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CAD, CAE in Restoring the Statue of Liberty

# COMPUTERS, COMPLEXITY, AND THE STATUE OF LIBERTY RESTORATION

*Twentieth-century techniques such as computer-aided engineering and finite-element analysis were used to restore the nineteenth-century monument.*

KAREN A. FRENKEL

Situated in New York Harbor, the century-old colossus, formally named Liberty Enlightening the World, will resume her reign refurbished this July. The two-year restorative process was far from a simple touch-up job; it encompassed the efforts of numerous American and French consultants, over 30 contractors, several foundations, American government agencies, and many contributors of time and money—which totaled $31 million. Just coordinating so many players would be complicated enough. But the aging Statue's design and complex nineteenth-century structure presented an unusual challenge to solving the problems of the stresses, strains, and exposure that her size and location demanded she endure. Before one firm could even begin its analysis, it faced the additional task of creating blueprints from scratch—the originals were destroyed in a Paris fire at the turn of the century. Such an ambitious undertaking necessarily called for new techniques; hence this account of how the restoration was accomplished with the help of twentieth-century technology.

Although the Statue of Liberty is unique in many ways, the use of computers and other modern technologies to facilitate the restoration is expected to yield other applications. Ideally, these techniques could facilitate sorely needed repairs of our nation's aging infrastructure, most notably bridges. On the other hand, some of the difficulties encountered in efficiently applying such techniques to the Statue reflect limitations in the state of the art. Several computer-aided engineering (CAE) and computer-aided design (CAD) systems were used to provide data that otherwise would have been too time consuming to gather manually. But, in this application, as in others, vendors and users do not always agree on whether these systems can always communicate with one another. Some firms' capabilities improved within the two-year period; they were troubleshooting when their assignment began and rode the learning curve throughout the job. To examine and share the knowledge that was gained from the Liberty project, 15–20 historic, architectural, and engineering societies will sponsor a conference in October 1986.

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## GLORIA VERSUS LIBERTY

Had Hurricane Gloria threatened to whip through New York City a few years earlier instead of last September, engineers would not have known whether the Statue could withstand the storm's force. As it turned out, the forecasted 130-MPH winds never blustered across the harbor. But they could have meant a less-than-welcome test of assumptions that engineers had incorporated into their analyses of the Statue's condition. Besides modeling her geometry and then conducting static load and dynamic analyses, they had included in their calculations the effects of corrosion and the amount of fatigue she had consumed during 100 years. Until the very last moment, consulting structural engineers from the civil-engineering firm of Ammann and Whitney of New York remained concerned about the potential consequences of the storm.

One concern was the consequence of the 130-MPH winds forecast by the weather bureau, which could affect the monument in different ways at various heights; the 150-foot Statue is mounted on a 154-foot pedestal, giving a total height of 305 feet. In engineering terms, wind velocity is normally given as the fastest mile of wind at 30 feet above grade. If the predicted velocity of 130 MPH had conformed to this standard, the wind forces would have greatly exceeded the 100-year recurrence velocity for which the Statue was designed, that is, the fastest mile equal to 90 MPH. This design velocity converts to a peak wind velocity at the torch of 140 MPH, including escalation for height and gusts above grade. Most likely, however, the predicted velocity for Gloria was measured from an aircraft at some height above ground, the engineers say.

Concern for safety of the Statue against wind effects was also reflected in the design of the scaffold that was erected to aid in the reconstruction. Because the scaffold was to be in place for a period of nearly 2 years and because it posed a potential hazard to the Statue in the event of high winds, the scaffold itself was designed for the same 100-year recurrence velocity used in the analysis of the Statue. This is uncommon for most scaffolds, which are normally designed for recurrence velocities of less than 25 years. Because the Statue of Liberty is irreplaceable, it was prudent to use the higher value.

## EIFFEL AND LIBERTY

Liberty's supporting mechanism was designed in 1879 by Gustave Eiffel, who is known principally for the Parisian tower that he later built and that bears his name. Eiffel's service was enlisted on the death of Viollet-le-Duc, whose design solution for supporting the massive copper skin was to simply fill the Statue with cubicles of sand. Trained as a bridge engineer, Eiffel applied his knowledge of rigid truss frameworks to create the Statue's central pylon using a towerlike construction with four tapering legs, horizontal struts, and diagonal cross brackets. This skeleton resembles those of today's radio towers. Attached to the central pylon, which is made of "puddled" iron elements, is a secondary truss structure of lighter angle members. The skin assembly, composed of 2-mm-thick copper reinforced by a grid of 20-by-80-mm iron armature bars, is connected to the secondary frame by inclined compression struts with articulated joints that allow the copper sheath to "breathe" or "float." This unusual design solution is similar to curtain-wall construction commonly used today for buildings.

Because there were little documented data available, it was necessary to go into the field to take Liberty's measurements. At first, Swanke, Hayden, and Connell, the architects of record who were responsible for conducting the physical survey, had hoped to bypass the rigors of a field inventory by scanning the monument. They knew that Robotic Vision Systems of Hauppauge, New York, had created a holographic sculpture of huge ship propellers for the navy, and hoped they could apply that technology to Liberty as well. Another approach was to scan one of the two meter-high models of the Statue and hope that it would approximate the scaled-up version. But, when the quoted cost of the first approach proved prohibitive, and it was determined that the second would not have been representative of the actual structure, the design team painstakingly counted and measured members of the central pylon, secondary structure, the locations of thousands of rivets, gusset plates, the intricate and complex shapes of the armature and skin, and so on.

Unlike Eiffel, who had analyzed only the central pylon, Ammann and Whitney treated the pylon as a composite structure with the secondary frame. "Eiffel's analysis was perfectly valid," says Ammann and Whitney managing partner Edward Cohen, "except that he used one wind-loading direction and did not consider the dynamics. He used a static wind load of 56 pounds per square foot—which is in fact higher than the wind load we used—and a smaller exposed area for the upper part of the statue." Eiffel's mathematical tool for analyzing Liberty was a force polygon. This was possible because the structure he used is statically determinate—there are no redundant members to share loads based on their relative stiffnesses. The net effect was that the stresses computed by Ammann and Whitney using present-day standards were substantially similar to those calculated by Eiffel. "He could not have analyzed the dynamic effects the way we did," explains Cohen, whose method of choice was finite-element analysis, "because the mathematics wasn't available at that time and neither was the computing machinery."

## FINITE-ELEMENT ANALYSIS

Finite-element analysis (FEA) is in fact less than three decades old and evolved as computers became available. Both hardware and software developments have contributed to the method, and it has enabled engineers to handle structures that are too large, complex, or expensive to tackle using manual methods, without greatly simplifying the models. Today, FEA is still computationally expensive for very large projects, but it is expected that, as supercomputers become more common and accessible, more and more FEA will be done. In addition, during the last 10 years, many of these packages have been ported to minicomputers, and some can now run on personal computers.

The first finite-element codes were developed in 1956 by aerospace engineers at Boeing, Grumman, and McDonnell Douglas. The technique can be applied not only to structural analysis, but also to a wide range of engineering problems like heat transfer, aero- and hydroelasticity, acoustics, and electromagnetism. FEA problems require the solution of algebraic simultaneous equations in which there are as many unknowns as there are equations. To model an object and determine its response to forces and loads, the object is divided into a finite number of smaller elements, which are often uniformly shaped beam elements, and triangular and quadrilateral plate elements, but the elements may also have arbitrary shapes, thereby allowing flexibility of modeling. The elements connect to neighbors at a finite number of points, or nodes, which can be characterized by their positions in space, translational and rotational movements in space, and connectivity to other nodes via finite elements. Translation and rotation are the "unknowns" or variables and are often called "degrees of freedom." Unlike static analysis, dynamic analysis requires that a structure's mass be "discretized," or distributed, among selected nodes throughout the model. The motions of such "lumped mass points" are calculated and indicate stress points on each member. This way, when the resulting equilibrium and continuity equations are solved, the model simulates the behavior of the real-world structure. A small model contains 50–200 nodes, a medium-sized model contains 250–1,500 nodes, and as many as 6,000 equations must be solved. Large Cybers and Crays are usually called on to solve the 100,000–200,000 equations necessary for large models.

To assist them with their structural analyses, Ammann and Whitney used two commercial software packages for structural analyses of the support system and skin: Stardyne,® by System Development Corporation (SDC) of McLean, Virginia, and STAAD-III, by Research Engineers of Marlton, New Jersey. They then input data from those two systems into their in-house custom program, "Dywnd" (from Dynamic Analysis Wind Loading), which gives the response of a structure to the power density spectra of wind.

Stardyne, the first commercial FEA package, was written in Fortran. It was introduced in 1968 by Research Mechanics, which was later bought by SDC, a Burroughs Corporation subsidiary. As one of the first users, Ammann and Whitney was also one of the first troubleshooters and encountered some typical problems. "We ran an analysis one night and received a five-figure bill," reminisces structural engineer Joseph Vellozzi, "and we refused to pay because it seemed there were no bandwidth minimizers and they had told us there were. These are internal workings that automatically reorganize the problem so that it uses less core space on the computer and the program runs efficiently and faster. It turned out that there was a minimizer, but it had a bug in it, so in the end they didn't bill us." Initially, Control Data Corporation had exclusive rights to market Stardyne, and users leased it through CDC Cybernet Service Centers. In 1979 that agreement dissolved, and Stardyne became available on the Cray I through United Information Services, where Ammann and Whitney subscribed to use the FEA package for the Statue analysis. Today, Stardyne can run on in-house VAXes—it was ported to minis in November 1984. Users no longer have to pay for external computer time, but they still must pay a royalty fee.

Because number crunching for such analyses is so expensive, engineers try to limit the number of equations. The original FEA model of Liberty contained hundreds of nodes and thousands of elements. The stiffness of the system, part of the static analysis, was described by a 1000-by-1000 matrix that had to be condensed using matrix inversion in order for the dynamic analysis to be more manageable. Vellozzi and Pakajan Rasan, also a structural engineer, chose to reduce the original model's more than 300 nodes and over 1000 finite elements to 49 key points with three degrees of freedom totaling 147. For the dynamic analysis, the structure can be thought of as a series of springs supporting dead-load masses; the engineers had to approximate the tributary weight of the Statue and then calculate the motions of the end points on each member of the pylon and secondary structure units. To do this, they distributed the weight among 22 "lumped mass points" each of which had three degrees of freedom (see Figure 1). This included the mass of the skin applicable to those points. A separate analysis of the stresses in the copper sheath was not possible, says Cohen. "The skin was a much more complicated structure because of its complex shape. Whether or not we could ever have gotten an accurate analysis, we don't know. This was not necessary for the integrity of the structure, nor was it within the time we had available, with or without a computer." The

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Stardyne is a registered trademark of System Development Corporation.

final FEA model was relatively small and created a database of 2–3 kbytes.

## THE SHOULDER AND ARM

The analyses showed that no repairs on the central pylon were necessary. But the shoulder was in serious need of reinforcement despite a 1932 repair during which several members were reinforced and added. The shoulder attachment is actually a birth defect. For unknown reasons, Eiffel's original design was not executed during construction, and the arm was offset by 18 inches in two directions from its intended support. This weakness has caused Liberty to literally wave her torch in the wind, oscillating so much that one of her crown's seven spikes has continually pricked her arm (see Figure 2, p. 288).

Project Manager for Engineering Pat DiNapoli summarizes the situation this way: "The basic problems with the arm were obvious to us. There were elements that didn't go to the panel points (points where all members meet), and that created bending stresses in members that were not intended to carry bending, so this made the structure very flexible. We had to eliminate the bending effects, and so we came up with a repair scheme to solve the problem. A second solution, replacing the shoulder with a new structure, was also designed. Both schemes were manually designed using stress data from the FEA, and both were found to be sound engineering solutions."

To relieve some of the torsional stress, Ammann and Whitney wanted to add a diagonal element, but this led to a difference of opinion with engineers from the French team, who wanted to add a metal plate or diaphragm. "So we agreed to adding the diaphragm with the diagonals below it," says DiNapoli. This, too, was evaluated on the computer, using STAAD-III for FEA (see Figure 3, p. 289).

Knowing that both shoulder schemes were structurally sound enabled the National Parks Service to make a philosophical decision rather than an engineering or design decision—they chose the scheme that involved more repair than replacement. "They chose not to accept the recommendations of their consultants," says John Tesoro, a Parks Service adviser who is director of Corporate Information Ser-

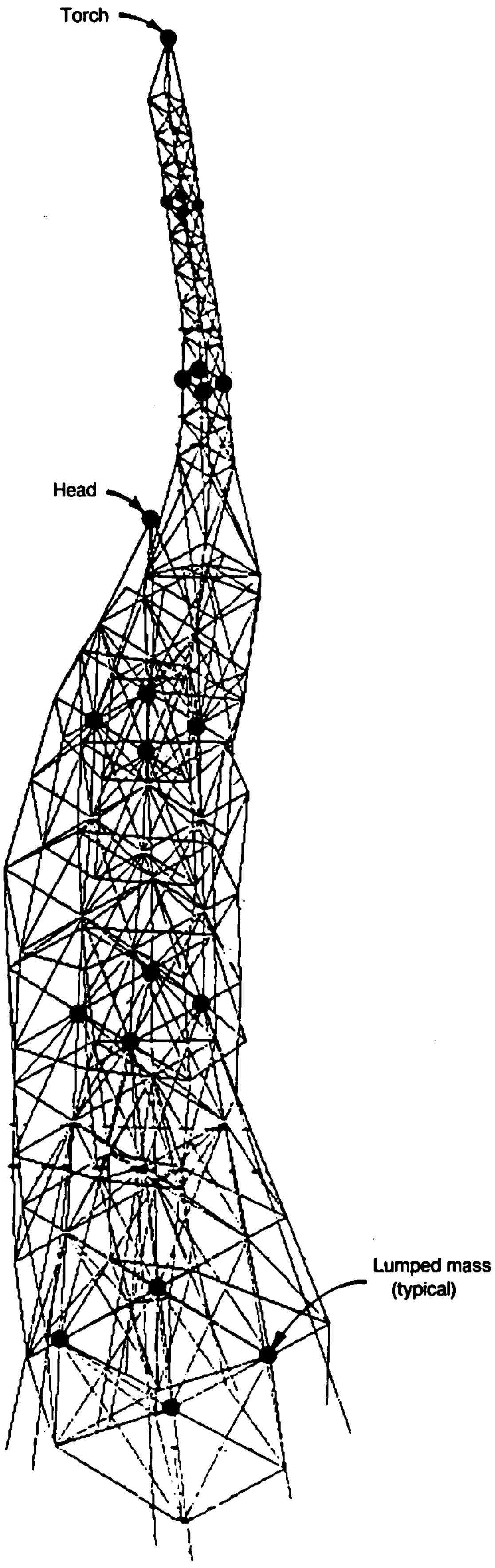
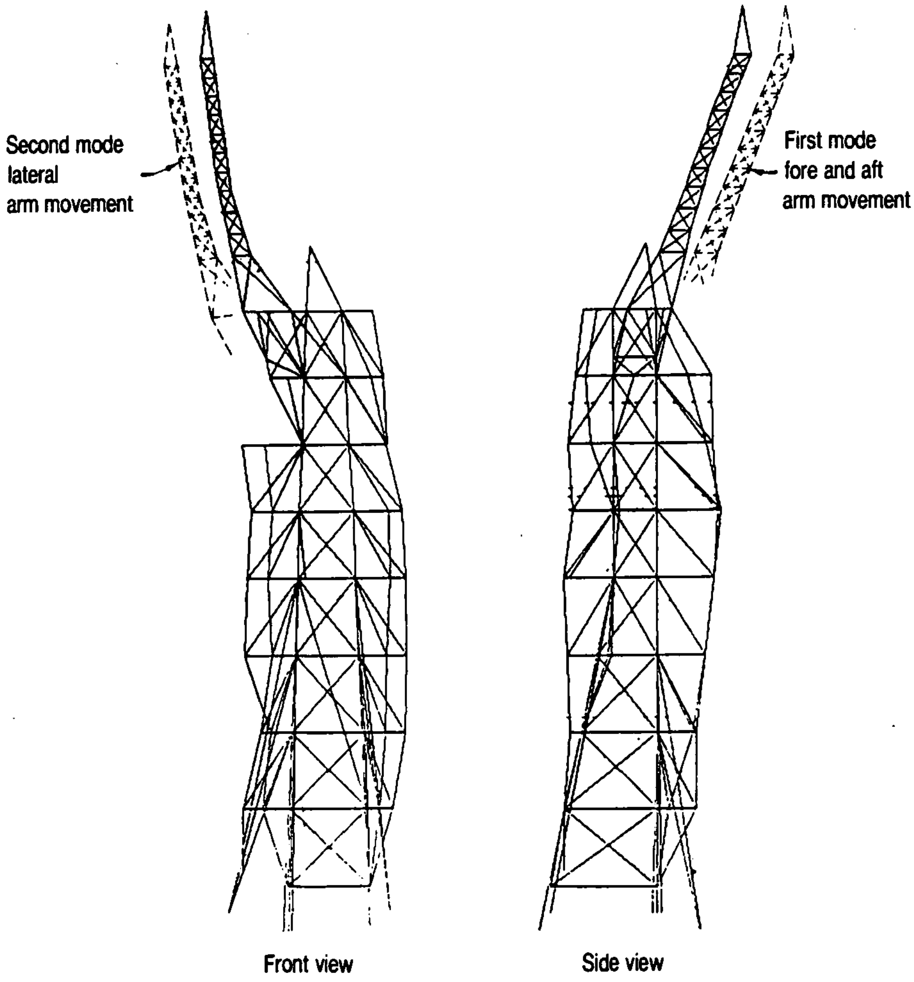


**FIGURE 1. Dynamical Model**

This dynamical model shows thousands of finite elements and the 22 lumped mass points on the full model of the Statue of Liberty. Courtesy: Ammann and Whitney.



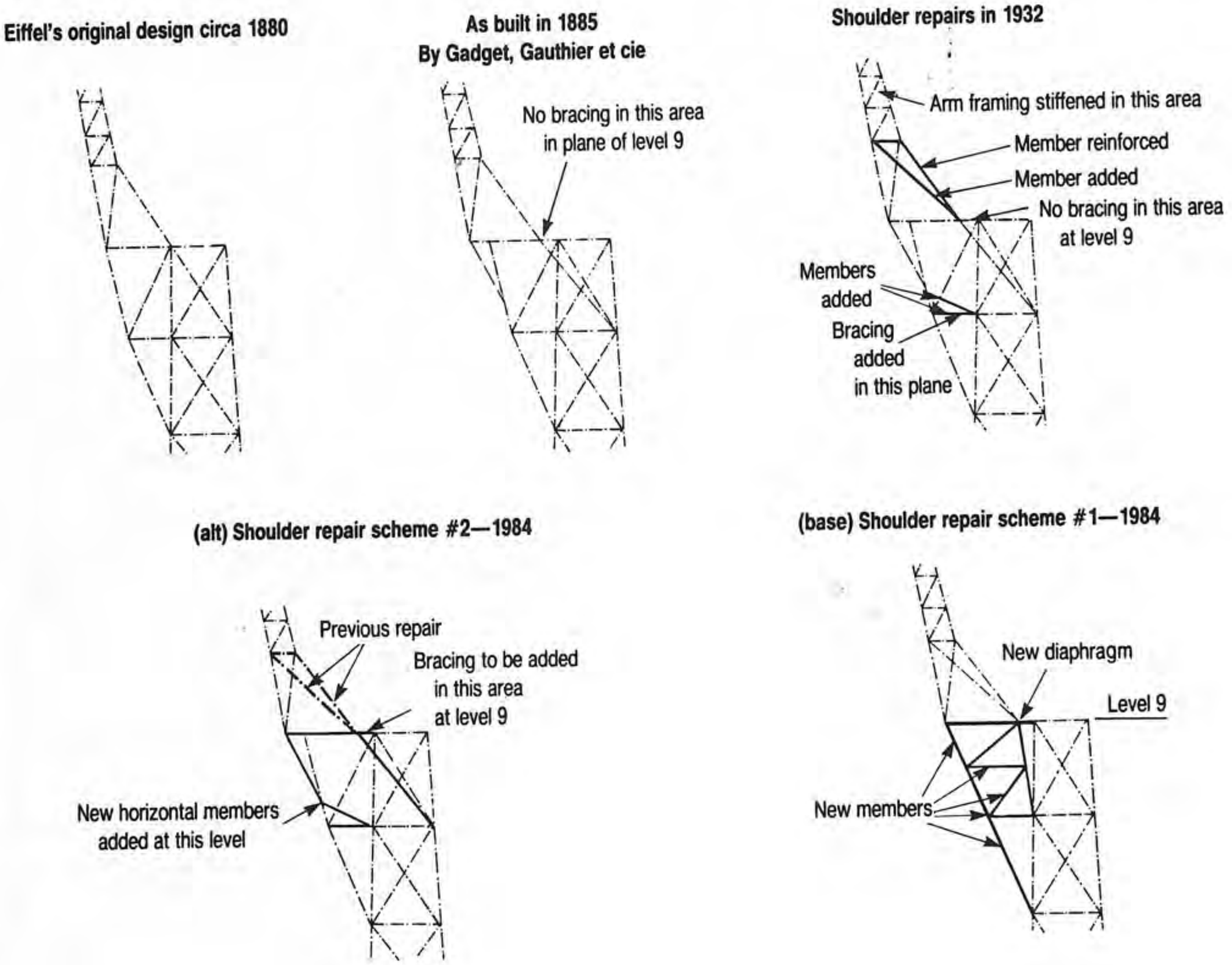
The major contributors to the stresses in the Statue under dynamic wind conditions are the first and second modes. These are the lowest frequencies at which the structure vibrates—the slower the oscillations, the bigger the displacements. As shown here, the part of the Statue affected most by the first mode, and slightly less by the second mode, was the raised arm. Courtesy: Ammann and Whitney.

**FIGURE 2. Dynamical Modes**

vices at the civil engineering firm, Burns and Roe in Oradell, New Jersey. "Part of the reason is their realization that the schemes were equally strong, and also their fundamental belief in the spirit of the restoration—that you save the error that was lived with for a hundred years. That gives historic value to it."

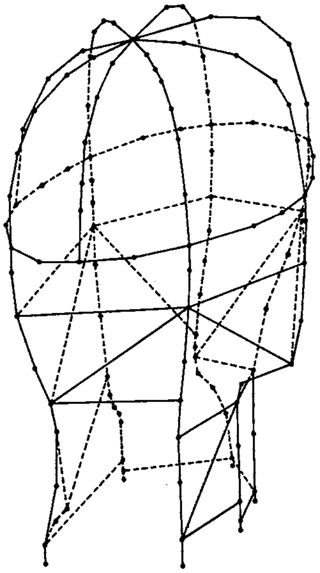
## THE HEAD

The next location that suffered complications was the head. Instead of using Stardyne, Ammann and Whitney used STAAD-III to create 200 nodes, 1200 degrees of freedom, and 300 finite elements (see Figure 4, p. 290). Information was entered on a DEC rainbow microcomputer, and the file was sent to a Cray I, which gave results in 10 seconds. Paradoxically, the first run showed that the head could not carry the loads, and yet somehow the head was still intact after a century. This was a surprising finding. Says Etan Agai, Ammann and Whitney's director of computer and CAD operations, "Usually when you analyze a building, you don't take into account the walls. You just assume that the walls will not play a part in carrying the structure. But actually they do—they somehow add to the stiffness of the structure." So Ammann and Whitney incorporated the skin into the analysis and found that the copper shell was carrying more load than the framework inside. The skin was much stiffer—"like an eggshell," according to DiNapoli—than the structure. Cohen suspects that because Viollet-Le-Duc did not have the tools to compare these stiffnesses, he made assumptions that eventually caused the head to distort. It may have deflected enough to be responsible—along with the faulty shoulder—for the two-inch dent made in Liberty's arm by the spike. "The fact that one of the spikes is actually pricking the arm may indicate that there was some movement. It's not conceivable that they would have erected the Statue so that the spike and the arm were touching, and the motion of the arm at that level wouldn't have been anything like two inches. So it's likely that the head has distorted," he says. They went through a series of iterations, finding that, in some cases, strengthening one area made the situation worse somewhere else. This was further complicated by the new crown platform that had been proposed by Swanke, Hayden, and Connell, says DiNapoli. "Originally we had envisioned the platform to be independent of the head structure. When we tried to install it, we found that there were a lot of elements in the head that weren't obvious before the old platform was removed, and these interfered with the new platform." Ammann and Whitney simulated nine repair schemes, settling on one that was integrated with the new platform



As Eiffel's original design shows, all the members at the shoulder joint on level 3 converge to form a panel point. As later constructed, no panel point exists because the arm was offset, resulting in flexure. The final repair scheme shows a diaphragm or metal plate extending from the intended panel point to the left-most point of level 9. In addition, six new members below the diaphragm buttress the arm. Courtesy: Ammann and Whitney.

**FIGURE 3. Shoulder Design and Repair Schemes**



This finite-element model of Liberty's head arches has 121 nodes and 153 beam elements. Refitted with the new platform (not shown here), the new model has 158 nodes and 214 beam elements. The skin for both models (also not shown) has 65 nodes and 64 plate elements. Plate elements have a tighter ratio to nodes than do beam elements. Courtesy: Ammann and Whitney.

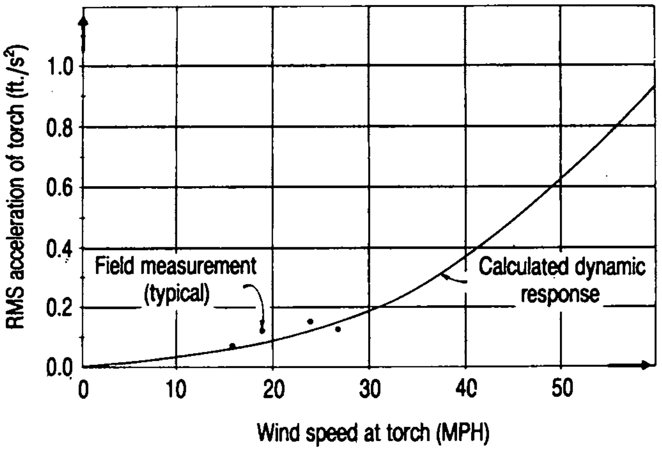
FIGURE 4. Head Arches Model

design. The final design ensures the integrity of the head structure without the aid of the copper skin.

## WIND-LOAD AND FATIGUE ANALYSIS

Finally, Ammann and Whitney conducted probabilistic analysis of steady and variable wind loads, and a fatigue analysis using Dywnd. Developed seven years ago by Vellozzi and his students at Polytechnic Institute of New York in Brooklyn, the program was written in Fortran 4 and was first tested and verified by hand calculations of the Golden Gate Bridge. Vellozzi says that Dywnd is unique in its ability to perform random wind analysis, which gives a structure's response to the power density spectra of wind in a particular location. It combines structural characteristics with different wind environments to give the standard deviation of the deflection of all points in a structure. In this case, input consisted of characteristics of Liberty's structure as found by Stardyne and quantifications of turbulence in Dywnd's subroutines called "City Center Environment," "Suburban Environment," "Coast Environment," and so on (see Figure 5). Comparing the stress levels due to winds that Liberty had already experienced with how much she could sustain led to a prediction of how much fatigue life remained. The engineers dug through one hundred years of historical records of winds that had passed through the harbor to determine a "Harbor Environment" Dywnd subroutine. "Using that, we predicted that very little fatigue life had been consumed and that probably the existing structure would last 1000 years, if no other factors entered into it—strictly from a stress viewpoint," DiNapoli concludes.

To Ammann and Whitney's team, the computer's role remains that of a tool. "We're not able to solve engineering problems because we have a computer," says DiNapoli. "The computer makes them easier to solve, you can display information faster and more accurately, and you can do analyses that you really couldn't do by hand as well or as quickly." Agai goes further, noting that it can be dangerous to rely too much on computers. "Right now we have powerful computers and pretty good software. But it is still not economical to model a structure the way it really behaves. That means you're not inputting every element of the structure, and to make simplifying decisions, you really need to understand the structural behavior to determine the key elements." So to know where you can afford such a trade-off and still obtain reliable results requires astute engineering judgment. Eventually, that may be incorporated into expert systems, Agai says, but for now, "You need experience and a 'feel' for the structure's behavior to decide how fine you need to chew your model."



Field measurements versus the dynamic response of the torch as calculated by "Dywnd." Courtesy: Ammann and Whitney.

FIGURE 5. Torch Dynamic Response

## THE FLAME

While engineers were deciding the extent to which they should reconstruct the shoulder, there was no such debate regarding the torch. In 1886, while under the jurisdiction of the Lighthouse Board, the original solid flame was altered to serve as a lantern. Its copper surface was cut up so that light from the interior could shine through 600 amber windows. But, despite putty and tar, the lantern leaked and became so damaged that access to it has been barred since 1916. Because the torch was in such bad shape and violated Bartoldi's original design, the flame, the surrounding balcony, and the pendant at the torch's base are being replaced. French architects for the restoration created a wooden model approximating the original flame. The new flame will emerge using *repoussé*, a technique for shaping copper by hammering it over wooden or metal forms. Finally, it will be gilded and illuminated by external lights.

To ensure that the new flame would have the same dimensions as the original, and to amass data before the original was transported to the Rose Bowl where it would appear in the parade, the restoration team called on the Denver Research Institute (DRI), a branch of the University of Denver in Colorado. Analysis and modeling were done with DRI's custom software, which it usually uses for government contracts to model trucks, airplanes, ships, and buildings, or to simulate a projectile hitting an airplane, for example.

Charged with creating computer models of both flames so that they could be compared, DRI's Donald Saum gathered data using stereo photogrammetry, a technique of taking pairs of photographs of the same location from different points of view, every 45 degrees. The photos were then digitized by Analytic Surveys of Colorado Springs, Colorado, to generate X, Y, and Z coordinates of 18,000 points on each flame.

John Thompson and Willis Walter, both research analysts at DRI, prepared those data for input onto a Harris 125. This proved to be an arduous task, both because of the flames' complex shape and because, according to Thompson, the points were digitized without enough knowledge of DRI's software. Ordinarily, the researchers would have used several different geometric shapes, or mathematical tools, like a cubic spline, to generate curves. "But the flame is so complex that it wasn't worth the effort to try to define curves because you'd have to define them every few inches and in different directions," says Thompson. "So we went to triangles. When the surface is fairly flat, you can have pretty big triangles. Where there are fairly tight curves, the triangles get small and numerous. With 18,000 points, we were able to model very closely, so it came out looking very smooth" (see Figure 6, p. 292–293).

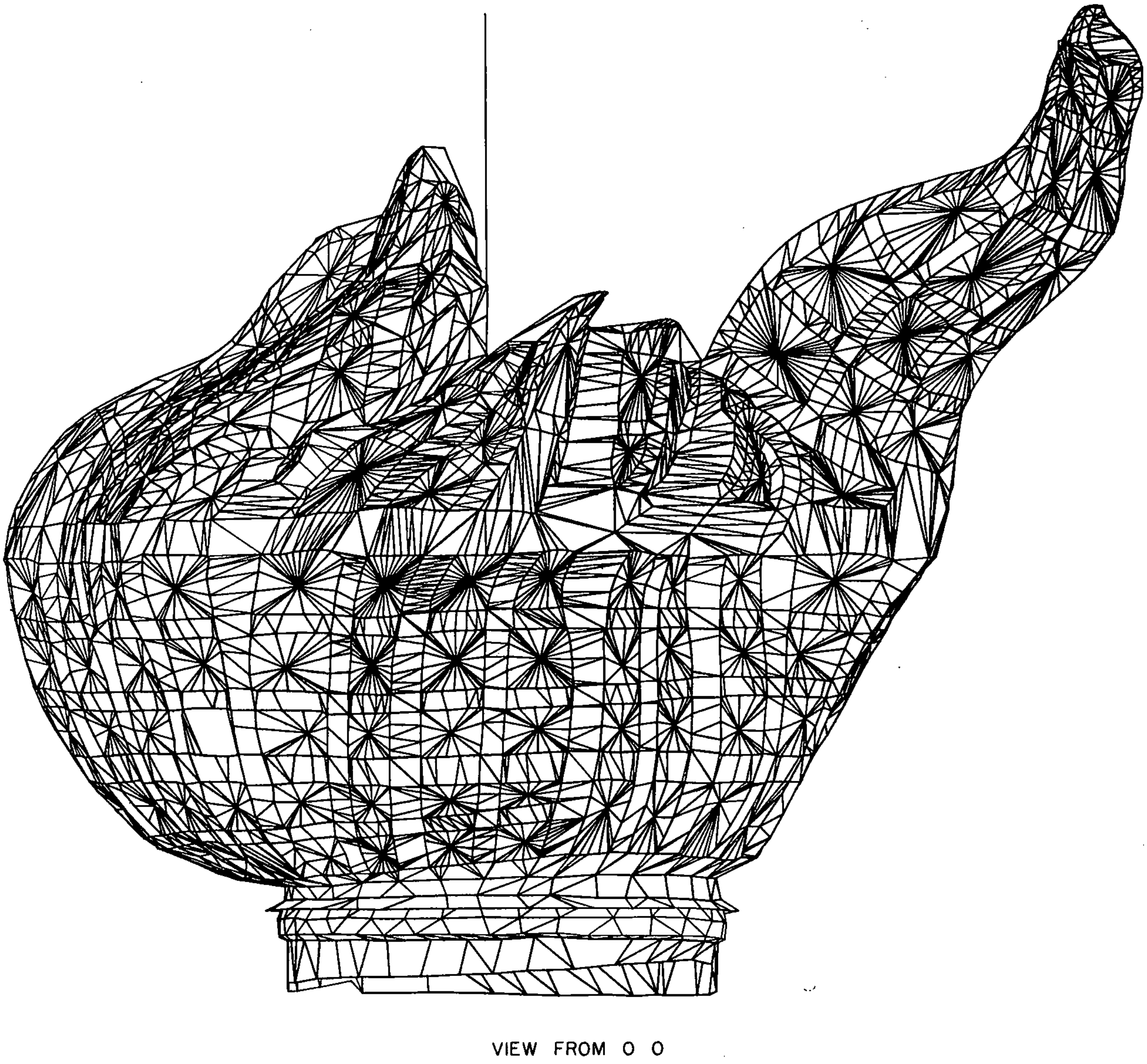
But the complexity of the shape made it hard to digitize those points in an orderly manner. In fact, they were digitized almost at random, says Thompson. On the old flame, for example, "they would pull off points going around a piece of glass or up a copper strip, and if it happened to be irregular, they would digitize a number of points in a random fashion just to make sure we knew it wasn't a smooth surface." But John Thorpe, Analytical Surveys president, replies that he would have preferred to measure horizontal cross sections at vertical intervals and was told not to.

The solution would have been better communication initially between both teams, Thompson suggests, so that points could have been digitized keeping in mind a final series of thousands of triangles. Instead, Walter spent three months manually sequencing the coordinates logically so that, if one picked out any three successive points, they would form a triangle on the surface of the flame. These data were inputted into several program modules so that Thompson and Walter could select and plot various sections and points of observation of the flame without having to call up the entire 3-D database. Once the data were complete, the new flame was scaled up to the size of the old one, points on both were satisfactorily compared, and, for the record, the computer model of the old flame was used to render architectural blueprints.

Lacking an interactive system, Thompson and Walter had to view their models by printing out sequences and correcting them on hard copy. Although DRI can perform the same operations as most CAD systems—like rotations, perspective views, and hidden-line removal—they cannot look at the results on-line; they must print them out, which is time consuming. They have investigated mainframe CAD systems, but have found them too expensive, and await cheaper 3-D CAD systems. But Thompson finds that so far these microsystems are geared mainly toward architectural needs, which can be satisfied by 2-D systems. Although occasionally DRI analyzes buildings, "they are very simple compared to an airplane or the flame, where you really have to have true 3-D," Thompson says.

## LIGHTING LIBERTY

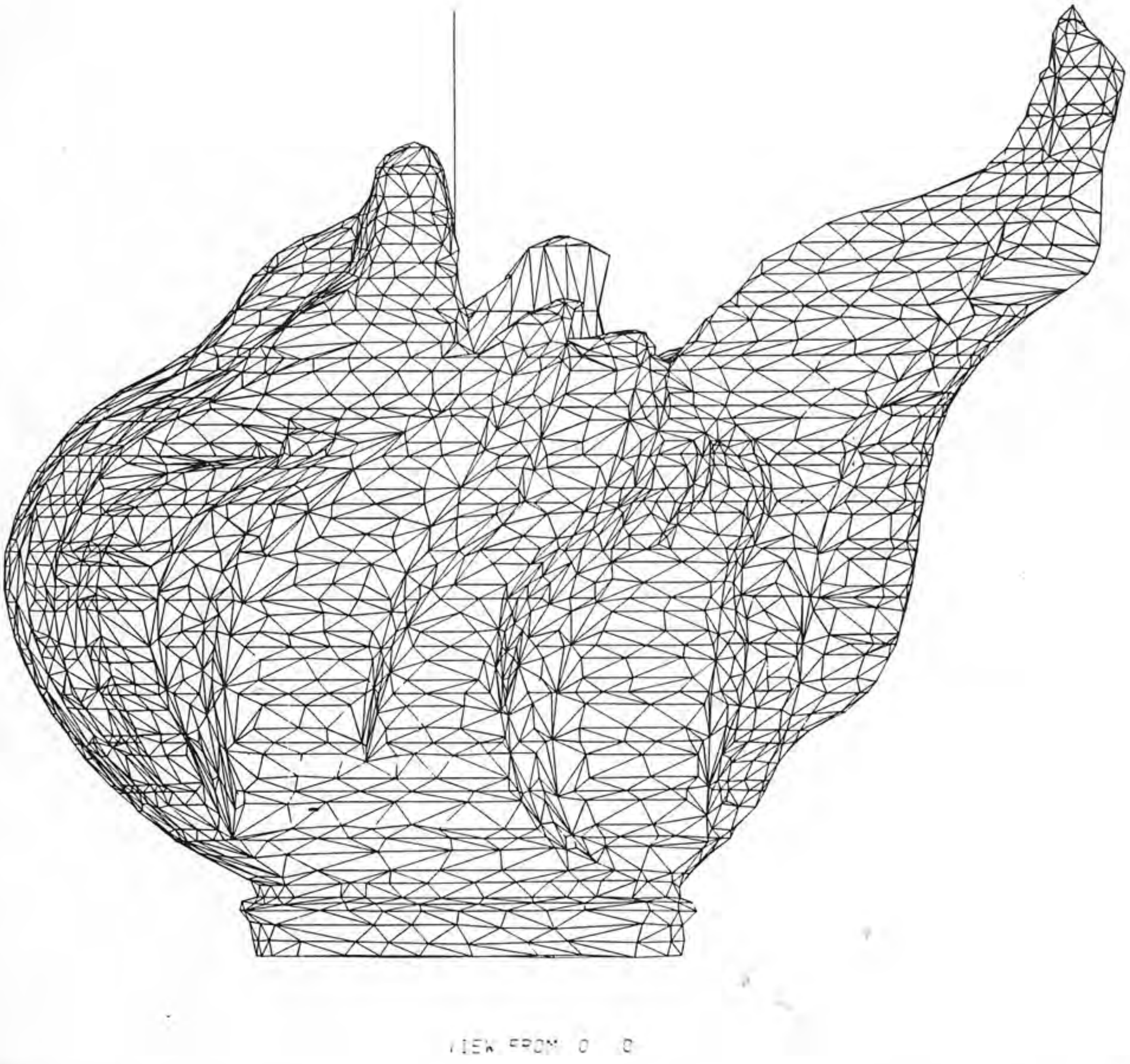
Even though the flame will be illuminated externally for the first time, the body of the Statue has basked under several night-lighting designs since its construction. Yet none has been entirely satisfactory; in the first design, light from the pedestal caused a shadow that obscured the Statue's shoul-



The original flame on the left is described by 15,874 triangles, whereas the model of the new flame, on the right, has 7,320. Although each was generated from 18,000 digitized points, the old flame's detailed glass panels required approximately 46 percent more triangles. Relatively flat surfaces

**FIGURE 6a. Old Flame**

ders and head, and incandescent lamps used in the 1916 effort lacked the brightness and beam control to light the torch from the exterior. The new design, by Howard Brandston, president of Howard Brandston Lighting Design in New York, will be fine-tuned to reveal some of the subtler details. "In our design, we softly light the fort, light the pedestal a bit brighter, and the hem of the skirt even brighter. Then we bring the level of illumination to a crescendo as we move to the top. The brightest lights of all will be at the crown and torch," says Brandston. His ability to achieve this has been enhanced by computer simulation of the Statue and by the positions and brightnesses of specially developed lamps, and by using a mechanical engineering solid modeling system.



allow larger triangles, and tighter curves require smaller triangles. These drawings were generated for the National Parks Service by the Denver Research Institute of the University of Denver.

**FIGURE 6b. New Flame**

In the early stages of the design, before the scaffolding was up, Brandston conducted surveys and lighting tests on-site, from boats, and from roads surrounding the harbor. On considering the light sources, he found none suitable for a green statue—they would either make the figure look too dramatic or too muddy. So he approached General Electric's Lighting Business Group in Cleveland, Ohio, to develop two halide lamps. One would emulate daylight from blue sky, projecting blue-white light to emphasize the folds and shadows of the robe. The other would resemble warmer light from the sun and would highlight and complement the patina.

Testing the complete design out in the field was too difficult and expensive, so Brandston experimented with sections of the Statue on a piecemeal basis. At one point, his team hung gold foil over the torch, evaluated it by day, and then lighted it by night. But there was no way to visualize the effect if all the lights were on, so GE lamp technology manager Gilbert H. Reiling, who developed the halide lamps, proposed simulating the final design using a solid modeler called GEOMOD.® GE's designers were well familiar with the program, and the company had a long-standing business relationship with GEOMOD's creators. Developed by Structural Dynamics Research Corporation (SDRC) in Milford, Ohio, this geometric solid modeling program is one of several modules that comprise a CAE package called I-DEAS® (for Integrated Design Engineering Analysis Software). I-DEAS was written in Fortran and first offered in 1971 by SDRC. Other modules perform finite-element, static, dynamic, and fatigue analyses. GE bought a minority interest in SDRC in 1981, and the two companies formed a joint venture, CAE International, which now markets the package.

The lighting group was experienced in using GEOMOD for less-exotic applications than statues, so it became SDRC's task to create Liberty's solid model geometry. Using four photos of front, back, side views, and architectural sketches of cross sections at 20-foot intervals, Senior Support Engineer Geoffrey Nay, assisted by Keith A. Kowalski, built the visual representation in 200 person-hours. Says Nay, "We blocked out basic shapes using the software to sculpt shapes similar to ones we saw in the photographs. In a kind of iterative process, we manipulated them until they looked appropriate for the shape. So it is very much an abstraction rather than a detailed model of the Statue."

Three of GEOMOD's principal commands were used to sculpt the sculpture's fingers, for example. After drawing a 2-D crescent-shaped representation of a finger's length and width based on one photo, Nay and Kowalski inputted numerical information measured from a photo of another point of view. Using the "extrude" command, the system incorporated this third dimension. Since all of Liberty's fingers curve either around the tablet or the torch, Nay and Kowalski used the "blend" feature to smooth the edges of her bent knuckles. Once the shape was right, they scaled it up proportionately relative to the rest of the Statue. Other commands include "revolve," which paints axially symmetric shapes; "hidden-line removal" to eliminate lines that hamper 3-D visualization; "cutting" or "Boolean" operations that use one object to bore through another; and "skinning," which strings together cross sections. The last two commands were not used in the Statue's case because no sections of the Statue pass through one another. "Skinning" was tried, but was not successful since the 20-foot-interval cross sections contained minimal information resulting in too much guessing in between.

This database was ported to the lighting group, where CAE Applications Project Engineer Steven H. Arshonsky spent another 200 person-hours modifying SDRC's model and inputting the lighting design according to Brandston's specifications. The final database, on a Vax 780, consisted of 8,000 blocks (a block has 512 bytes). Picture files, which are separate, take 12,000 blocks. The final model showed shadows and highlights on the Statue due to the position, aim, intensity (the power), color, and concentration (the width of the beam) of 10 lamps. The actual design calls for 42 lamps, clustered in five bays, to shine on the Statue. The model approximates their effect by aiming two lights per bay at the average of points illuminated by each actual fixture in each actual bay. Arshonsky admits that the difference between the warmer and cooler lamps is somewhat lost unless the amounts of red and blue are exaggerated (see Figure 7).

Nevertheless, Brandston was enthralled with the ability to test his mind's eye on a screen rather than out in the field. It saved countless thousands of dollars, he says, and allowed him to refine his design. "You can change (the aim of a fixture) by 10 degrees here, lower or raise it there," he says. "That doesn't mean that that's what we're going to do (in the end), but it certainly is a help in giving us a starting point. It is really very close. We have a sense of what those angles should be."

Echoing Ammann and Whitney's engineers, Brandston notes both the good and bad potential of computers. The good aspect is that, in the hands of someone skillful, the computer is a shortcut to design. But the problem with most lighting projects, he says, is that "they're not looked at; they're only measured." Those who are not trained to see might rely on computer-generated calculations as if they were the design, instead of thinking of computers as design aids.

## RECORDING THE RESTORATION

Another CAD system, by Intergraph Corporation of Huntsville, Alabama, is being used not as a design tool, but to keep a record of the restoration. Initially, attempts were made by Swanke, Hayden, and Connell to create a database of the entire monument based on information from Ammann and Whitney. But Swanke's Calcomp system at that time could not store more than the Statue's wire-frame drawing of

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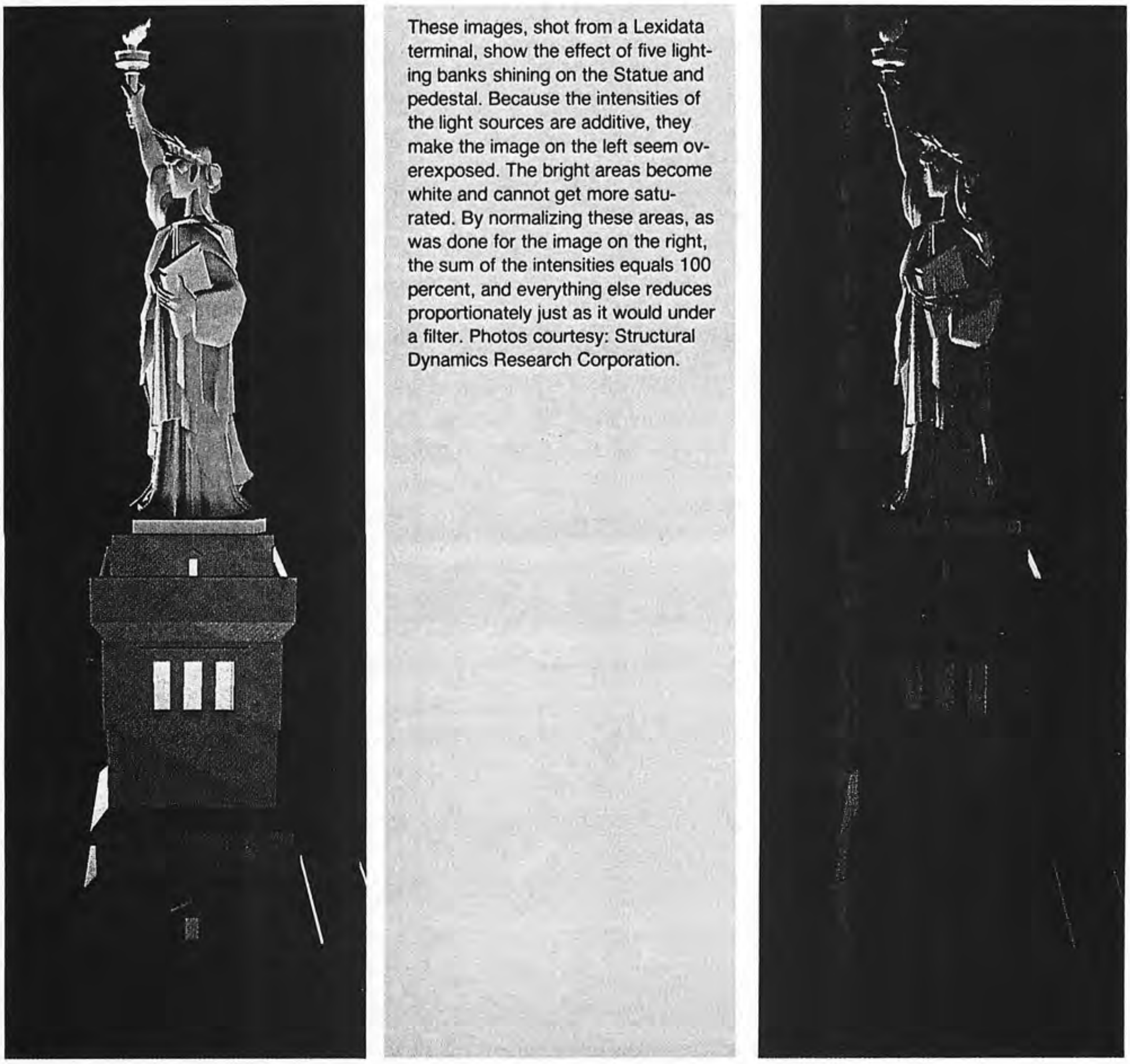

These images, shot from a Lexidata terminal, show the effect of five lighting banks shining on the Statue and pedestal. Because the intensities of the light sources are additive, they make the image on the left seem overexposed. The bright areas become white and cannot get more saturated. By normalizing these areas, as was done for the image on the right, the sum of the intensities equals 100 percent, and everything else reduces proportionately just as it would under a filter. Photos courtesy: Structural Dynamics Research Corporation.

**FIGURE 7. Lighting Liberty**

the finite-element model, so that information was transferred to Burns and Roe. The company's Intergraph system runs on a VAX 1170 and is generally used as an aid in designing large projects like nuclear power plants. When John Tesoro attempted to input the wire frame, he found it too lacking in detail, so instead he manually entered Ammann and Whitney's FEA data and confirmed the geometry of their finite-element model. Then, adding information from field surveys and Swanke's architectural drawings, a 3-D graphics database including details as specific as the rivets and gusset plates was created (see cover, center figure). It now contains a 7000-block 3-D graphics database of the Statue and pedestal. The images generated appear three dimensional because of the hidden-line removal feature. At press time, the project had taken 2500 person-hours, and information continues to be entered.

Unaware that a database of the Statue's skin already existed, Intergraph decided in January 1986 to create a sculptured surface model database of the Statue's skin based on a 1-m-high model (or marquette) of Liberty by Bartoldi that is housed at the Canton Art Institute in Canton, Ohio. Just as DRI did for the flame, they are using Analytic Surveys for photogrammetry, which will be done taking horizontal cross sections every centimeter. The points will be digitized, and then nonuniform rational B-spline boundaries will be used to complete their database. It is expected that Intergraph's file, which will be able to interface with the files on Burns and Roe's system, will contain 10,000 blocks and take 200 person-hours to input. Graphics generated from both Intergraph systems will be on display in a museum housed in the Statue's fort.

Today, many architectural CAD systems are used to demonstrate to clients what can be done. In the case of the Liberty restoration, by keeping a record, CAD could be used to facilitate future restoration efforts and, to some extent, is being used as a marketing and educational tool to show the public how its money has been spent. In addition to the exhibit, the American Society of Civil Engineers has created a slide show of the restoration process with the hope of encouraging engineering students.

## CAN CAD AND CAE TALK?

Four different computer systems were used to assist in Liberty's restoration and made studies possible that otherwise would have been too taxing. Overall, there will never again be a loss of information as occurred with the destruction of the original blueprints at the turn of the century. Yet, because of the difficulty of translating several different digital formats, their utility may be hampered, according to Intergraph's executive manager of product marketing, Robert A. Glasier. But SDRC's director of product planning and support, Wayne McClelland, disagrees. The difficulty is not in translating because IGES (Initial Graphics Exchange Specifications), which was developed by the National Bureau of Standards, enables databases to communicate with and read one another. The problem arises in synchronizing changes between files, says McClelland, for example, if you decide that one of Liberty's fingers is too long, and shorten it in one database, it would not automatically be shortened in another. Glasier also notes problems with updating information. "I am concerned with the maintenance of these databases over time," he says. "Manually generated drawings are hermetically sealed—years later you can still read them. In digital formats, with the changing technology, what are the odds that they will be readable 10 or 20 years from now?" But McClelland says that these objections apply to a single database as well. Tesoro argues that translating is in fact problematic despite 10 years of efforts to make IGES comprehensive. "When you get down to the nitty-gritty, (databases) don't talk to one another very well because, while they talk geometry, they don't talk attributes," he says. So an element's definition can be converted, but IGES is not detailed enough for nongraphic information like a beam's manufacturer, date of delivery, and bill of material data, Tesoro says. In fact, while Stardyne (and also STAAD-III and I-DEAS) can interface with Intergraph, Tesoro simply took three hours to manually input the data generated by Stardyne because he knew the database was very small.

For years, Intergraph and SDRC/CAE International have stressed integrated packages so that these translation complications would not arise, and such systems have been used more by mechanical than civil engineers. Mechanical engineers have been better able to justify the cost because they work on longer term projects than do civil engineers, who have a project-to-project orientation, Glasier explains. As consultants, civil engineers have been less likely to run the risk of buying capital-intensive equipment since it might not be compatible with that of their clients. They are more likely to buy cheaper PC-based systems that are becoming available now, says Glasier.

And how might the CAD/CAM and CAE industries be affected by IBM's entry into the 32-bit workstation market with the RT? Glasier expects Intergraph—a systems seller—to be less threatened than 32-bit workstation suppliers. "The RT is not a technological earthshaker, but people felt that way about the PC. And it's debated as to whether the RISC processor makes things faster in a highly interactive environment," Glasier says. "It may be a significant factor because of who built it." So it remains to be seen how these industries—whose revenues according to Intergraph jumped from less than $250 million to over $4.3 billion in a decade—will continue to grow as new users are attracted to cheaper workstations.

**CR Categories and Subject Descriptors:** I.3.3 **[Computer Graphics]**: Picture/Image Generation—*digitizing and scanning*; I.3.5 **[Computer Graphics]**: Computational Geometry and Object Modeling; I.3.7 **[Computer Graphics]**: Three-Dimensional Graphics and Realism; I.4.1 **[Image Processing]**: Digitization; I.6.3 **[Simulation and Modeling]**: Applications; J.2 **[Computer Applications]**: Physical Sciences and Engineering—*engineering*; J.6 **[Computer Applications]**: Computer-Aided Engineering—*computer-aided design (CAD)*

**General Terms:** Design, Measurement

**Additional Key Words and Phrases:** computer-assisted engineering (CAE), finite-element analysis

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