front of the right hip—and this dual connection meant that the length of the arm after assembly would be critical to its proper alignment. The degree to which bond-line thickness would add to the length of the arm could not be predicted with absolute precision, but with so many joins in such a small area, the use of an adhesive with a minimal bond line was as crucial here as it was in the legs.

The assembly of the right arm and hand progressed throughout the summer and fall of 2010, commencing with bonding the forearm fragments to the elbow. Where the vertical split in the forearm was so great as to be unstable, plaster was used to create a structural fill between the fragments. The subsequent attachment of the right hand to the forearm was additionally complex because the fragments had broken away from the hand at a sharp angle. Moreover, the fracture surface was smooth, leaving little frictional interface to aid in aligning the fragments. This attachment required the development of a new carbon fiber strap on the lower forearm to hold the large assembled section of the arm upright in a rigid armature.

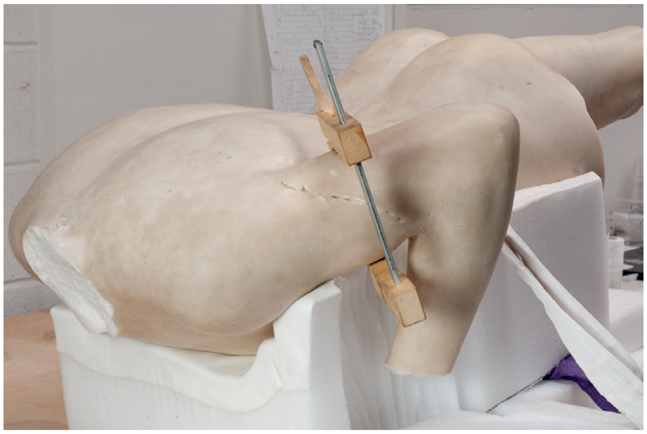
Once again, a supporting strap was fabricated on the corresponding fragments from the milled *Adam* and then transferred to the marble arm. This small armature also used ball joints to hold the forearm in a vertical position so it could be suspended over the hand, which was braced in a padded box below the arm (Figure 69). Large gaps in the wrist join were filled with bulked adhesive,[106] and to ensure a good join, the assembly was clamped for several weeks. During this time we attached many tiny fragments to the arm. In addition, we further filled the large loss along the repair of the forearm, adding strength to the area (Figure 70).

70. The right arm fully assembled. The fragments surrounding the extensive loss to the forearm were further supported by the addition of a recessed structural fill.

***Left Arm Assembly***

The next adhesive join was *Adam*'s left arm. It had broken away from the torso in one large fragment at an acute, almost vertical, angle. A combination of forces would act on this join: the downward forces of gravity would create shear forces along the fracture, but the arm extends forward from the body, creating a cantilever in which the arm fragment pulls down and back. As a result, the top of the shoulder join would experience compressive and shear forces, while the bottom of the join would be primarily in tension. Furthermore, the area around the fracture was internally damaged from the impact of the fall.

We considered pinning this join and even went so far as to design a drilling setup for it, but the nature of the break deterred us. We determined that the angle of the fracture was so close to vertical that drilling would be especially risky, and no good location for a pin could be identified. Instead, we decided to affix the join using a B-72–epoxy



71. Bonding the left arm to the torso. The left arm was attached before the torso was placed into its corset. A simple clamping arrangement was used to secure the fragment.

resin sandwich rather than the B-72–B-48N blend.[107] Because the left arm is a terminal element on the sculpture, the increased bond width of a sandwich was not a concern in the way it was with the legs, where the sandwich was avoided because testing determined it would cause an unacceptable amount of displacement. The use of epoxy resin adhesive had the added benefit of providing a known cure time, at which the join would reach full strength.

When the torso was lifted in its corset for the dry run, it became clear that the left arm join needed to be accomplished before the torso was put into its corset. The logistics of supporting and immobilizing the left arm while the torso was suspended in its corset were simply too complicated and would risk further damage to the fragments. The left arm was therefore attached while the torso was lying in a horizontal position. The torso and the arm fragment were oriented so that gravity could be used advantageously; positioning the fracture parallel to the floor greatly facilitated alignment of this large arm fragment (Figure 71). This join was accomplished on November 29, 2010. After the epoxy resin cured, the torso was once again placed in its corset and suspended from the bridge crane, and work on assembling *Adam*'s legs could begin.

***Assembly of the Ankles***

The ankle pinholes had been drilled in October 2009 (Figure 72), and during November and December 2010 the pins—2 inch (5.1 cm) long, ¼ inch (0.64 cm) diameter fiberglass rods—were inserted into the ankles. At first we had planned to create "potted pins," adhering a pin into one side of the join while preparing an epoxy resin sleeve for the other side. We went forward with the process until results from the finite element modeling of the left knee join led us to opt for fully sleeved pins. Because we had not yet bonded the fracture surfaces of the ankles, we were able to reverse the fiberglass pins potted into the ankles by cutting them back and then drilling them out with a twist drill. We also drilled away the cured epoxy resin, taking care not to enlarge the holes in the marble. We then began the process of inserting fully sleeved pins, but only into the upper fragments. Completion of the lower portion of the sleeves was put on hold until the armature could be further refined.

By September 2011, the armature was fully designed and we were ready to join both ankles. The fiberglass pins, already prepared with the release agent, were inserted into the

72. Overhead view of the base after the ankle pinholes were drilled

73. Completion of the ankle joins. The ankle pins were set into epoxy resin sleeves, and the fracture surfaces were bonded with the B-72–B-48N blend. After the sleeves had cured, the carbon fiber armature straps could be removed.

previously prepared upper epoxy resin sleeves of the ankle fragments. Then the lower pinholes were partially filled with bulked epoxy resin. The B-72–B-48N blend was applied by brush to the upper fracture surface. The amount of adhesive applied was not measured precisely; rather, the focus was on good coverage of all areas of the fracture surface, as we recognized from our testing that a consistent film over the entire surface was critical to a good adhesive join. The fragment with the adhesive layer and the pin in its epoxy resin sleeve was immediately put in place and firmly pressed down by hand, applying a gentle rocking pressure without imparting any significant movement to the fragment itself. This important step helped to move adhesive through the join and thin the adhesive layer by squeezing out the excess.

The ball joints were then put into place, but only lightly tightened down. Once both ankles were in place, the remaining leg fragments were assembled, but without adhesive. As in the dry run, the lift table was slowly raised to bring the legs to meet the torso, just enough to allow the full weight of the sculpture to be applied to the newly bonded joins. By reassembling the sculpture each time adhesive was applied to a fracture, the alignment of all of the fragments could be closely monitored.

The sculpture remained immobilized until the epoxy resin was fully cured around the pins, locking the ankles in place and acting as a mechanical break from creep during setting. After about ten days the carbon fiber straps that were supporting the ankle fragments could be safely removed (Figure 73), but the sculpture was left in place, dry stacked in its armature.

### *Left Knee Armature Modification*

As we have seen, the left knee was one of the most difficult joins. Over time, the armature holding it in place was continually adjusted, but we concluded that the carbon fiber straps and ball joints were not sufficient to fight the shear forces present in this join. The relatively smooth upper wedge join would experience shear force, while the large calf fragment that is angled forward had to be properly supported to prevent separation of the join at the top of the ankle, the back of which would experience tension. All these fragments needed to be locked in place, so in May 2011, special braces made to conform to these areas on the sculpture were attached directly to the armature.

These braces were made of easily conformable epoxy resin putty.[108] Small wads of this putty were applied directly to the metal components of the armature on two sides of the left knee. With a layer of plastic wrap in place to protect the stone, the putty was pushed against the correctly aligned fragments and allowed to cure. This process created small pads to brace the sliding fragments in place. One epoxy resin brace was placed on the left leg just below the kneecap, keeping the large calf fragment from pitching forward. Additional braces were placed on the inner knee to keep the lower thigh fragment from sliding down the slope of the knee wedge (Figures 74a,b; see also Figure 77). This modification added a great deal of stability to the armature and made it simpler to put the fragments back into correct alignment when they had to be taken on and off the armature.

### *Upper Left Thigh Assembly*

With the final modification of the armature around the left knee completed, we were confident that all the fragments were successfully immobilized. We then undertook the join between the upper left thigh fragment and the torso, as this bond would simplify the leg-thigh connection for future joins. This large fragment connects at the very top of *Adam*'s thigh, while a small vertical section connects to the inner right leg. This slight link between the legs made it difficult to raise and lower the leg fragments without causing the torso to shift to the right. Furthermore, the fracture surface at its bottom had a more horizontal geometry, making it a better choice to be the available connection between the legs and the torso as work progressed.

To attach this join, the lift table was lowered, allowing the torso to be maneuvered to one side. Next, the upper thigh fragment was removed and set aside. As before, the join was cleaned with a soft brush to remove any dust or loose grains of marble, and the B-72–B-48N blend was applied. The fragment was put back in place on the assembled leg fragments, the torso returned to its correct position, and then the lift table was slowly raised to close the join. This particular fragment did not have a carbon fiber strap but instead was held in place by the upward pressure of the lift table (see Figure 7). Following attachment of the join, on June 13, 2011, the sculpture was allowed to remain in its closed self-clamping position for more than one month. Then we separated the legs from the torso by lowering the table.

We encountered problems with this join sliding while the adhesive was fresh, and it was difficult to achieve the tight connection accomplished during testing without adhesive. After adhesion, the upper thigh join did not achieve the same tightness as when dry fit. This outcome helped us to appreciate the importance of applying gently rocking pressure by hand to get the tightest possible connection.

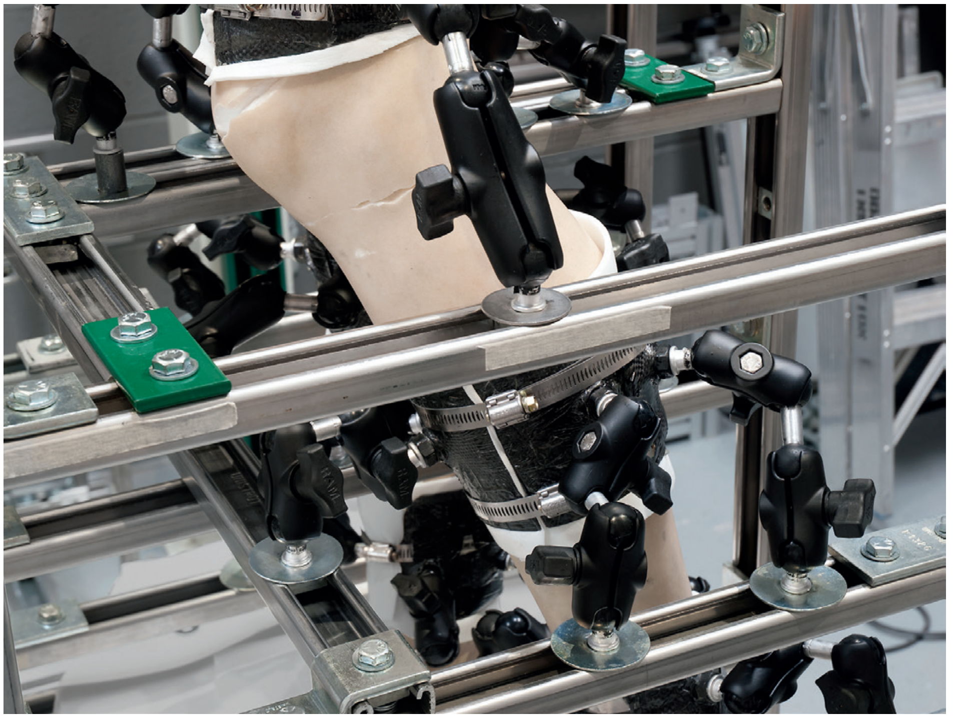
***Left Knee Wedge Join***

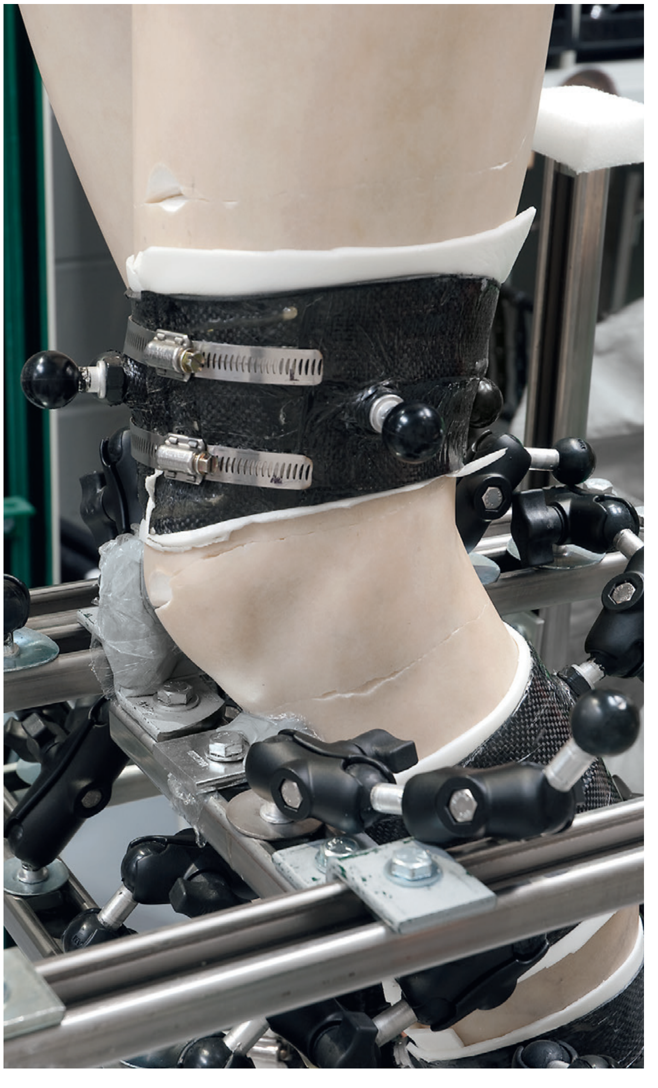
On August 17, 2011, the problematic left knee wedge was attached to the lower left thigh fragment in the same process described above, applying adhesive and using the bridge crane and lift table to maneuver the torso and legs and to apply pressure to the join. This very shear join had been hard to align even when dry fit. Although the armature had been modified with braces around the knee, it was still difficult to align and immobilize the wedge fragment with liquid adhesive in the join. As it proved impossible to align it satisfactorily when stacked in place, the wedge and lower left thigh fragments were removed from the armature and taken to the workbench. There the fragments could be inverted—placing the wedge at the top—and gentle rocking pressure was applied by hand until, eventually, excellent alignment and a tight join were achieved. The adhesive was allowed to set for approximately one month before the two fragments, now bonded, were returned to the armature.

***Right Calf Assembly***

*Adam*'s right leg was broken in just two places, at the ankle and at mid-calf. The top of the calf fragment connects to the torso just below the right knee. With the exception of the ankle join, the remaining two connections in the right leg appeared relatively straightforward, and we undertook these joins on October 5, 2011. However, it took two attempts to attach the right calf to the ankle fragment, as we encountered problems in getting the piece well-seated on its interface. The join rocked slightly after it was put in place, and it was not possible to get the adhesive to move through the interface and achieve a tight connection. We decided to remove the fragment, clean adhesive from the fracture surfaces, and try again the following day.

After rechecking the alignment by dry fitting the fragments in the right calf, we decided to go ahead with attachment because the fragments seemed to be aligning well. We used clamps and tried a strategic arrangement of ball joints to brace the fragment, front and back. Once the supplemental clamping procedure was established, the now standard procedure of maneuvering the fragments and applying adhesive was followed, but this time, we sought to apply a still thinner coating. At last the fragment aligned very well with minimal excess adhesive emerging from the join when hand pressure was applied. With all the other leg fragments in place, we raised the lift table to apply pressure from the torso. The sculpture was left immobile for at least two months before the next join was attempted.





74a,b. Left knee armature modification. Above: the original knee armature was not able to immobilize this complicated join. Left: the addition of form-fitting braces made of gray epoxy resin putty around the knee helped to stabilize the area.

### *Left Leg: Assembly of Knee and Calf Fragments*

By April 2012, the left calf fragment and the wedge-thigh fragment had been placed in the knee-drilling armature and the pinhole had been created, as described in "Knee-Drilling Armature," pp. 91–92. Now it was time to put the left knee pin in place. Once again, we used an epoxy resin sleeve for setting the pin. We made the sleeve in the upper portion of the join first, using a syringe to insert the bulked epoxy resin at the base of the pinhole to avoid creating air pockets.[109] The pin, prepared with a release agent, was then inserted into the epoxy resin. The fragment was inverted and placed on the left calf fragment to ensure proper alignment of the pin, and then the armature was tightened and the leg fragments raised to the torso. Twenty-four hours later, the wedge-thigh fragment was removed from the armature and the pin was pulled out of its hole, revealing the new epoxy resin sleeve.

On June 31, 2012, the base of the left calf fragment was bonded into place. While the difficulties presented by this join had caused some consternation earlier in the project, the immobilization procedure carried out on the armature made affixing this join relatively straightforward. The standard procedure was followed. The join was allowed to set for approximately two months.

After the lower portion of the calf fragment was fully set, we moved back to the left knee to complete the join, including the lower pinhole that passed down into the calf fragment (Figure 75). Because we were setting the pin and adhering the join simultaneously (as was the case with the ankles), we were careful to place sufficient epoxy resin into the lower hole to create a full sleeve but avoid overflow upon pin insertion. On August 21, 2012, the wedge-thigh fragment, with its pin installed and adhesive applied onto the fracture surface, was carefully put in place, and gentle rocking pressure was applied by hand to distribute the adhesive into a thin film. The torso was returned to its correct position, and then the lift table was raised to close the connection between the legs and the torso, putting a slight load on the legs.

### *Final Leg Joins*

On September 20, 2012, one of the milestones in the *Adam* project was achieved, as the last two joins on the legs were bonded. Because this was the final connection between the legs and the torso, both the right and left legs had to be bonded simultaneously. After all the other leg joins had been bonded with adhesive, the two connections remaining were at the middle of the left thigh and just below the right knee. For this procedure, three conservators worked simultaneously: one on each leg, with a third monitoring the overall alignment (Figure 76). Further complicating this procedure was limited access to the fracture surfaces, as the lift

75. Final left knee join. In this photograph, all of the lower leg fragments are bonded, and the pin for the left knee has been temporarily placed in the lower pinhole in preparation to make the epoxy sleeve. The lower portions of suspended torso can be seen at left.

76. Conservators Michael Morris, Lawrence Becker, and Carolyn Riccardelli preparing for the final leg joins. Screenshot from video: Kate Farrell

77. Conservators Michael Morris and Carolyn Riccardelli attaching small fragments at the base of the tree trunk. The braces made to support the left knee are visible in the center of the photograph.

table could not be lowered sufficiently to maneuver the torso out of the way.

The right and left joins were prepared simultaneously with the B-72–B-48N blend, applied this time using a syringe and then spread with a brush to ensure full coverage. The lift table was raised painstakingly, over a half-hour period, allowing the liquid adhesive to be distributed and the joins to close very tightly. Eventually, the lift table was raised to a point at which the torso and corset lifted slightly, signaling that the full weight of the sculpture was now loading the legs, and over the following hours, the joins were monitored carefully. The next day, all the joins were still aligned; small beads of adhesive had formed around the joins—a good indication of a complete coating of adhesive.

***Tree Trunk: Joins 2 and 3***

With the legs and torso fully bonded together, the bottom fragment of the tree trunk could be attached to the base. This join, accomplished on September 22, 2012, was straightforward and required no clamping. The many small associated fragments that overlaid the major fractures on the tree trunk were attached to the area at this time (Figure 77).

Several weeks were spent studying how to attach the bottom of the tree trunk to the upper portion, now composed of two fragments joined previously (see “Tree Trunk: Join 1,” p. 93). In the sculpture the tree trunk stands almost independently, connecting to the right hip by a small strut, approximately 4½ inches (11.4 cm) long. The thin strut was badly damaged in the fall, leaving a small portion attached to the tree trunk and another to the hip but most of it shattering into at least twenty-five small pieces, with much pulverization resulting in areas of loss. When all the large fragments were stacked, it was discovered that the tree trunk did not align perfectly to the hip, although the discrepancy of about $1/32$ inch (0.08 cm) is not readily observable. We speculated that the misalignment in this area arose from the tree trunk’s not having had enough pressure on it when its parts were bonded, making the joins slightly thicker than those in the legs.

The upper trunk was affixed to the lower trunk fragment, and, at the same time, the connection between the tree trunk and the hip was attached using a bulked mixture of the acrylic resin adhesive blend.[110] Bulking the adhesive in this area helped to fill the gap created by the impact. The trunk was clamped horizontally to counteract the slightly shear join between the upper and lower fragments as well as to provide some compressive force vertically. Finally, by November 19, 2012, the small bits of the strut had been bonded in place (Figures 78a,b).

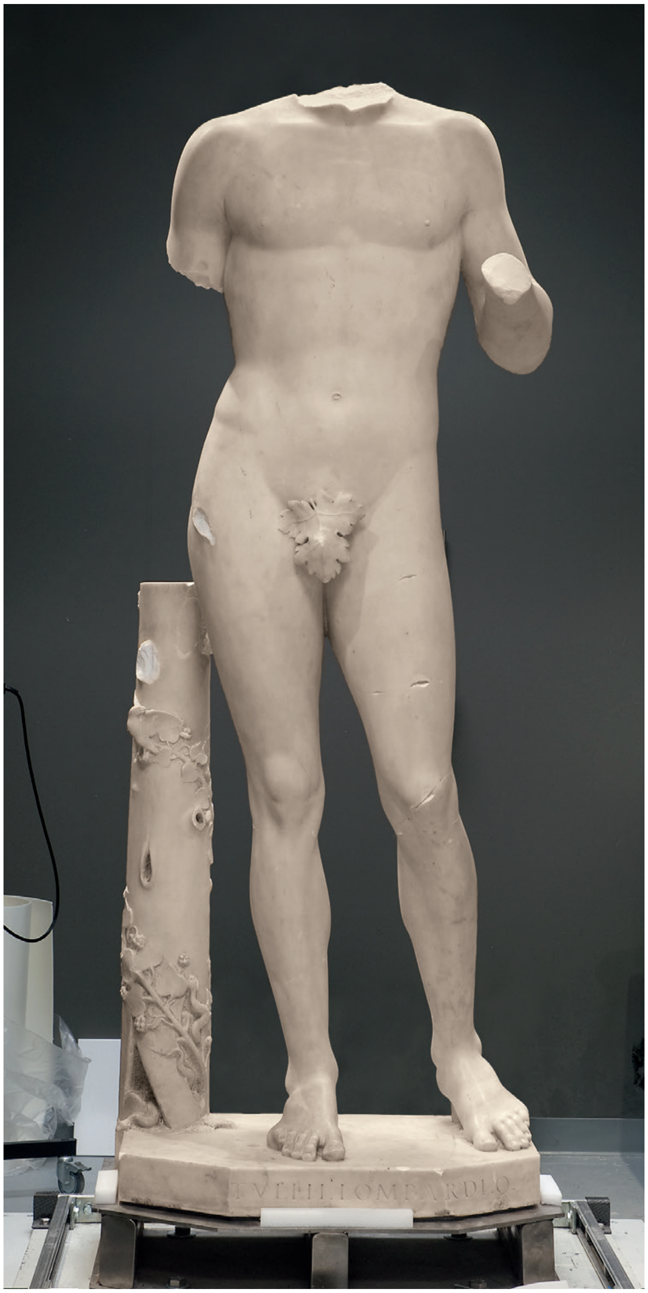
***Armature Removal***

After the final leg and tree trunk joins had set for more than two months, we could dismantle the armature and remove the corset from *Adam*’s torso. At last, on December 12, 2012, the sculpture was freestanding (Figure 79). It was a triumphant moment.

***Left Hand Attachment***

The little finger of the left hand was a point of impact in the fall, resulting in substantial loss. However, many fragments survived and were bonded in place in the fall of 2007, and later the area was given a recessed structural fill of bulked B-72 to further protect the small fragments. Because of the vertically orientated connection between

78a,b. Attaching small fragments to the tree trunk–hip connection. Left: the gap between the tree trunk and the hip was filled with bulked B-72–B-48N blend. Right: some of the fragments in place

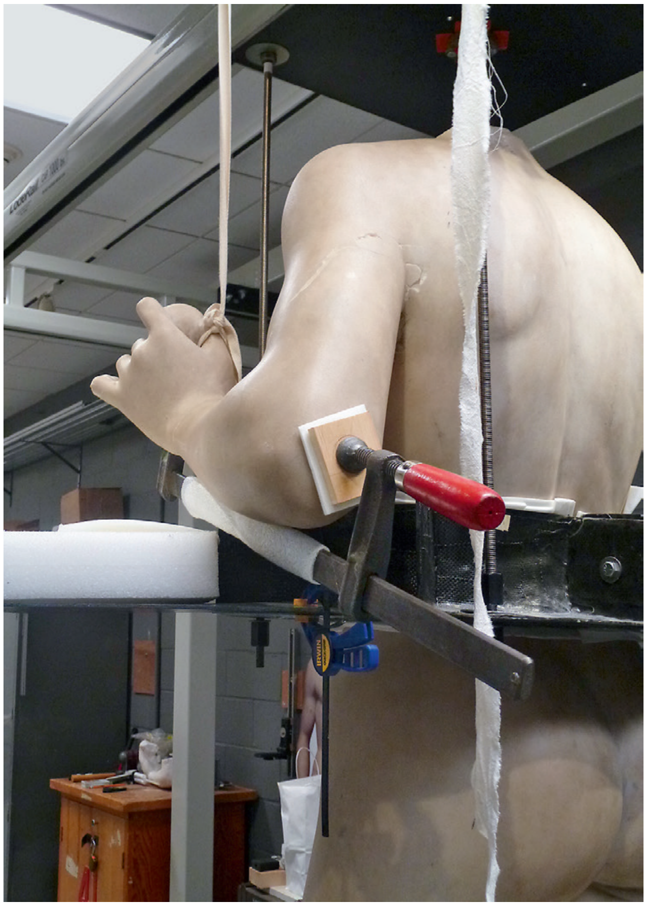


79. *Adam* after the corset and leg supports were removed. The left hand, right arm, branch, and head are yet to be attached.

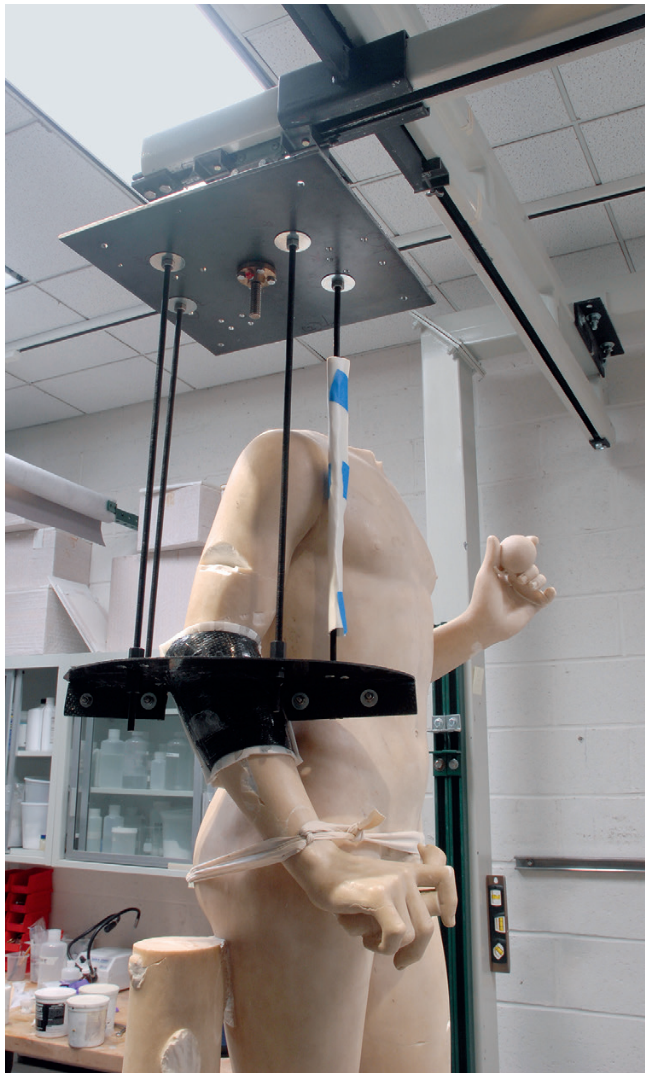
the left hand and the arm, the B-72–epoxy resin sandwich was used on this join. The thickness of the join was less of a concern than elsewhere, because the hand is the terminus of the arm. This join did not require a special carbon fiber strap and was simply held in place with a long clamp (Figure 80). To protect the marble surface, a small block of wood was placed where the clamp made contact with the back of the elbow. The elegant area of the palm was protected with a small pad made of epoxy resin putty and silicone rubber molded to the hand while still soft (Figure 81). While the pad cured, a plastic film barrier prevented the material from adhering to or staining the hand. After practicing and perfecting the clamping over a two-week period, the hand was put in place and clamped on December 17, 2012. The clamp remained in place for one week before removal.

***Right Arm Attachment***

With the armature removed, the focus then turned to determining the best method for attaching the right arm to the torso. After assembly, the right arm was a large, unwieldy fragment that needed to be suspended precisely alongside the torso, tucked under the right shoulder, and aligned at the right hip. It was an especially complicated join, possibly the most difficult in the sculpture. Once again, the milled model of *Adam* was used to fabricate a carbon fiber strap. Rather than being attached to a rigid armature with ball joints, this strap was modeled after the torso corset. A horizontal flange surrounded the strap that allowed the arm to be suspended from the overhead bridge crane by means of threaded rods (Figure 82). This brace had the same adjustability as the torso corset, but the closeness of the arm to the torso and its dual points of attachment made fine-tuning difficult. In this attachment procedure, the arm became the stable element that could be maneuvered away when needed, and the lift table was used to raise or lower the rest of the sculpture to align with the fixed arm.



80. Attaching the left hand. A simple clamping arrangement was used to hold the fragments in place. This image shows a trial setup performed prior to removing the torso corset.



82. Assembly for attaching the right arm to the torso. This carbon fiber support strap was modeled after the torso corset. A flange extended from the strap to accommodate threaded rods that connected to an overhead steel plate. The entire assembly was suspended from the bridge crane, allowing lateral movement of the arm when required.

81. Detail of the left hand while being attached. A small pad made of epoxy resin putty and silicone rubber provided a protective point of attachment for the clamp.

83. Attaching the right arm to the torso. Conservators Carolyn Riccardelli, Michael Morris, and Lawrence Becker work to attach the right arm simultaneously at the bicep and the hip. A cotton twill tape strap clamped the lower portion of the arm to its point of attachment at the hip. Screenshot from video: Stephanie R. Wuertz

On February 6, 2013, we attached the right arm to the torso using the B-72–epoxy resin sandwich. Once again, it was agreed that an adhesive with a known cure time would be crucial to achieving the best result. Taking into consideration the tensile join at the top of the arm as well as the shear join at the wrist-hip and the fact that the join was difficult to immobilize, we believed the epoxy resin was a good solution. To attach the arm, the fracture surface had been prepared with a B-72 layer. Now bulked epoxy was applied to the fracture surface at the shoulder, where there was extensive loss—indeed there were gaps—in the join. However, the connection between the wrist and the hip was tighter, and unbulked epoxy resin was used in addition to a B-72 barrier layer.

The lift table was raised to create space between the arm and the torso, and then the adhesive was applied to both locations simultaneously. The upper join was closed by lowering the table and torso down onto the arm, while the lower join at the hip required an additional clamp to pull it in toward the body. Thus a cotton twill tape strap was tied tightly around the sculpture (Figure 83). After the adhesive had cured for one week, the straps were removed from the sculpture. At this time bulked acrylic adhesive was inserted into the large loss at the top of the bicep. This material acted as a structural fill, helping to increase the bond surface between the arm and the torso.

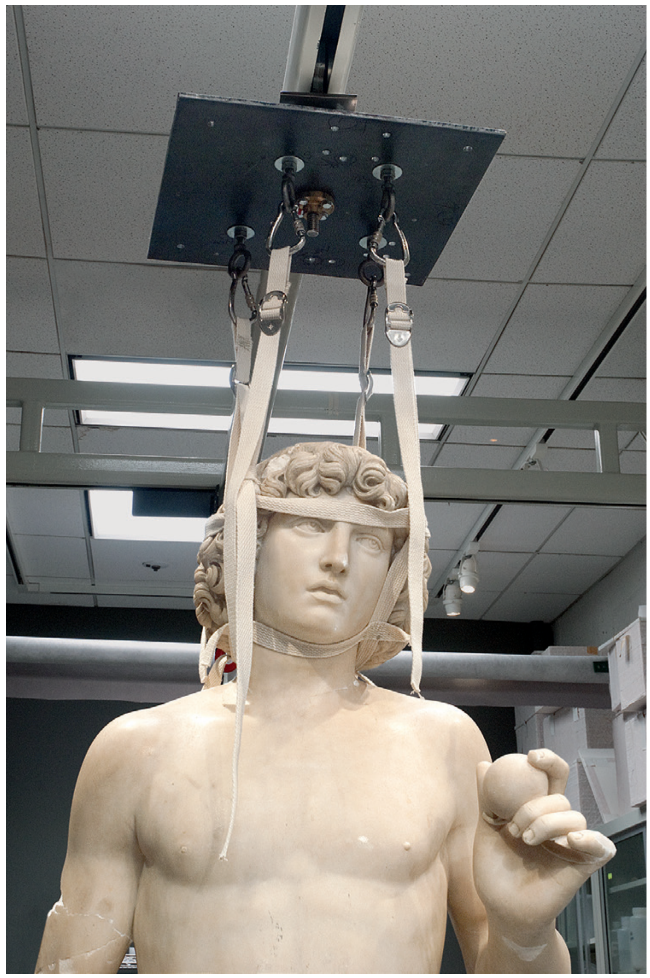
***Branch and Head Attachment***

Because there was a lack of overhead clearance in the Tullio studio, it was necessary to move the sculpture off the lift table before the head could be attached. The working base on which the sculpture was assembled was designed so it could be moved with a forklift; thus lowering the sculpture was relatively simple but accomplished with great care. Placed at floor level in the studio, *Adam* seemed completely transformed; we were rewarded with a rare opportunity to see the lifesize sculpture at eye level.

While a strap for supporting and lifting the head was being developed, we attached the branch that extends from the tree trunk to the right hand. The base of the branch had suffered extensive loss, and so it was necessary to add bulking agents to the B-72–B-48N blend to fill resulting gaps (Figure 84). The weight of the branch, composed of many previously assembled fragments, was supported with cotton twill tape tied back to the sculpture. This join was allowed to set for one month before the straps were removed.

While the break at *Adam*'s neck was relatively horizontal, and therefore in compression, it would not have been safe simply to lift the 65-pound head with our hands and place it on top of the torso. Instead, we devised a more controlled method that took advantage of the screw jack on the

84. Attaching the branch from the tree trunk to the right hand. The base of the branch suffered extensive loss in the impact and was filled with bulked B-72–B-48N blend.



85. Lifting strap for attaching head. The basketlike strap was made of cotton webbing and connected to the overhead plate by using buckles to loop the webbing through eye hooks. Visible at the center of the plate is a portion of the screw jack used to raise and lower the head without changing its alignment to the torso.

overhead plate. The screw jack, which allowed movement along the vertical axis, had been installed between the hanging plate and the overhead rail system early in the armature design process but had not yet been put to use. It now provided the perfect way to raise and lower the head once it was suspended from the overhead rail system.

A custom-fit strap system was designed to hold the head in alignment while adhesive was placed on the join, and then the head was lowered down to the torso. With no milled version of the head, we had to work directly on the marble piece. A cotton webbing strap, resembling a basket, was sewn together to ensure that all the connections were tight and could support the load.[111] Four vertical extensions served as points of attachment to the overhead hanging plate; the straps were equipped with heavy-duty buckles to allow adjustment of their length, thereby leveling the head (Figure 85). While on the overhead rail system, the head could be moved away from the sculpture to apply adhesive and then maneuvered over the torso to settle it down into place.

On April 1, 2013, we were ready to join the head. As this was the final join to be closed on the sculpture, the head was attached with some ceremony in the presence of the Metropolitan Museum's director, Thomas P. Campbell, and curators from the Department of European Sculpture and Decorative Arts (Figure 86). Three conservators worked as a team to attach the head. One operated the screw jack to raise the head, which was then positioned to one side to improve access for the application of the acrylic adhesive blend (Figures 87a,b). The head was brought back into place, and then the screw jack was used to lower it onto the torso. Another conservator guided the head down, while the third monitored the position of the strap at the back of the head, preventing it from getting caught within the join. A bit of gentle pressure was applied to the join to ensure the adhesive had spread to a thin layer, but no clamp was used. Because the cotton strap was used primarily for lifting and did not provide a clamping function, it was removed from the sculpture a few days later. Seeing the sculpture at last fully assembled, with the head attached, was enormously gratifying.

**Cleaning the Surface**

Now that the structural work was completed, it was time to address the aesthetic components of the treatment, which commenced with cleaning the surface. For cleaning, the sculpture was moved to a studio with strong northern daylight. Even before the accident, the sculpture had required cleaning. The surfaces of the marble had darkened with dirt accumulated primarily on the horizontal areas, the tops of *Adam*'s head and shoulders, the base, and the feet (see Figures 88a–d).

86. Preparing to attach the head to the torso. The Metropolitan Museum's director, Thomas P. Campbell (left), is looking on. Photographs of Figures 86, 87a,b: Christopher Heins, The Photograph Studio, MMA

Consideration of the sculpture's cleaning was additionally complicated by past surface applications. Documents as well as analytical results of Renaissance sculptures indicate that fats and oils, among other materials, had been applied to marbles well into the nineteenth century to mitigate salt contamination or to impart gloss.[112] These applications almost always yellow or darken over time. Because marble is unevenly porous and may be carved and finished to various degrees, these fats or oils are absorbed differentially across a sculpture's surfaces. Consequently, those parts of the sculpture that are more porous are likely to have yellowed and darkened more than parts in areas of lesser porosity. Moreover, because these materials were usually not evenly applied, some areas remain lighter. As we observed on *Adam*, the result can be an uneven tonality across the surface. Varying degrees of penetration into the marble were evident upon examination of the break edges of the fragments. In places, the applications had penetrated to a depth of as much as ¼ inch (0.64 cm) into the marble (see Figure 9).

To investigate the surface further, a sample of the yellowed marble was submitted for analysis. The distribution of the fatty acids in the sample suggested the presence of animal fat, perhaps tallow, in addition to alkanes found in wax.[113] Given the relatively deep penetration and insolubility of these materials, it was not possible to extract them from the marble safely. Consequently, a selective cleaning was determined to be the best means for ensuring an even tonality across the marble surfaces. In this way, areas of less yellowing were cleaned more lightly than parts that were more significantly yellowed. A dry—or almost dry—method was chosen: vinyl eraser strips slightly moistened with

87a,b. Conservators Michael Morris, Lawrence Becker, and Carolyn Riccardelli attaching the head to the torso. Left: adhesive was applied to the neck join. Right: the head was lowered into place using the screw jack, which was operated with a hand-held drill.

saliva.[114] This process was considered the most controllable procedure for the cleaning problem (Figures 89a–c). The close conformation of the fragments had caused some excess adhesive to extrude onto the surface, especially at the ankles, and the removal of this adhesive produced a whiter marble surface than deemed desirable for the planned cleaning approach. These areas were toned using pigments in a polyvinyl acetate medium to conform to the level of cleaning of the surrounding areas.[115] Since the torso slid across the patio floor facedown, skid marks were produced on the upper chest and abdomen. The shine of these marks was reduced by dabbing their surfaces with micro-crystalline wax.[116]

**Filling the Losses**

Once the cleaning was completed, consideration of the fills could be undertaken. The goal of loss compensation was to integrate the fills as closely as possible with the surrounding stone. We considered this approach necessary in the case of *Adam* for both aesthetic and philosophical reasons. Because the breaks were largely horizontal, if they were left undisguised, they would interrupt the verticality of the figure, so essential to its impact. These interruptions could be corrected only by making the fills less visible. We believed, further, that as the losses were caused by an accident, they did not represent a moment in time that needed to be preserved, or, at least, not by laying the burden of this history on the figure itself. This comprehensive approach to the filling could be further justified by our thorough documentation of the treatment, whereby the sculpture's condition after the accident had been recorded in detail for both scholars and the general public. Indeed, by filling in this way, what art historical opinion of the sculpture would be altered? What attitude of the museum visitor would be changed?

In considering the appropriate filling material for *Adam*, conservators were aided by Julie Wolfe of the J. Paul Getty Museum and by attentive study of her 2009 article in *JAIC* outlining the results of experiments with filling materials for marble.[117] Using her research as a starting point, we experimented with several of her recommended bulking materials mixed with the acrylic resin B-72 prepared in acetone and ethanol as well as several bulking agents commonly used at the Metropolitan Museum.[118] Among the latter, a blend of powdered aluminas proved to be the most useful for our purposes.[119] To this mixture we added various colored materials including natural white earth, pumice, sepiolite, and occasionally rottenstone.[120] In combination with the pure white alumina, these coloring agents created a translucent fill material that approximated marble (Figures 90a,b–93a,b).

To work with this fill material, alumina was added to the prepared B-72 until it formed a stiff paste. It was possible to make the mixture "dry" enough to work into a doughlike consistency that could be flattened into thin sheets between the fingers. In this way, the fill could be slowly built up in thin layers, a method we found beneficial as it allowed solvent to most effectively evaporate from the mixture. Working with a doughlike mixture was particularly useful when building up losses in areas of relief, such as the bird on the tree trunk.

As the depth of the fill neared the level of the surface, it was more effective to apply thin layers of a slightly looser mixture of bulked B-72. After a few hours, the outer layer was hard enough to shape with scalpels, fine riffler rasps, files, and customized micro-sanding tools. These tools proved valuable for precisely shaping the fills without harming the surrounding fragments. When required, riffler rasps

88a–d. *Adam* with structural work completed, before cleaning. Photographs: Anna-Marie Kellen, The Photograph Studio, MMA

89a–c. Details of the cleaning process. Left: top of the base before cleaning. A band of lighter-colored marble across the feet was due to the removal of excess adhesive after joining. Center: right foot before cleaning. Right: right foot during cleaning. Photographs: Jack Soultanian

90a,b. Details of the upper tree trunk. Left: before filling. Right: after filling and retouching. Recessed fills of bulked B-72 were added to areas of substantial loss. These white fills protected the delicate edges of small fragments and provided structural stability. Photographs of Figures 90a,b–93a,b: Anna-Marie Kellen and Joseph Coscia Jr., The Photograph Studio, MMA

91a,b. Details of the lower tree trunk. Left: before filling. Right: after filling and retouching

92a,b. Details of the fig leaf. Left: before filling. Right: after filling and retouching

93a,b. Details of the left hand. Left: before filling. Right: after filling and retouching

and plaster carving tools with serrated edges were used to texture the fill to match the tool marks in the surrounding marble. The fills provided a base color and required retouching in order to integrate them fully with the surrounding marble. The retouching was achieved by using pigments in a polyvinyl acetate medium applied to varying degrees dependent upon the specific part of the marble requiring matching.

Archival photographs of the sculpture, some dating back to the time of its acquisition in 1936,[121] were essential references for reconstructing areas of the most severe loss. The photographs were especially useful when filling areas of carved relief, for example, those on the tree trunk.

In September and October 2014 the fills neared completion, integrating the twenty-eight large pieces and more than two hundred small fragments that now constitute the

94a–d. *Adam* after cleaning, with fills completed. Right side view, during treatment

sculpture. The viewer can see *Adam* whole once again (Figures 94a–d). Installed in a new gallery, Tullio's masterpiece is displayed in a context inspired by the proportions of a Renaissance chapel and within a niche based on *Adam*'s location in the Vendramin monument.

## CONCLUSION

Among the unusual aspects of this conservation project was the long period of time between the fall of the sculpture and both the commencement and the completion of its treatment—in all, nearly twelve years. This long gestation period brought several benefits: first and foremost, it allowed for the initial shock associated with the accident to dissipate. Immediate action—following traditional conservation practices—would have been easily explained and understood, but a more considered and deliberate approach was established almost from the start.

As stated earlier, a guiding principle for *Adam*'s conservation was to explore and challenge those traditional conservation practices. Part of that exploration was determining what questions to ask—what we needed to know—to carry out a successful treatment of *Adam*. Establishing the questions to ask involved an expansion of disciplines involved in the project. Conservators and conservation scientists have broad and deep knowledge reservoirs, but what was needed for this project was beyond their capacities.

The reconstruction of *Adam* was fundamentally about its physical and structural properties, so it seemed natural to turn to the world of material science and engineering. In addition, within the engineering community computer science has recently taken on a substantial role in modeling structures through laser scanning and finite element analysis. These innovative approaches were able to provide us with a nearly complete picture of the stresses resident in the sculpture and potential responses to those stresses. Building on this information, material scientists designed methods to evaluate the performance of adhesives and pins and assisted in interpreting the results of these experiments. Several important lessons were learned from these initial collaborations. From laser scanning and finite element analysis, we learned how critical were the joins at the ankles and the left knee. From the testing of adhesives and pins, we learned that reversible, thermoplastic adhesives alone were more than adequate, in both strength and creep behavior, for reconstructing most joins. We also learned that displacement by adhesives along join lines could be minimized without sacrificing strength and that a pinning material should have a bending elastic modulus or stiffness similar to the material being mended, in this case, marble.

In addition to allowing time for testing, the long gestation period provided an opportunity for the results to "sink in"—for their full meanings to be absorbed. This initial testing might be characterized in the language of science as fundamental studies. In moving from theory to practice, the fundamental studies provided background for the next phase of empirical studies—trials of interventions based on the former studies. These empirical studies both confirmed information from the fundamental studies and provided new information. First, we confirmed that bond lines were small enough not to cause displacement problems when joining leg fragments with different numbers of breaks in each leg. Second, we concluded that high modulus pins are not appropriate for reconstructing marble and, in fact, can cause substantial damage to the marble under high-stress scenarios. In addition, the mode of failure of the pin versus the marble is also important. Third, we came to understand that armatures with configurational flexibility would be necessary to stabilize and provide adequate pressure to joins during the setting of the thermoplastic adhesives.

It may be obvious that the multidisciplinary aspect of this project was highly important to its success, but it may be even more important to emphasize the value of creating functional connections between and among the disciplines. Knowledge is created and absorbed from diverse experiences. In the end, conservators had to carry out the reconstruction of *Adam* relying on all the knowledge acquired from the supporting studies but also relying on their experience and their senses. No amount of scientific study could guide them in knowing how well aligned a fragment might be to its mating surface, or whether enough adhesive covered the join or had squeezed out. They knew these things by feel. These different forms of knowledge are sometimes characterized as *comprehensive* (knowledge created by the mind) and *apprehensive* (knowledge acquired through the senses). Perhaps the project's greatest lesson was establishing an arc from virtual reality to material reality and finding and valuing the contributions of each participant in the successful completion of that arc.

In the end, while our approach to the conservation treatment may have preserved the intent and impact of this seminal work of art, the fact remains that as a result of the accident the sculpture is not the same, and never can be; the damage incurred from the fall cannot be reversed, regardless of how securely repaired the structure or carefully integrated the surface. We only hope that the memory of the accident and the image of the sculpture in fragments will fade over time, allowing *Adam* to retain its status as a masterpiece of Renaissance art.

## ACKNOWLEDGMENTS

The project began under the supervision of Ian Wardropper—then Iris and B. Gerald Cantor Chairman of European Sculpture and Decorative Arts at the Metropolitan Museum and now director of the Frick Collection—when the Museum was still under the directorship of Philippe de Montebello. We thank both of them for recognizing the importance of the project and supporting the investigative and comprehensive approach to the conservation treatment. We also thank our current director, Thomas P. Campbell, for his continued support, especially toward the completion of the project as we planned conservation-related didactics for the gallery and this article. Luke Syson, Iris and B. Gerald Cantor Chairman, and James David Draper, Henry R. Kravis Curator, both of the Department of European Sculpture and Decorative Arts, kept a close eye on the progress of the sculpture under their charge, and to them we are grateful for their continued support and patience. Valeria Cafà also contributed insight into the sculpture during her tenure as Andrew W. Mellon Postdoctoral Curatorial Fellow, European Sculpture and Decorative Arts, and we thank her for her collegiality.

Critical to the success of the project was close collaboration with many experts from outside the Museum who conducted research that included finite element analysis and materials testing. A team of scientists from the School of Engineering and Applied Science, led by Winston O. Soboyejo, Department of Mechanical and Aerospace Engineering, guided us in designing, executing, and interpreting the many materials research studies for the Tullio project. From the Department of Civil and Mechanical Engineering, Nima Rahbar served as an adviser for the pinning and creep studies with the help of Ting Tan. George Scherer and Joseph Vocaturo were invaluable in designing testing apparatus. To them and to the Princeton School of Engineering and Applied Science in general, we express appreciation for their expertise and thanks for providing access to their mechanical testing instruments. George Wheeler was instrumental in making our connections to the Princeton Engineering team, without which this project would not have been possible. His connections at Columbia University were equally helpful, as we were advised by Norman R. Weiss throughout the pinning testing and by Andrew W. Smyth with regard to vibration reduction, particularly when it came time to move the sculpture within the Museum for the first time after the completion of the structural component of the treatment.

We were fortunate to collaborate with Michael Bak, Patrick Cunningham, and Daniel Fridline, engineers from Computer Aided Engineering Associates, who worked with us to perform the finite element analysis. A team of structural engineers at the firm Simpson Gumpertz & Heger, including Leonard Morse-Fortier, Frank W. Kan, and Omer O. Erbay, played a critical advisory role in interpreting data from the finite element analysis and from the materials research. This large team of advisers worked with us throughout the twelve-year period of the project, meeting regularly to discuss the extensive research and to guide us in our decisions, and we are indebted to them for their hard work on this challenging and unusual project.

Numerous graduate interns from multiple conservation programs provided assistance. Most important were the Columbia University students who undertook Tullio-related studies for their master of science theses in historic preservation; they were Mersedeh Jorjani, Christina Muir, and Andrea Buono, whose work on adhesives and pinning was essential to the project. While it is not covered in this article, the work Laura Michela carried out related to fatigue was immensely helpful. We also are indebted to New York University graduate conservation student Joannie Bottkol, who fabricated the specimens for the fractured-surface pinning tests, and intern Elizabeth Kovich, who not only fabricated specimens for an impact study but was also instrumental in the design and implementation of the study, the results of which will be reported in a later publication. Gregory Bailey, Kari Dodson, and Emily Hamilton, graduate conservation interns from the Art Conservation Program at Buffalo State College, assisted with the modulus testing, and we thank them for their contribution to the project.

We are indebted to our colleagues who contributed advice and sometimes simply acted as sounding boards for the multitude of ideas emerging from our work, most notably Anthony Sigel and Stephen Koob, who followed the project and generously offered their opinions and valuable support along the way. Our colleagues at the J. Paul Getty Museum, Jerry Podany, Erik Risser, and Eduárdo Sanchez, were particularly helpful in the early planning stages of the project. Julie Wolfe was generous with her time and expertise as we prepared for and carried out the fills. We thank the conservators at the Worcester Art Museum, in particular Philip Klausmeyer and Paula Artal-Isbrand, for teaching us about RTI. Winifred Murray traveled to the Metropolitan Museum with the Worcester Art Museum's equipment and helped us carry out the RTI of the underside of *Adam*'s base, for which we are grateful. Gregory Dale Smith of the Indianapolis Museum of Art was generous in performing $T_g$ testing of our acrylic adhesives. He also provided advice for our solvent retention testing, which was carried out by the Museum's graduate intern Ariel O'Connor. We express our appreciation to Lorenzo Lazzarini, Università IUAV di Venezia, for his petrographic analysis of *Adam*'s Carrara marble. We also thank Anne Schulz, whose ambitious photography campaign of the Vendramin monument gave us the unique opportunity to examine it closely.

Many others in the Museum have assisted us and therefore made contributions to the project. From the Department of European Sculpture and Decorative Arts, Erin E. Pick has been steadfast throughout our work, and we express our deep gratitude to her. We extend our great appreciation also to Luke Syson and Peter Bell, whose guidance and leadership contributed to the beautiful exhibition that accompanied the sculpture when it was first displayed after completion of the conservation treatment. In the Design department, Michael Langley, who was responsible for the design of the Venetian Gallery, and Mortimer Lebigre, the graphic designer on the project, have been patient in understanding this complex project and designing a space befitting *Adam*.

We are grateful for the valuable expertise of the Digital Media department, in particular Christopher A. Noey, for taking an interest in the project. He and members of the Creative Production team devoted substantial time and made important contributions to the extensive video documentation of the reassembly of *Adam.* Stephanie R. Wuertz, Kate Farrell, Jessica Glass, and Robin Schwalb each contributed to filming portions of the treatment. A particular note of thanks goes to Maureen Coyle, who served as the project's digital media coordinator, in which capacity she logged and archived the video recording of the project as well as performed, filmed, and edited video interviews of Tullio team members.

The Department of Scientific Research also made valuable contributions to the project. Marco Leona served in an advisory capacity early on in our work, and we thank him for being supportive in the preparation of this article. To Adriana Rizzo and Federico Carò, the research scientists who performed instrumental analysis related to the examination of the stone's surface, we are very grateful. We extend special thanks to everyone in the Sherman Fairchild Center for Objects Conservation. Our dear colleague Richard E. Stone, conservator emeritus, played a crucial advisory role throughout the project, and we have valued his input enormously. Special thanks go to conservator Donna Strahan for suggesting the acrylic adhesive blend of B-72 and B-48N. Our deep appreciation goes to the conservation preparators, Frederick J. Sager, Jenna Wainwright, Mathew Cumbie, and Warren L. Bennett, for being accommodating whenever we popped in to borrow tools or raid their metal stock supply. We also thank Nancy C. Britton, who securely sewed the strap that supported *Adam*'s head during attachment. Dennis Degnan, a freelance conservator who frequently works in our department, was helpful on the day the fragments were collected in the Vélez Blanco Patio, and we thank him for that. We are also grateful to Marika Strohschnieder, who had much to do with the initial approaches to the treatment.

We extend our appreciation to Barbara J. Bridgers and members of the Museum's Photograph Studio, in particular Peter Zeray, who graciously sacrificed his studio space to house the sculpture for several years. Additional thanks go to Anna-Marie Kellen for initial photography of the major fragments, and to Thomas Ling, who introduced us to and equipped us for time-lapse photography. Christopher Heins was also on hand to do still photography as we attached *Adam*'s head, and for his fine documentation of the special day, we are grateful. Lastly, we thank Joseph Coscia Jr. for his masterful photography of the sculpture for this volume.

We thank Taylor Miller for his work in coordinating *Adam*'s move from the ground floor to the fifth floor, and in constructing the Tullio studio. Members of the Museum's Carpentry, Electric, Plexi, and Plumbing Shops all made important contributions to the project. We extend a special note of gratitude to the staff in the Machine Shop, Abdool Ali, Marcel Abbensetts, and Miroslaw Mackiewicz, for being especially accommodating over the years. For their careful attention to our needs throughout the project, we are grateful to Crayton Sohan and his team of riggers: Ray Abbensetts, Michael Doscher, Michael Guercio, Derrick Williams, Raouf Ameerally, Todd Rivera, and Mark Dickinson. Staff from the Registrar's Office, Gerald Lunney, John Laughner, and Benjamin Dillon, designed and built the moving crate to support the sculpture during its first move within the Museum, and we are grateful for their skills. For their work related to the construction of the Tullio studio, we express thanks to the Buildings and Construction Departments, in particular to Tom Scally and Eric W. Hahn, and to Nicholas Nedostup, who served as the project manager.

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We are indebted to editor Ann Hofstra Grogg, who not only diligently edited this essay but also led us in transforming a once unwieldy document.

Finally, we express our gratitude and appreciation to our families and friends who have listened so carefully to our accounts of the project, in particular Aleksandr Victor Kouznetsov, Annetta Alexandridis, Hannah Blake Soll-Morris, and Carmen C. Bambach. Their simple questions about complex methods helped to form our thinking and contributed to *Adam*'s standing again.

## NOTES

1. The individual fragments (including the tiny pieces and marble dust collected) were weighed after the accident occurred.
2. For details about the petrographic study, see the report by Lorenzo Lazzarini in the Sherman Fairchild Center for Objects Conservation MMA, departmental records for 36.163. For a description of statuario marble, see Dolci 1980, p. 158. For comparison, technical studies of samples taken from Michelangelo's *David* point to the Fantiscritti site of Miseglia as the origin of its marble and are described in Attanasio, Platania, and Rocchi 2005, pp. 1374–76, and Attanasio, Rocchi, and Platania 2004, pp. 130–31.
3. See "*Adam*, by Tullio Lombardo," by Luke Syson and Valeria Cafà in the present volume, for details on the sculpture's origins.
4. Drill holes in the hair range from 2.1 mm to 6.2 mm in diameter.
5. Matteo Ceriana, director, Gallerie dell'Accademia, Venice (now director, Galleria Palatina, Florence), personal communication, 2012.

6. In 2007, when we used this technique, RTI was being actively introduced to the conservation field by Cultural Heritage Imaging (CHI) as an invaluable examination and documentation method, but few museums had yet been trained in the technique. Winifred Murray, Andrew W. Mellon Fellow in Paintings Conservation at the Worcester Art Museum, assisted us in capturing an RTI of the base. For a clear explanation of this imaging technique, see Schroer 2012.
7. Falletti 2004, p. 58.
8. Danti et al. 1998, p. 40.
9. The figure of the youth may be identified as Daniele, grandson of Doge Andrea Vendramin (d. 1478). In his will the doge left a considerable sum to Daniele. The will is published in Sheard 1978, p. 150, app. 1. The examination of the Vendramin monument, undertaken by Michael Morris, Carolyn Riccardelli, and Jack Soultanian, took place in November 2012, when a scaffold was erected in front of it for the Museum's photography campaign, coordinated by Anne Markham Schulz.
10. The analysis was conducted by Adriana Rizzo, associate research scientist, Department of Scientific Research, MMA. Azurite was confirmed by both Fourier transform infrared microspectroscopy (FTIR) and Raman microspectroscopy. FTIR analysis was performed on the samples crushed in a diamond anvil cell (Spectra-Tech). A Hyperion 1000 Microscope interfaced to a Vertex 70 (Bruker Optics), equipped with a 15x FTIR objective and a MCT detector (mercury cadmium telluride), liquid nitrogen cooled, was used. The FTIR spectra were acquired in 64 scans in the range 4000 to 600 $cm^{-1}$ and 4 $cm^{-1}$ resolution. Raman microspectroscopy was performed with a Bruker Senterra dispersive Raman microscope system, with a 1,200 lp/mm holographic grating and a CCD detector. A 785 nm excitation, 50x objective, and 30 second acquisition time were used; resolution was in the range of 3–5 µm and laser power ranging between 1 and 10 mW.
11. Cennino Cennini (ca. 1370–ca. 1430) describes water gilding with bole on stone; see Cennini 1960, pp. 118–19. For our investigation, initial X-ray fluorescence (XRF) analysis was performed by Federico Carò, associate research scientist, Department of Scientific Research, MMA, using a Bruker Tracer III-SD at 40 kV, 12.5 µA and an acquisition time of 30 seconds. The presence of clay minerals with other coarser silicates such as quartz and feldspar, as well as iron oxides, was determined using energy dispersive X-ray spectrometry in the scanning electron microscope (SEM-EDS), also conducted by Federico Carò. SEM-EDS analysis was performed in variable pressure with a Zeiss Σigma HD VP electron microscope equipped with an Oxford Instruments X-MaxN 80T SDD detector.
12. In addition to laser scanning, X-ray computed tomography (CT) scans were undertaken to determine if there were internal fractures stemming from the accident. CT scans were produced with a medical scanner and performed by Georgeann McGuinness, MD, chief, Thoracic Imaging, and by Emilio Vega and Robert Grossman, all at New York University Medical Center. The scans were inconclusive, and so these results are not reported here. Conservators researched the possibility of improving results with a high-energy industrial CT scanner; however, because of logistical and other considerations with transport of the fragile sculpture, this option was not pursued.
13. "3D virtual model" refers to a numerical description of an object. For further explanation, see Bernardini and Rushmeier 2002.
14. The 1:1 fragment models were milled either from 40 lb. density polyurethane fine-celled foam using a computer numerically controlled (CNC) ball end milling cutter at Satellite Models (fabricators of digital fine art sculpture enlargements, Belmont, Calif.), or built in a Zcorps rapid prototyping machine.
15. A 16-inch (40.6 cm) model of the sculpture was produced from the STL scan data on a Multi-Jet Modeling rapid prototyping machine. The model was then molded and cast in epoxy resin.
16. De Roos 2004, p. 25.
17. On this early technology, see Nilsson 1969.
18. This increase in activity was the result of the success of projects reported in the "Digital Michelangelo Project" (Levoy et al. 2000), *Exploring* David*: Tests and State of Conservation* (Bracci et al. 2004), "The 3D Model Acquisition Pipeline" (Bernardini and Rushmeier 2002), and the MMA's laser-scanned production of facsimiles of Bernini's two monumental terms intended for display in the Giardino Segreto of the Villa Borghese (Street 2002).
19. Beraldin et al. 2007.
20. The complete 2GB polygon model of *Adam* contains almost 40 million triangles in 24 binary stereolithography polygon mesh files. Although placing targets on the surface of a sculpture is the preferred method for aligning scans, we opted not to do so due to the risk that adhesives from the targets might affect the surface of the marble. Therefore, each set of scans from one fragment was aligned using an iterative closest point algorithm and grouped into one file within a common coordinate system. Once the individual scans were aligned, a global alignment was performed, and the aligned scans were then merged into one polygon surface model using a mesh integration technique.
21. Besl and McKay 1992. Laser scanning, point cloud data editing, and compilation of polygon models was undertaken by Ronald Street and Scansite LLC (Woodacre, Calif.) using Geomagic Studio 5, ATOS Professional, and Mesh Lab, software programs designed for transforming 3D scanned data into polygon models.
22. Michael Bak in Cunningham and Bak 2013.
23. Podany et al. 2001, p. 17.
24. The digital model of *David* was generously provided by Marc Levoy, director of the Digital Michelangelo Project of Stanford University and the Soprintendenza per Ai Beni Artistici e Storici per le Province di Firenze, Pistoia, e Prato. The analysis for the finite element mesh and proof of concept for the *David* study was generated in ANSYS8, a suite of advanced engineering simulation technology software. The finite element mesh and proof of concept study for the *David* analysis was generated by Ronald Street. The scanned data were imported into SolidWorks and used to create an electronic database of the *Adam* sculpture's 3D geometry. The same laser-scanned data can be translated directly into ANSYS. ANSYS is a finite element simulation code used for a wide variety of engineering analyses. ANSYS has a powerful mesh generation tool to handle a wide variety of complex geometries, can accept laser scanned data (point cloud data), and generate a mesh. Within ICEM is a subroutine tool called Mesh Prototyper, which provides a resurfacing of the point cloud data. Once the mesh is finalized, appropriate load and boundary conditions are applied. Then ANSYS solves for stresses, strains, and deflections.
25. The finite element analysis in Studies 1 and 2 was performed by Dan Fridline of Computer Aided Engineering Associates, Inc. (CAE Associates), Middlebury, Conn.
26. For a detailed explanation of stereolithography file format (STL) and the standard interchange file format that can support STL file features (Additive Manufacturing File Format, AMF), see ASTM 2013.
27. Elastic modulus describes the stiffness of a material and is also known as Young's modulus. In Study 1, an isotropic linear elastic material law was assumed with the following properties: elastic

modulus of 39 GPa, Poisson's ratio of 0.45, and density of 2.7 g/cm$^3$. The models were supported in all directions at the bottom of the base to simulate the sculpture as placed on a rigid platform. A gravity load was applied to the entire model.

28. Study 2 tested nonuniform rational basis spline (NURBS)–based geometric representations in the form of initial graphics exchange specification (IGES) geometry files; for a more detailed explanation of this format, see Piegl 1991. IGES is a file format that defines a vendor-neutral data format, thus allowing the digital exchange of information among computer-aided design (CAD) systems. NURBS surfacing of original polygon models was undertaken by Ronald Street using Geomagic Studio 6, software for transforming 3D scanned data into highly accurate surface, polygon, and native CAD models.
29. The finite element models for these studies were generated by CAE Associates using the ANSYS Workbench Environment software. This software was selected for its ability to generate robust tetrahedral meshes from NURBS geometry. It automatically detects setup contact surfaces based on proximity of disjointed surfaces. Unlike polygon-based geometry, the addition of midside nodes in the NURBS model allows for more accurate representation of curved geometry. The fracture surfaces were modeled using "perfectly bonded" contact elements. Each contact surface was isolated, and then the distribution of contact normal pressure and shear traction was determined.
30. Study 3 was carried out by Patrick Cunningham and Michael Bak of CAE Associates.
31. Also new in the Study 3 model was the fact that one of the Carrara marble characteristics, the elastic modulus, was updated with an experimentally determined value that more accurately reflected the bending modulus of Carrara marble, the characteristic of greatest concern at *Adam*'s left knee. See "Additional Finite Element Modeling," pp. 83–85.
32. The lower part of each fracture interface from the STL model was imported into the continuous NURBS model. The imported surfaces were attached to their adjacent fragments, resulting in two parallel interlocking faces at each fracture location within the NURBS model. Thus the new interfaces consisted of one side of a fracture interface used as a way to cut through the continuous NURBS geometry.
33. Paraloid B-72 is ethyl methacrylate–methyl acrylate copolymer; Paraloid B-48N is methyl methacrylate–butyl acrylate copolymer. Both are manufactured by Rohm & Haas.
34. See Koob 1986, Horie 1987, pp. 22, 106–9; and Down et al. 1996.
35. Koob 1986.
36. Podany et al. 2001.
37. Ibid., p. 18.
38. Ibid., p. 27.
39. This research has been discussed in detail in the following publications: for interfacial fracture toughness and bond-line thickness, see Jorjani 2007 and Jorjani et al. 2009. For a more technical explanation of the interfacial fracture testing results, see Rahbar et al. 2010. For creep testing, see Buono 2009 and Tan et al. 2011.
40. Mersedeh Jorjani performed the interfacial fracture study for her master of science thesis at Columbia University in the Graduate School of Architecture, Planning and Preservation's Historic Preservation Program. She worked under the supervision of her adviser, George Wheeler, and in coordination with Princeton University's Winston O. Soboyejo in the Department of Mechanical and Aerospace Engineering and Nima Rahbar, then a doctoral candidate in the School of Engineering and Applied Science, Department of Civil and Environmental Engineering. See Jorjani 2007.
41. See Kuhl and Qu 2000; Wang and Suo 1990.
42. Jorjani 2007, p. 17.
43. The Brazilian test is named for its inventor, Brazilian scholar Fernando L.L.B. Carneiro, and is a commonly used testing protocol in the study of fracture mechanics. See Wang and Suo 1990 for further information on this type of testing, and Ma and Hung 2008 for historical background on the testing protocol. The term "Brazilian disk" is used to describe a specimen that is made of a single material, in our case, the unfractured marble control set, while "Brazilian disk sandwich" refers to a specimen that has been split and then bonded. Brazilian disks have specific ratios of diameter to flaw-size, and so precision fabrication was necessary. Our disks were created using an abrasive water-jet machining technology, which couples high-pressure water with a garnet abrasive. The water-jet cutting was carried out at Hydro-Cutter, Inc., North Oxford, Mass.
44. Interfacial fracture toughness testing was conducted using an Instron 8281 dual column mechanical strength analyzer controlled with a proprietary data acquisition software application. For details on the testing procedure, see Jorjani 2007, p. 25.
45. Ibid., pp. 25–26.
46. This adhesive blend was suggested by former Metropolitan Museum conservator Donna Strahan (now head of Conservation and Scientific Research at the Freer and Sackler Galleries, Smithsonian Institution, Washington, D.C.), who uses it at the archaeological site Troy in western Turkey. She has used a blend of 3 parts B-72 to 1 part B-48N on objects such as large pithoi that are stored outdoors and therefore subjected to high ambient temperatures. Strahan's theory for creating the mixture was that the addition of B-48N raises the glass transition temperature ($T_g$) high enough that the adhesive will not slump in summer temperatures regularly reaching 51°C. The blend, which is a 40 percent solution mixed by weight, is created as follows: make one batch of each adhesive (40 g B-72, 54 g acetone, 6 g ethanol; and 40 g B-48N, 54 g acetone, 6 g ethanol) and then combine by volume 3 parts B-72 and 1 part B-48N.
47. Podany et al. 2001, pp. 26–27.
48. The bond-line measurements were done using a Keyence VHX-500 series digital microscope. The instrument has a measuring feature that records a quantity of measurements. Fifty measurements were taken along the join line of each specimen in increments of approximately 0.02 mm. The work was done at 175x magnification. See Jorjani 2007, p. 26.
49. Bradley 1984, p. 24; Podany et al. 2001, pp. 22–25.
50. These B-72–epoxy resin sandwiches were made by applying thin B-72 barrier coatings (5 percent by weight in acetone) to the marble surface, waiting several days to allow the solvent to fully evaporate, and then bonding the two sides with Epo-tek 301-2, an optically transparent epoxy adhesive manufactured by Epoxy Technology, Inc., Billerica, Mass.
51. Podany et al. 2001, pp. 23–25. See also Bradley 1984, pp. 24–25.
52. Jorjani 2007, pp. 31–34.
53. Andrea Buono carried out the adhesive creep study for her master of science thesis at Columbia University in the Graduate School of Architecture, Planning and Preservation's Historic Preservation Program. She worked under the supervision of her adviser, George Wheeler, and in coordination with Nima Rahbar of Princeton University's School of Engineering and Applied Science, Department of Civil and Environmental Engineering. The study employed a testing procedure developed at the Princeton

Center for Complex Materials at Princeton University. For complete details of sample preparation and testing protocols, see Buono 2009. For a technical examination of the study, see Tan et al. 2011.

54. Risser and Podany 2005. An empirical study of creep behavior carried out at the J. Paul Getty Museum was presented at the American Institute for Conservation Annual Meeting in 2005 but was not published. In general, results of our studies agree with the results of the Getty team.
55. The specimens bonded with epoxy resin were given at least two weeks for the adhesives to cure fully, while the specimens bonded with acrylic resin adhesives were given no less than four weeks to set, allowing sufficient time for acetone and ethanol solvents to evaporate.
56. All testing took place at room temperature.
57. Tan et al. 2011.
58. The thermosetting adhesive tested was Epo-tek 301-2 epoxy. A join made with epoxy resin along with a B-72 barrier (the B-72–epoxy resin sandwich) was also tested.
59. Tan et al. 2011.
60. Riccardelli et al. 2010, p. 98.
61. Some examples are Glavan 2004 and Saikia, Ramaswamy, and Rao 2005.
62. Christina Muir carried out the modulus and pinning studies for her master of science thesis at Columbia University in the Graduate School of Architecture, Planning and Preservation's Historic Preservation Program. She worked under the supervision of her adviser George Wheeler, and in coordination with George Scherer and Joe Vocaturo of Princeton University's School of Engineering and Applied Science, Department of Civil and Environmental Engineering. See Muir 2008.
63. For sample preparation details, pin testing procedures, and results of additional tests not discussed here, see Riccardelli et al. 2010.
64. See, for instance, "More about Steel, Iron, and Tungsten," McMaster-Carr document 88645KAC (available at www.mcmaster.com), for examples of how material characteristics are commonly reported by retailers and distributors.
65. Specimens were tested using an Instron 4201 mechanical strength analyzer, following the procedure for the ASTM Standard Testing Method for Ceramic Whiteware Materials (ASTM 2006), which is a three-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. Five specimens of each material were tested until either the material failed or the testing instrument reached full extension.
66. Riccardelli et al. 2010, p. 100.
67. An example can be found in Ondrasina, Kirchner, and Siegesmund 2003.
68. For this portion of the pinning study, the Tullio team and Christina Muir were advised by Winston O. Soboyejo, George Scherer, and Joe Vocaturo of Princeton University's School of Engineering and Applied Science, Department of Civil and Environmental Engineering.
69. The smooth-surface pinned marble cylinders were tested using an Instron 8501 mechanical testing analyzer with a maximum load capacity of 100 kN.
70. Muir 2008, pp. 7–8.
71. Ibid., p. 62.
72. Ibid., p. 59.
73. Titanium has sometimes been used to repair marble sculpture and outdoor stone monuments because of its resistance to corrosion and because its coefficient of thermal expansion is similar to that of marble. Although prior tests showed metal pins to be inappropriate for repairing *Adam*, titanium remained in the testing series to maintain some continuity, as it was being performed as master's thesis research by an architectural conservation student, Christina Muir. See note 62 above.
74. At the time of sample preparation, the Tullio team was considering using two small pins in each ankle to counteract the natural torque of the figure, as was determined by finite element analysis. The team ultimately decided to use a single pin in each of the ankle joins. The fractured-surface specimens were prepared by Joannie Bottkol, a graduate student at New York University Institute of Fine Arts Conservation Center, as part of an independent study in 2009. The specimens were kept in their clamping devices while the adhesives cured or set fully, which, in the case of acrylic resin adhesives, was at least three months.
75. Riccardelli et al. 2010, p. 108.
76. Ibid., p. 109.
77. Ibid.
78. 3M Glass Bubbles K15, manufactured by 3M Performance Materials Division, Saint Paul, Minn.
79. Krumrine and Kronthal 1995.
80. The replica *David* sculpture was purchased from www.wishihadthat.com.
81. This experiment was carried out in 2009 by the Metropolitan Museum's Objects Conservation Department graduate intern Ariel O'Connor. The complete results of her study, "Summary of Tullio Solvent Evaporation Experiment, June 2–August 18, 2009" (last modified September 2013), are in the Sherman Fairchild Center for Objects Conservation departmental records for 36.163.
82. Measurements were made on a Mettler AE163 Delta Range Electronic Analytical Balance.
83. The original adhesive mixture contained 40 g of resin and 60 g of solvent. Theoretically, if all of the solvent were to evaporate from the adhesive, we would expect to see a maximum of 60 percent loss from the initial weight.
84. The analytical portion of the Carrara cylinder experiment was performed by graduate student Jin Dou at Princeton University's School of Engineering and Applied Science, Department of Civil and Environmental Engineering.
85. Risser and Podany 2005.
86. Podany et al. 2001, p. 24.
87. Gregory Dale Smith, senior conservation scientist, Indianapolis Museum of Art, Indianapolis, Ind., personal communication, January 28, 2009.
88. Research at the Getty Conservation Institute found that B-72 retains solvent even in the form of cast films allowed to sit in the open air for six months. See Hansen 1995.
89. Smith, personal communication; see note 87 above.
90. The lengths of the unbroken marble blocks were measured precisely by placing them in the Instron mechanical analyzer and lowering the load cell to the top surface of the block. The resulting gauge length reading given by the Instron software thus corresponded to the length of the marble block.
91. The modifications to the *David* replica's right (engaged) leg were performed by Dror Heymann, a sculptor based in Brooklyn, N.Y.
92. Armature straps were made with carbon fiber fabric and laminating epoxy resin manufactured by Fibre Glast Development Corp., Brookville, Ohio.
93. Throughout the treatment of *Adam* we used undyed Twintex endless slings for the rigging. These were obtained from McMaster-Carr as a special order request following our discovery of dye transfer from purple slings to the *David* replica after a period of

several months. Undyed slings prevent transfer of dye from the sling to the marble surface.

94. We used RAM Mounts ball joints, which are composed of hard rubber ball components and metal clamping components. They are marketed as supports for GPS devices and other electronic equipment. RAM Mounts are manufactured by National Products, Inc., Seattle, Wash., and distributed by e-mounts.com.
95. The strut channel framing system used in this project was produced by Unistrut International, manufacturers of metal framing and telescopic tubing and struts, Harvey, Ill. This system can be used to rapidly assemble rigid framework structures.
96. Laweco GmbH specializes in lift systems, machinery, and apparatus engineering. The table was manufactured at Laweco headquarters in Espelkamp, Germany; the company's U.S. distributor is ETK International, Indian Trail, N.C.
97. Patrick Cunningham in Cunningham and Bak 2013.
98. Simpson Gumpertz & Heger is an engineering firm in Boston, Mass. Consulting engineers on the Tullio project were Leonard Morse-Fortier, Frank W. Kan, and Omer O. Erbay.
99. The raw data (load vs. displacement) from the unbroken marble Brazilian disks were used in creating this finite element model, thus incorporating the failure stress limit of the marble into the model of the whole sculpture.
100. The M.BL Bench Lathe, manufactured by Foredom, has a ⅙ horsepower variable speed motor (500–7000 rpm).
101. The linear actuator was a custom fabrication by MK Automation, based in Lawrenceburg, Tenn., a company that manufactures parts for automated systems such as factory assembly lines.
102. The barrier coating used inside the pinholes was a 10 percent solution of B-72 in acetone.
103. Soap served as the release agent. Orvus WA paste, sodium lauryl sulfate, was applied to the pin and allowed to dry overnight before the pin was inserted into liquid epoxy.
104. Sleeves were made with Epo-tek 301-2 epoxy bulked with 3M glass microballoons.
105. Although Epo-Tek 301-2 epoxy resin achieves full cure after three days, we found it easier to remove the fiberglass pins from the sleeves midway through the curing cycle. At this stage, the partially cured epoxy resin was hard enough to withstand this kind of manipulation without deforming. The sleeves were allowed to cure fully before the pins were replaced.
106. The bulked adhesive consisted of B-72–B-48N blend mixed with 2:1 cellulose powder:glass microballoons.
107. To make the join reversible, a barrier layer of B-72 adhesive was applied to the fracture surfaces (5 percent by weight in acetone). The surfaces were then allowed to sit open for two weeks. After that time, the join was closed using Epo-tek 301-2 epoxy. Research by Podany et al. 2001 and an empirical test undertaken by the Tullio team confirmed that the B-72 barrier layer does indeed make the epoxy join reversible.
108. The epoxy putty was Phillyseal R (a two-part epoxy putty manufactured by ITW Philadelphia Resins, Montgomeryville, Pa.), which is no longer manufactured. A good substitute is Magic-Sculpt (a two-part white epoxy putty manufactured by WESCO Enterprises, Rancho Cordova, Calif.).
109. A relatively wide 16-gauge needle was required to extrude the bulked epoxy resin mixture.
110. The acrylic resin adhesive blend was bulked with equal parts glass microballoons and cellulose powder.
111. The cotton webbing head strap was sewn by the Metropolitan Museum's upholstery conservator, Nancy Britton.
112. Rossi-Manaresi 1996, pp. 26–27.
113. Mutton tallow in a mixture with wax is suggested in a sixteenth-century recipe. See Rossi-Manaresi 1996, p. 26 and n. 60. The sample from *Adam* was analyzed by Adriana Rizzo, associate research scientist, Department of Scientific Research, MMA, using gas chromatography–mass spectrometry (GC-MS) through extraction with chloroform. The solvent was evaporated under a stream of nitrogen. Then an aliquot of heptadecanoic acid in ethanol was added as internal standard. The solvent was evaporated under a stream of nitrogen, and the residue was treated with a solution of Meth Prep II (0.2N in methanol), 1:2 in toluene. The samples were left to react at 60°C in a Reacti-Vap evaporator (Thermo Scientific) for one hour before analysis; 1µl of solution was injected in the gas chromatograph Agilent 6890 coupled with the Agilent 5973 Network Mass Selective Detector. The analysis was carried out in splitless mode. A J&W DB-5MS capillary column (30 m x 0.25 mm x 0.25 µm) was used. The inlet was kept at 300°C and transfer line at 320°C. Helium was used as the carrier gas, constant flow 1.5 ml/min. The GC oven temperature program was: 40°C for 1 min. ramped to 320 at 10°C /min., followed by 11 min. isothermal period. Acquisition was performed in SCAN mode (m/z 35-550). Temperature at MS source was 230°C, and at quadrupole it was 150°C.
114. The vinyl eraser strips are manufactured by Staedtler-Mars Limited, Missisauga, Ontario.
115. Toning was done with Schmincke pigments in a medium of Mowilith-20. Schmincke pigments are manufactured by H. Schmincke & Co., Erkrath, Germany. Mowilith-20, is a polyvinyl acetate resin and is available from Museum Services Corporation, South Saint Paul, Minn.
116. Renaissance Wax is a micro-crystalline wax polish composed of a mixture of Cosmolloid 80 hard and BASF A waxes. Picreator Renaissance Products, Picreator Enterprises Ltd., London, UK.
117. Wolfe 2009.
118. A solution of 60 g B-72, 35 g acetone, and 5 g ethanol was the base material for the fills.
119. Synthetic Onyx is a brand name for a white powder designed for mixing into casting resins. It is a mixture of aluminum oxide $Al_2O_3$ and aluminum hydroxide $Al(OH)_3$. The source is Alec Tiranti Ltd., Thatcham, Berkshire, UK.
120. Natural white earth is a fine beige powder from Vicenza, Italy. Pumice is a powder composed of finely ground volcanic ash. Rottenstone, also known as tripoli, is primarily ground-weathered limestone or slate. Both pumice and rottenstone are used as furniture varnish polishing compounds. Sepiolite is a natural magnesium-silicate that can be used as a poultice, thickener, or antisettling agent. The source is Kremer Pigments, New York, N.Y.
121. The photographs are in the archives of The Photograph Studio, MMA.

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