THE FALL AND RISE OF ADAM

Conservators at The Metropolitan Museum of Art call on simulation experts to help reassemble a 600-year-old sculpture.

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▲Tullio Lombardo. *Adam*, ca. 1490–95. Carrara marble, H. 78.5 in. (191.8 cm). The Metropolitan Museum of Art, Fletcher Fund, 1936 (36.163).

Photograph: Bob Goldman, The Photograph Studio, MMA, 1937 © The Metropolitan Museum of Art.

If Humpty Dumpty — that reckless, wall-sitting egg of nursery rhyme fame — were to experience his great fall today, chances are good that all the king's engineers would be able to put him back together again, with the help of ANSYS Mechanical software. Engineers at Computer Aided Engineering Associates, Inc. (CAE Associates) of Middlebury, Connecticut, have proven the product's capabilities by working with art conservators at The Metropolitan Museum of Art in New York to reassemble the marble Renaissance statue of *Adam*, by the 15th-century sculptor Tullio Lombardo. It suffered its own great fall on October 6, 2002, leaving it in 28 recognizable pieces and hundreds of smaller ones scattered across the gallery floor.

Traditional restoration techniques would have involved drilling holes across each fracture and inserting metal pins to rejoin the fragments, with the help of adhesives. But the diligent conservators of the Metropolitan Museum opted for a slow, thoughtful conservation project that would be minimally invasive to preserve as much of the original artwork as possible, and be fully reversible so future conservators could undo their work if necessary.

At the end of the 12-year project, the statue again stands tall in the museum's gallery, with just three fiberglass pins — one in each ankle and one in the left knee — and a mix of strong,

According to a journal paper describing the process, this was the first time that computerized FEA had been used to reconstruct a broken statue.

reversible adhesives holding *Adam* together. This remarkably small number of pins to repair a broken statue is unprecedented. The achievement belongs to a large team of conservators, materials scientists and engineers that was assembled for the project, with a key contribution from Ronald Street, senior manager of 3-D imaging, molding and prototyping at The Metropolitan Museum of Art. He had the idea to laser scan each broken piece for digital reassembly and, later, to call in the engineers of CAE Associates to perform finite element analysis (FEA) of the statue using ANSYS structural software. There was a precedent for scanning and analyzing the complete statue of Michelangelo's *David*, but this was the first time that the technique had been used to reconstruct a broken sculpture. [1]

THE SCENE OF THE ACCIDENT

When *Adam* was found damaged on the gallery floor in October 2002, it was apparent that the work of art's supporting pedestal had collapsed, causing the statue to fall to the right. Approaching the scene forensically, the conservators used the rectangular tiled floor as a grid to capture the distribution of fragments. Labeling one grid axis with letters and the other with numbers, they then took photographs of each rectangle before collecting the fragments. This information would be critical for the reconstruction. The smaller fragments were placed in plastic bags labeled with the grid number. The pieces ranged from the 380-pound torso down to marble dust that could not be relocated during the reconstruction.

The challenge then became how to rebuild *Adam* — a 3-D jigsaw puzzle of brittle marble with some of the pieces missing because they had been pulverized. Street's experience with 3-D graphics led him to suggest scanning each piece with a laser and then using software to determine how these pieces fit together. These scans also allowed the Met's conservation team to machine full-scale polyurethane foam replicas of the larger pieces so that they could construct an external support armature composed of form-fitting carbon

▲ Finite element models of *Adam*. Left: assembled NURBS model. Center: continuous NURBS model with bonded contacts. Right: hybrid model with 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

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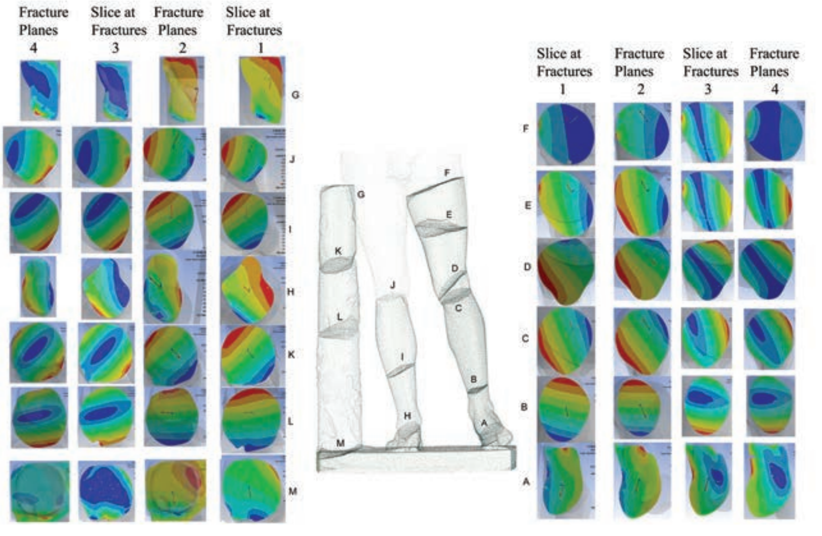
fiber collars. The milled models of the fragments allowed the conservators to practice the reconstruction process using relatively lightweight foam instead of heavy, brittle marble. Working with the model to develop the reconstruction armature ultimately helped to preserve the fresh breaks of the sculpture fragments, thus avoiding further loss to the surface.

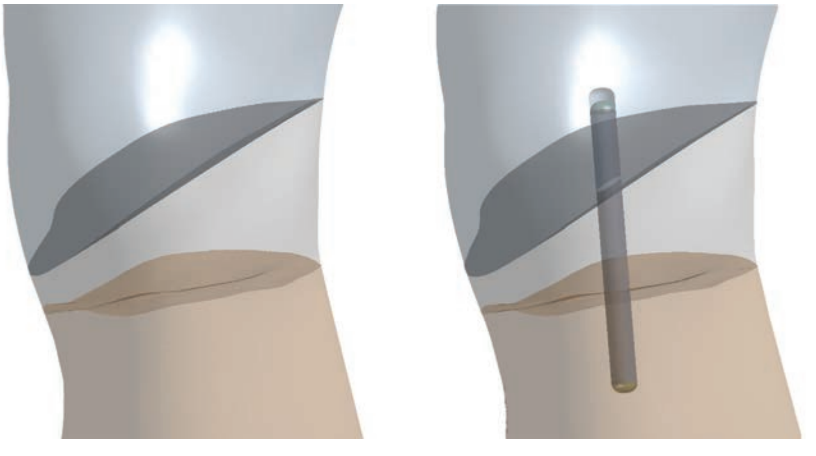
ENTER THE ENGINEERS

With the general plan for the assembly sketched out, it was time to bring in the engineers from CAE Associates to assess the structural challenges that lay ahead.

At this point, the conservators had already drilled holes in the ankles, where it was obvious that pins were needed because the small cross sections of the ankles support all the weight of the statue above them. Using the geometry of the statue obtained from the 3-D reconstruction, CAE Associates performed structural simulations using ANSYS Mechanical on the full statue model to determine the center of gravity, the overall flow of force and nominal stresses throughout the sculpture. Submodels of local pin regions at the left knee and ankle were constructed using much finer mesh density to investigate the detailed stress distributions near these interfaces with the pin locations.



Adam's tree trunk along with right and left legs (center), with ANSYS Mechanical stress results on either side. 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 stress.



Finite element submodels of *Adam*'s 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.

MODELING THE INTERFACES

In the left ankle and left knee regions, the actual condition of the adjoining surfaces was difficult to ascertain due to a combination of small fragment loss and the resolution of the scanned surfaces. Additionally, local crushing of fractured surfaces was likely to occur when the full weight of the statue was applied to the regions, resulting in local interlocking of the surfaces. To account for the possible variation of the join surface conditions, engineers at CAEA used the finite element model to bound the problem in the following fashion:

- A homogeneous geometry model (provided by the Metropolitan Museum) with all of the gaps in the left ankle and knee joins filled in was used as the baseline. This model was representative of the statue prior to the accident and was considered the best-case scenario.
- A model with a smooth planar cut aligned with the break surface was used to represent the worst-case scenario.
- The ANSYS DesignModeler geometry tool was used to create a rough but interlocking interface by importing surfaces from the broken model to be used as slicing tools in the baseline model. The result was an interlocking but fragmented geometry that represented the effect of local crushing of the marble surfaces when reassembled.

THE ANALYSIS AND THE PLAN

The FE analyses verified that the 5/16 inch diameter holes that had already been drilled were sufficient for the fiberglass pins that previous testing had determined would be best for the restoration of the ankles. The engineers were able to show the conservators that adhering the pins in place on one end and letting them float on the other, rather than adhering the pins on both ends, would be less likely to damage the marble if the adhesive in the join failed and the pin transmitted the full shear load.

The remaining question was how to repair the left knee, which was broken

Engineers used ANSYS DesignModeler to devise a unique hybrid model with an "interlocking" interface that would more closely represent the repaired structure.

into three pieces: the thigh, the calf, and a wedge of marble between the two. At the wedge–calf interface, the crack face was parallel to the ground. Because the weight of the statue was distributed through compressive stresses here, inserting a pin initially seemed unnecessary. But the wedge–thigh interface was angled, and therefore subject to shear forces. This was a more problematic configuration. Could it be repaired without a pin, as the conservators hoped, or was a pin, or perhaps two pins, necessary? Was it possible that an adhesive by itself would be sufficiently strong?

Photograph: Carolyn Riccardelli

Adam fragments in the external support armature made of rigid channel stock and carbon-fiber collars. A custom-designed lift table was used to raise the assembled legs up to the torso, which was suspended in its own carbon-fiber corset.

To be thorough, the conservators wanted to investigate three options: adhesive only; adhesive plus a pin connecting the wedge and the thigh; and adhesive plus a longer pin joining calf and thigh and passing through the wedge.

CAE Associates performed a series of parameterized simulations using ANSYS Mechanical to investigate how forces varied in the knee and throughout the statue, depending on the positioning and length of proposed pins. They also simulated how the strength of the adhesive bond between the pin and the marble — ranging from frictionless (free-floating in the drilled-out pin hole) to strong adhesion — affected the transfer of forces between the pin and the marble in case of a shearing event.

Further simulations showed that failure of the adhesive bond at the wedge–thigh interface was the worst-case scenario. An adhesive failure at the wedge–calf interface would produce compressive forces that could be absorbed mostly by the knee, but failure at the wedge–thigh location would significantly increase the stress in the right ankle and at the tree trunk–hip connection. It is interesting to note that it was standard practice for figural sculptors to utilize a third vertical element — such as a rock or a tree trunk — to triangulate the load of a statue, providing additional support to the figure's two legs. Tullio Lombardo designed the connection between *Adam*'s right hip to a tree trunk for this purpose. To avoid transferring stress to this vulnerable area, a pin at the wedge–thigh interface would keep the fragments aligned and allow the normal and shear forces from the weight of the statue to continue to be transmitted to the left leg. Extending the pin into the calf would provide additional stability in the event of adhesive failure.

With this engineering data in mind, the conservators ultimately elected to insert a 4-inch-long, 0.25-inch-diameter

IMPLEMENTING SUBMODELING IN ANSYS MECHANICAL
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fiberglass pin in the left knee, connecting the thigh to the calf through the wedge.

EXECUTION

The actual rebuilding process was carried out by Metropolitan Museum conservators working systematically over a period of many months. The conservators focused on one join at a time, supporting each major piece of the statue with the external armature and carbon-fiber collars that had been developed using the full-scale polyurethane model. To connect the fragments, conservators applied an acrylic adhesive on the fracture surface being joined, returned the fragment to the armature, and then gently aligned the fragments. Once adhesive was in place, the remaining leg fragments were dry-assembled (without adhesive). A custom-designed lift table was then used to raise the assembled legs up to the torso, which was suspended in its own carbon fiber corset. In this way, the full weight of the sculpture was applied to each newly bonded join. [1] Each join was allowed to rest in the external armature until the adhesive reached full strength (about 2 months), at which time the conservators could move on to the next join. The last join to be made was *Adam*'s head, which was lowered into place cradled in a sling, thus completing the structural portion of the conservation treatment. The remaining work involved filling in spaces where the marble had been pulverized, and toning the fills to match the surrounding marble. *Adam* was returned to public view in a new gallery for Venetian art at the Metropolitan Museum on November 10, 2014.

3-D model of *Adam* showing major breaks and locations of three fiberglass pins, in red

Adam after treatment, 2014

The conservation of *Adam* was a unique project for conservators and engineers alike. It was a learning experience for everyone involved, as every participant sought to understand the concerns, restrictions and vocabulary of the others. All came to appreciate the talents of their collaborators, and each group learned something of value.

The CAE Associates engineers, who have analyzed engineering structures in aerospace, medical, civil and manufacturing applications, enjoyed applying their structural finite element expertise to provide information that led art conservators to make difficult decisions regarding how to restore this priceless work of art. This project advanced the practice of large-scale marble sculpture conservation into new territory by adding extensive materials testing and finite element analysis to the process. Should another major statue take a great fall in the future, ANSYS Mechanical is likely to be part of the repair process.

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References

[1] Riccardelli, C; Soultanian, J; Morris, M; Becker, L; Wheeler, G. and Street, R.; The Treatment of Tullio Lombardo's *Adam*: A New Approach to the Conservation of Monumental Marble Sculpture, *Metropolitan Museum Journal*. **2014**. Volume 49, pages 49–116. metmuseum.org/research/metpublications/The_Treatment_of_Adam_Metropolitan_Museum_Journal_v_49_2014 (16/09/2015).

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