THE CONSTRUCTION WEEKLY

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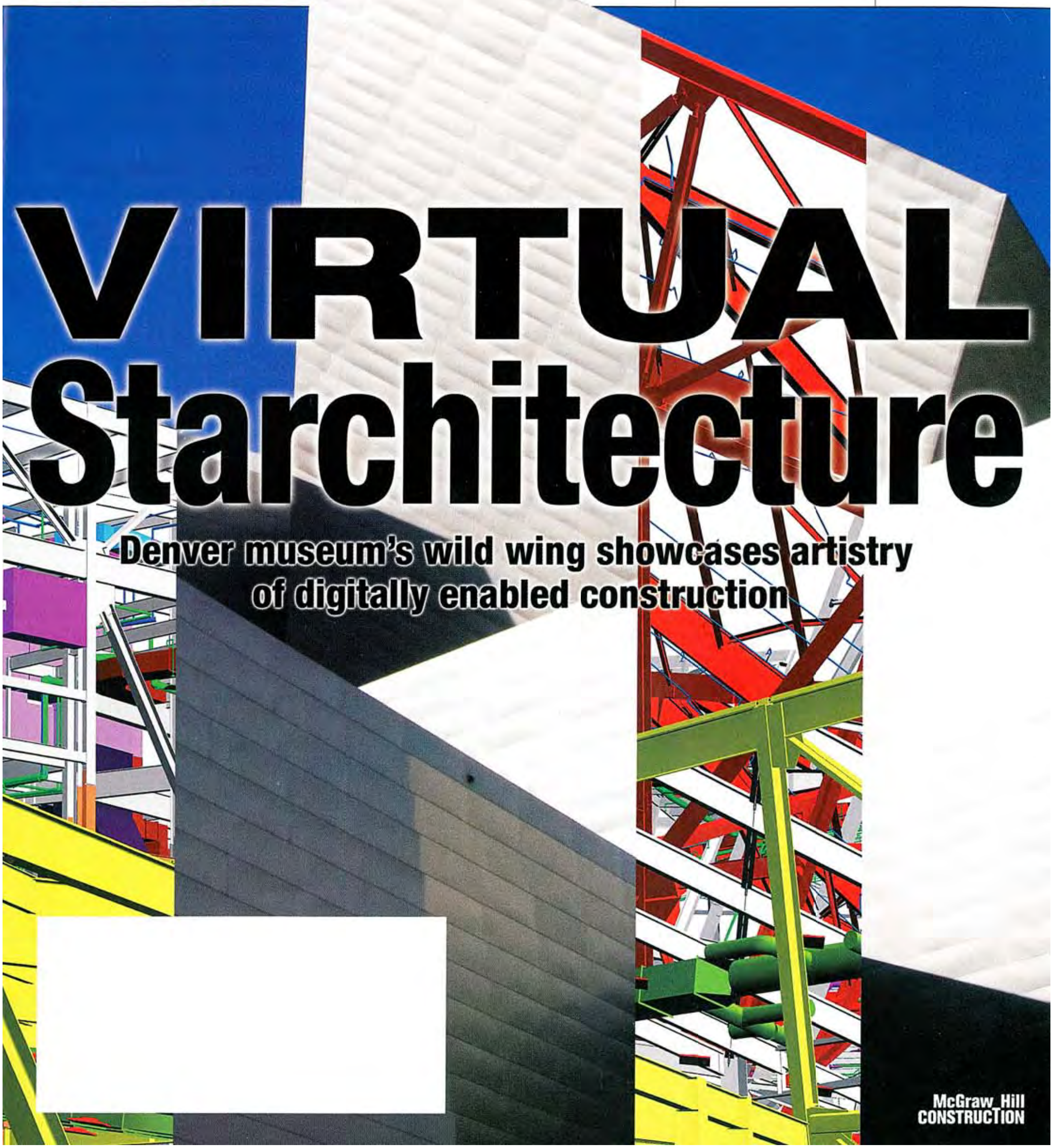

VIRTUAL Starchitecture

Denver museum's wild wing showcases artistry of digitally enabled construction

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By Nadine M. Post in Denver

Sharing High-Tech Tools Creates Rocky Mountain High

Denver's unfathomable form brought in on time and on budget

Another starchitect. Another unfathomable form. Another potential money sinkhole. On the surface, architect Daniel Libeskind's Denver Art Museum addition, a 146,000-sq-ft titanium-skinned "geode," had all the ingredients for disaster. Except in the eyes of M.A. Mortenson Co., which had recently cut its teeth—or been through the meat grinder—on the monarch of all description-defying U.S. architectural icons, Los Angeles' Walt Disney Concert Hall. Instead of running scared, Mortenson salivated at the prospect of turning the agonies of Disney into the ecstacy of DAM. It landed the $70-million job in August 2001.

By all reports, Mortenson has succeeded at DAM, despite the job's geometric complexity. "It's been a great project," says Lewis I. Sharp, the museum's director.

"Having just come off Disney was a big plus for Mortenson," he says. "Rather than being frightened by the new technology, Mortenson knew it could be the means to pull this off."

Sharp reports that, as first contracted with the city, DAM is "on budget and on schedule." Substantial completion is set for August. Opening day is Oct. 7.

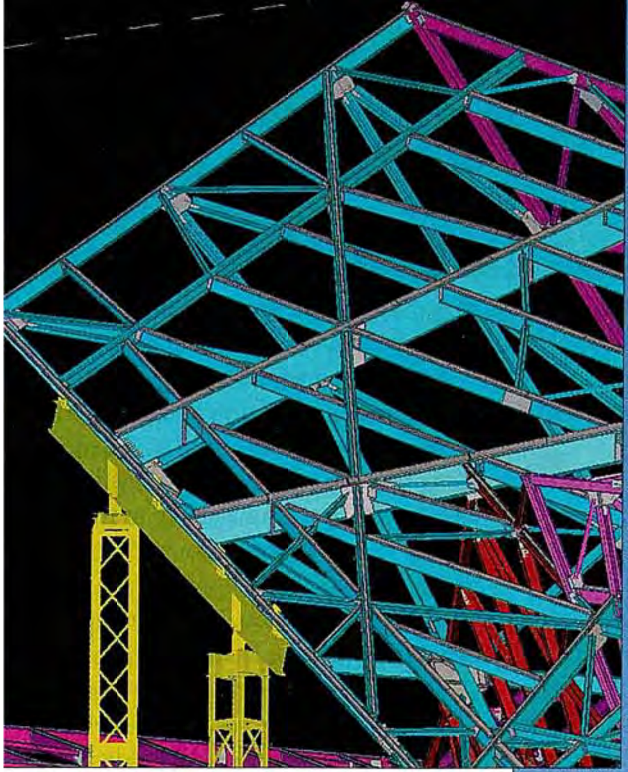
Though the city owns the building, the private museum, under a contract to the city, is really the client. DAM's expansion, including Libeskind's Frederic C. Hamilton Building, is financed by $62.5 million in city bonds and $28 million in private funds.

Inspired by the Rocky Mountains while flying into Denver for his job interview, Libeskind started sketching the building on the back of his boarding pass. The sculptural addition, likened to a piece of origami for its many folds, angles and prows, will house special exhibits and galleries of modern and contemporary art, architecture, design and graphics.

The five-level form is a series of spaces defined by nonorthogonal planar walls. There is little repetition and no typical floor.

DAM was the first public project in Denver to take advantage of a change in

▲ **Spirit of Collaboration.** Architect Libeskind (left), client Sharp support cooperation, not confrontation, on tough job.



Virtual Steel Work. 3D digital model for leaning structure included falsework, temporary steel, rigging frames and crane locations.

city rules, pushed by contractors and approved by the City Council in May 2001, that allows alternative project delivery systems, including construction management-general contracting, design-build and program management.

Studio Daniel Libeskind, New York City, was selected in July 2000. Libeskind then picked the local Davis Partnership as its joint-venture partner. Mortenson is the CM-GC, under a guaranteed-maximum-price contract.

The original construction schedule called for a 2004 completion. But among other things, an expanded scope and resequencing of related projects, including a parking structure, delayed the addition.

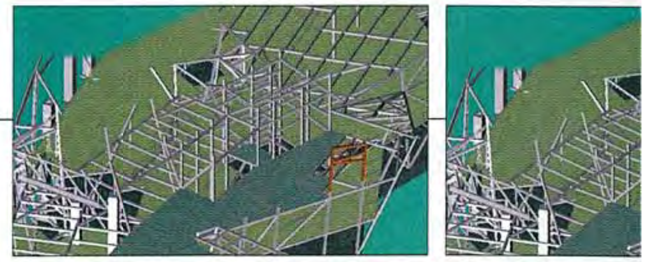
The role of CM and the contract award two years before groundbreaking gave Mortenson leave to form a strategy that included a preconstruction phase—started in February 2002—and computer-aided communication, coordination and construction. Mortenson pushed the sharing of three-dimensional (3D) electronic models between design and construction teams. Trust has replaced early suspicion, say sources. Collaboration, not confrontation is the job's mantra. A "spirit of resolving problems" was set early in the game by the client, says Tim Walsh, the vice president in charge of the job in Mortenson's Denver office.

"The process was different from the traditional linear process," says J.R. Barker, project engineer with Structural Consultants Inc., the job's Denver-based steel-connection designer. "Once a week, Mortenson brought the entire design and construction team together and let them influence each other's lives," he says. "Decisions were based on what was best for the project, not for an individual."

The steel construction team agrees. "Everybody was scared to death of this project going in, but preplanning made things work," says Rocky Turner, president of Loveland, Colo.-based LPR Construction Co., the steel erector.

Cooperation is one of the main things that made this job different, adds Mark

▲ **Teamwork.** Mortenson, with leader Walsh (right), relied on preconstruction phase to work on constructibility issues with design team.



Zimmerman, president of local steel subcontractor, Zimmerman Metals Inc.

"It proved to be a fantastic job for us," says Hugh Dobbie, president of steel detailer Dowco Consultants Ltd., Burnaby, British Columbia.

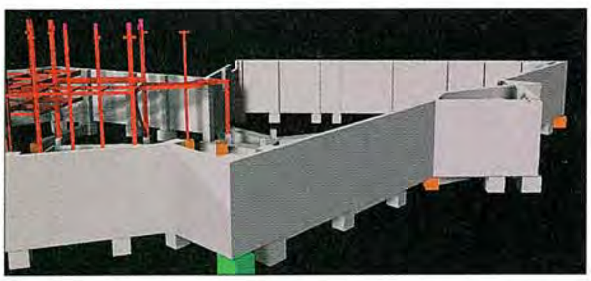
Even the architect gets stroked. "Libeskind's energy and passion inspired the team," says Walsh. Unlike some starchitects, "he goes out and mixes it up with the workers."

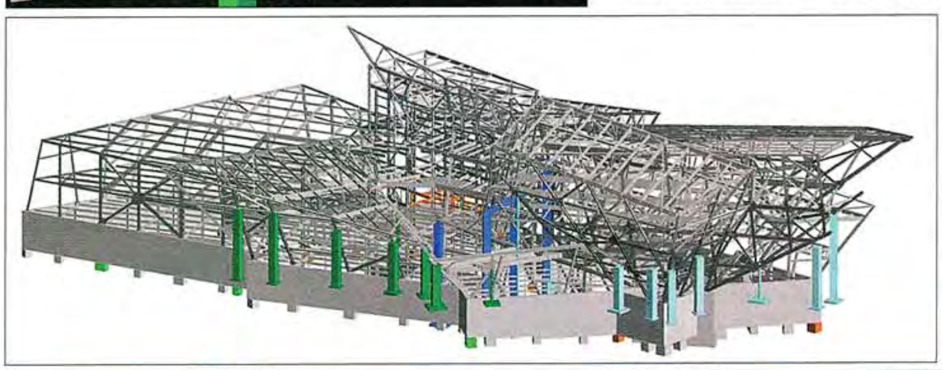
Libeskind, in turn, calls the workers, "heroes." Though not computer-literate himself, he values technology. "I could have designed the museum without computers but it could never have been built on time and on budget," he says.

Blurred lines between design and construction phases and high-tech aids aside, 2D construction documents still rule. The design consultants' 3D design models were given to the contractor for use without warranty, as a geometric control. This was done in parallel with 2D documents. "It was a big risk for the designers," says Shannon Rogers, Mortenson's model manager.

Though techno-soothsayers predict the coming of a single master digital model, for this job there was still one on the design side and one on the construction side. The architect and the CM each needed a full-time "model keeper." One of the tasks was to coordinate with each other to keep the models in sync.

Mortenson's 3D digital model, built from design-team models, included steel, concrete, ductwork, piping, conduit, fire sprinklers, scaffolds, temporary steel, falsework, crane locations, even rigging frames for steel lifts. It was used during construction for development and coordination of shop drawings, generated in 2D for field use. Mortenson's 4D model, which added the element of time, was used for visualization and construction sequencing—for virtual prebuilding as a way to educate subs and anticipate and eliminate field problems.





Success hinged on getting the structural engineer's digital wire-frame model to the steel detailer to create a solid model. At first, that did not sit well with the architect. "I don't think any of us [on the design team] going in knew we were going down that road—giving the contractor our 3D models," says Maria Cole, Davis's associate on DAM.

Believer

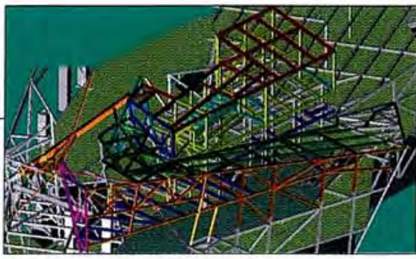
Skeptical at first, Davis is now a believer in sharing. Having the contractor on board early, studying the architect's 3D model and physical scale models, and offering suggestions on constructibility, "allows you to imagine spaces beyond what we're capable of in 2D," Cole says.

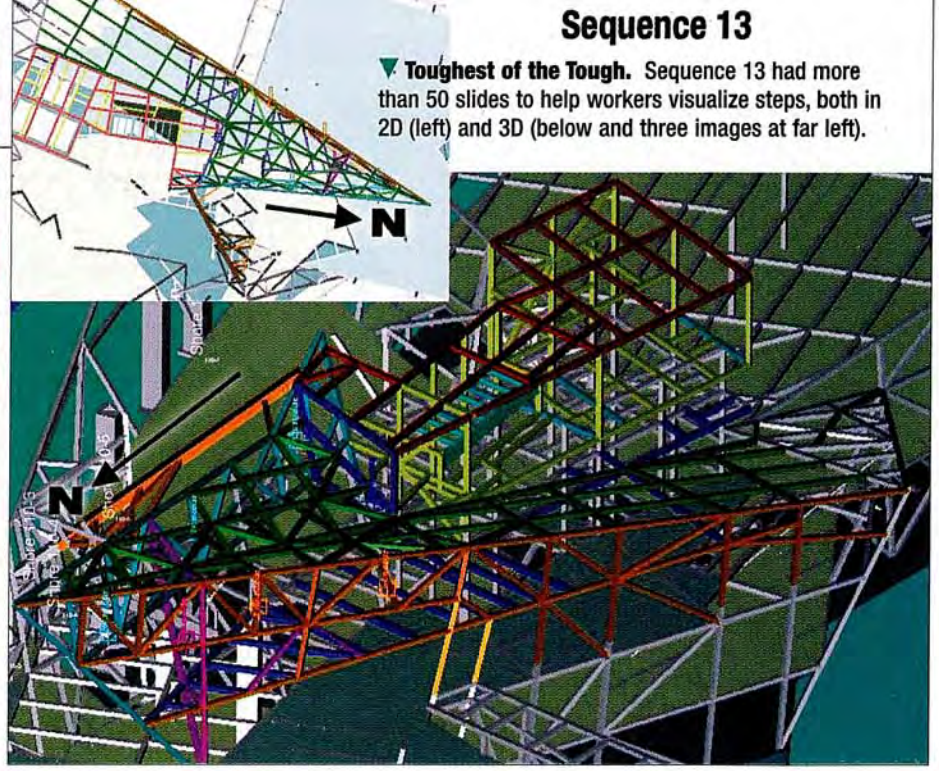
Sharing digital models still "puts challenges on design," says the architect. Certain things, lost in translation, need to be redrawn. Working with the model is cumbersome and time-consuming because it is information-intensive.

For the rest of the consultants, the process differed from the norm in that full 3D models were provided by the architect and the contractual deliverable included 3D versions of the design, says Erin McConahey, an associate principal in Arup's Los Angeles office.

Arup, also the mechanical structural consultant, extracted valuable informa-

▼ **In Time.** 4D solid model, which even included concrete, "prebuilt" the job from bottom to top.





Sequence 13

▼ **Toughest of the Tough.** Sequence 13 had more than 50 slides to help workers visualize steps, both in 2D (left) and 3D (below and three images at far left).

tion from the architect's volumetric digital models, including edge and top of flange and centerline of steel. Thanks to 3D, the firm was able to coordinate the frame, ductwork and piping, minimizing coordination-related requests for information. Every beam penetration was factory-cut and its location known during the design phase, says McConahey.

On the business side, Mortenson learned on Disney—the hard way—that to make the process work it is imperative to develop specific, detailed subcontractor contract language on generation and hand-off of electronic data. But all the models in the world won't help if people in the field aren't familiar with the system. "It's a learning process," says Walsh.

Biggest Bear

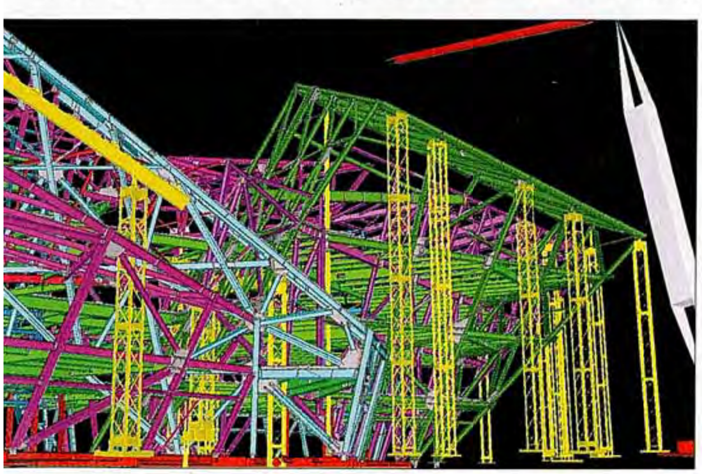
The steel frame was the biggest bear on the project. Mortenson had a process where issues were identified in a predetailing request and resolved through Web meetings and other correspondence. That, combined with use of the 3D digital model, prevented 1,200 "collisions" of steel elements and sped steel erection to the finish line three months early. Mortenson then gave nearly $400,000 back to the owner.

The frame consists of mostly sloping columns with diagonal braces to resist lateral loads. There are about 40 different slopes. Perimeter walls lean outward from the horizontal 40° to 84°. The only vertical elements other than some interior columns are elevator shafts.

The inclined walls generate permanent lateral loads throughout the floor system, which equate to similar design loads in a seismic zone, says Atila Zekioglu, an Arup principal. Horizontal beams, strategically placed, counteract instability of the inclines by acting like a tension tie.

Floor plates and individual roof planes are used as diaphragms to distribute lateral loads, with extensive use of drag-strut connections to distribute concentrated horizontal forces into the composite concrete-on-metal-deck diaphragm and back into perimeter walls and interior braced planes. Additional deck bracing and steel plates are under the deck in locations of high plane shear forces.

Inclined walls are supported at ground level on vertical planes, where shear forces are transferred to reinforced concrete walls. Interior walls are supported on steel bracing in the vertical plane which in turn takes shear forces to caisson foundations.



Precambering was required on some joints in the frame's vertical and horizontal directions to accommodate up to 3 in. of deflection when shoring was removed.

Because of the unstable geometry, the erection sequence took precedence during preconstruction meetings. Sources say that when LPR spoke, everyone—even the structural engineer—listened.

LPR created an 18-sequence erection plan for the 2,740 tons of steel. The plan, which included shoring, rigging design and crane reach drawings, was detailed in 3D, including step-by-step sequencing. Use of the 3D model in the office and the field was "paramount to the project's success," says Curtis Mayes, LPR's director of preconstruction and engineering.

One of the toughest sequences was the "erratic" 13th, under the roofline. LPR could not figure out a reasonable way to shore the sequence, so it had to figure out how to stabilize members temporarily until other pieces were in place. Mayes used more than 50 3D slides to teach the sequence to the team.

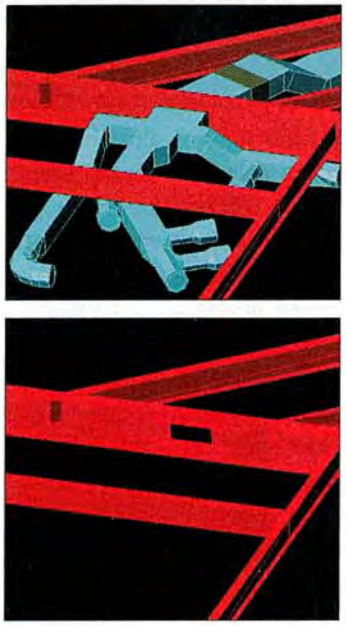
Coordinate geometry made alignment difficult. X-Y-Z survey coordinates were incorporated into the 3D model. All primary columns, sloping and vertical, were detailed and fabricated with shop-drilled control holes designed to hold a surveyor's prism at a theoretical spot in space. A second survey location was fabricated into the member using a center-punch mark to locate and install a reflective target on the surface of the column. High-tech transits were programmed with the coordinates.

Zimmerman fabricated oversized bolt holes to allow the erector to use full-size

Hollow Geode. No two floors of the five-level museum have the same footprint.

fit-up pins. This was key to the fit-up, allowing easy field adjustment for imperfections in plate alignment, says LPR.

During design, Arup checked the structure and the mechanical service for clashes. The challenge was to place ductwork in the walls to minimize shaft space. The museum also wanted to minimize water piping in the art galleries. That meant "home-running" ductwork to central mechanical rooms containing air handlers. That was difficult because risers sloped every which way.



▲ **Coordinated.** Engineer ordered beam penetrations for duct runs .

Arup laid out every duct run in 3D. When a run hit a steel member, a beam penetration was indicated on shop drawings and cut out during fabrication. Arup has already used 3D mechanical layouts on three other projects. Mostly it is used for mechanical rooms and tight ceiling-void pinch-points, says McConahey.

For the Loveland, Colo., office of U.S. Engineering Co., the mechanical subcontractor with a $6.3-million contract, the interface with other subs during Mortenson's preconstruction phase was novel and helpful, as was the 3D solid model.

The job's many bends were much easier to visualize in 3D. "We used more offsets than we ever could have imagined and more support steel to support plumbing," says Daniel Kern, U.S. Engineering's project manager.

On the air side, it was also difficult to follow the planes. "Nothing was square so we couldn't lay out normally," he says.

U.S. Engineering got involved in June 2003, replacing the original mechanical sub that had financial woes. "We had to jump in quickly on the 3D portion," says Kern.

It was a learning process. Despite all the efforts, Kern says there were several collisions on each floor.

The electrical conduit followed. To lay out systems, Dynalectric Co. of Colorado, which has a $5.4-million contract, coordinated with mechanical and sprinkler contractors through Mortenson. "The coordination was incredibly critical to locate their equipment, our equipment and how the systems run," says Craig W. Clark, president of the Lakewood, Colo.-based firm. "I wouldn't say it was perfect but it worked quite well," he adds.

Clark says that with so many wall inclines, getting access to the top of each for lighting fixtures was difficult. Workers had to use mechanical lifts with arms, instead of ladders. The installation was about 40% more labor-intensive compared to a typical building. "It's an OK job. I wouldn't say we got rich," he says.

Mortenson is already basking in the glow of its accomplishment, especially compared with Disney, although the concert hall was twice as big and in a high seismic zone. But Disney had 10,000 requests for information; DAM has 1,300. Disney, which opened in late 2003, has an outstanding claim, rumored close to settlement, of about $40 million. DAM has no claims pending or expected.

That said, without Disney there may not have been a DAM for Mortenson. ■

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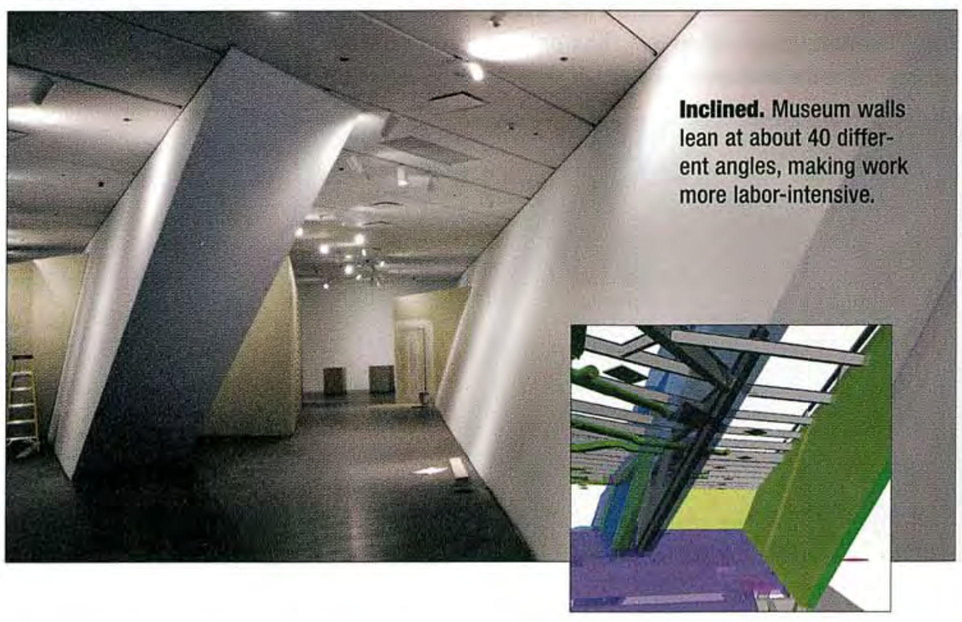

Inclined. Museum walls lean at about 40 different angles, making work more labor-intensive.