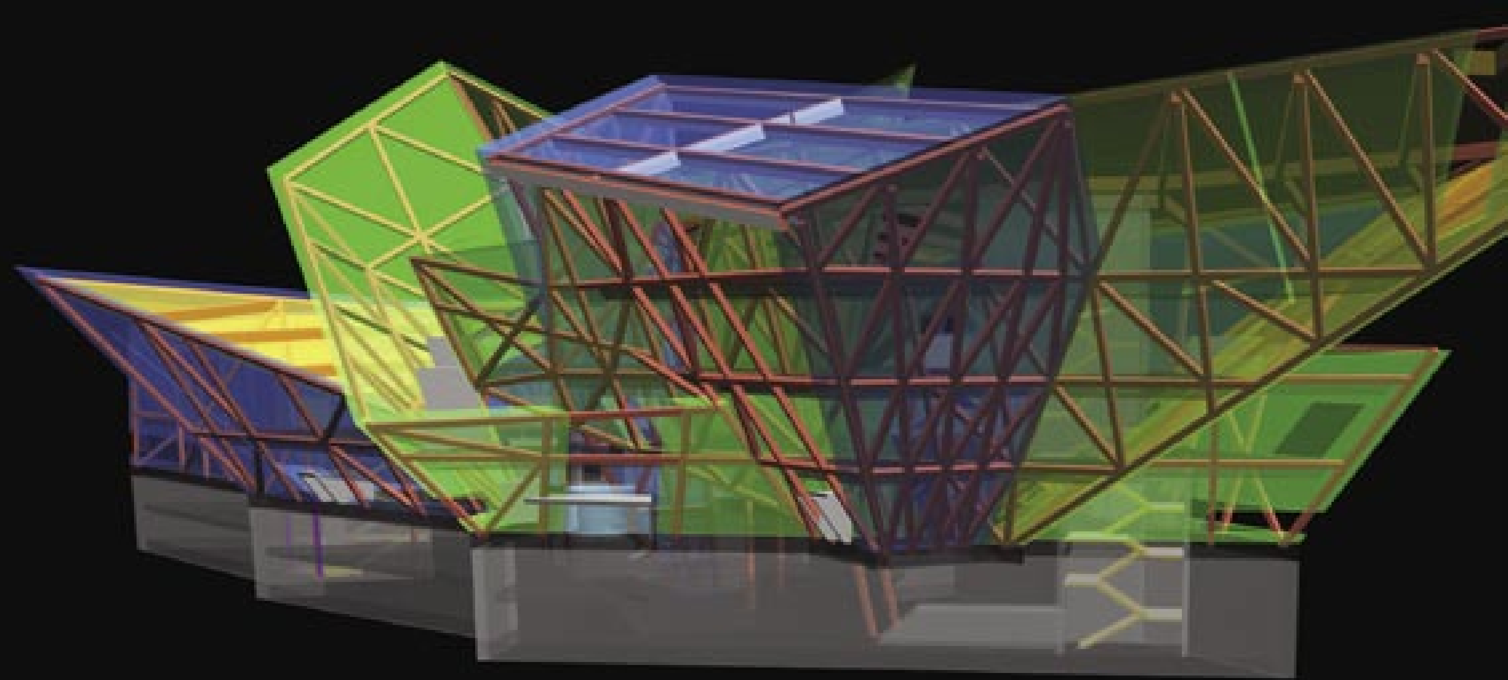

A New Slant

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Complex geometry made 3D modeling and structural steel musts for the skeleton of the Denver Art Museum's recent expansion.

The Denver Art Museum recently completed a dramatic expansion project with the addition of the new Frederic C. Hamilton Building. This new wing, completed last October, adds about 50% more exhibit space for the museum's 60,000-piece permanent collection, a 280-seat auditorium, display areas for traveling exhibitions, and an art storage area.

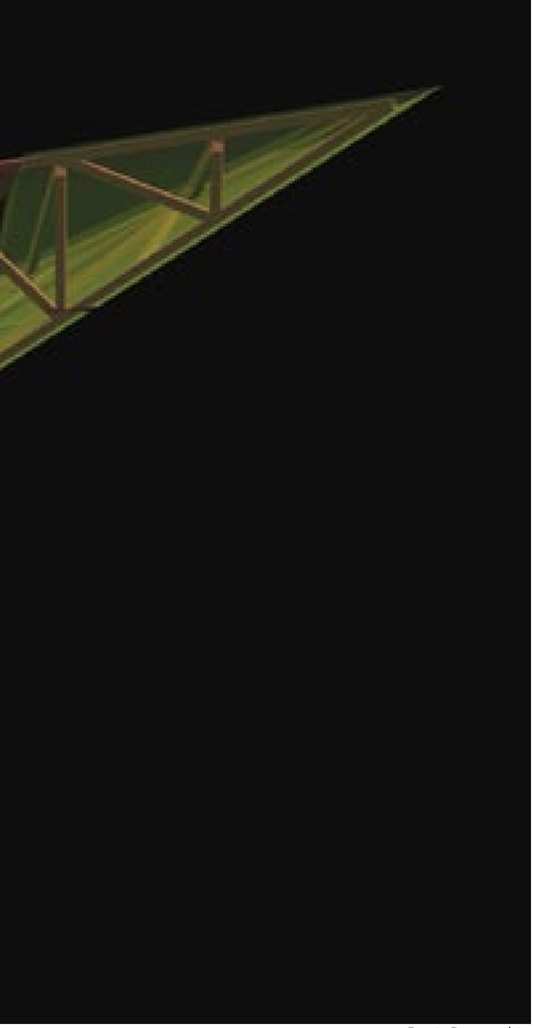
The original seven-story museum building, designed by Gio Ponti and James Sudler, opened in 1971 and fronts Denver's Civic Center Park near the Colorado State Capitol and the Denver City and County building. The Hamilton building, which serves as the new grand entrance into the art museum complex, is located south of the original museum across 13th Avenue. A 100-ft-long glass and steel footbridge connects the second floor of the expansion to the two original buildings.

Studio Daniel Libeskind, in a joint venture with Denver-based Davis Partnership, was selected to design the new wing in the summer of 2000, as the result of an international design competition. The resulting titanium-clad structure, a complex, angular, jagged form, was inspired by views of the Rocky Mountains and presented unique challenges for the design team. The structural design process began with a close collaboration between structural engineers at Arup and the architects to develop a viable structural scheme for the complex form. The City of Denver also chose to contract with M.A. Mortenson Company early in the design stage to provide guidance on construction issues related to the design. A structural steel "preconstruction team" was then selected to participate early in the design of the structure.

3D Modeling

It was clear from the start that a building as complex as the new Hamilton wing could not be completed using conventional 2D design and documentation methods, so the whole design team was required to produce 3D models of their work, which were coordinated into a single model. This holistic working model was manipulated throughout the design and construction phase, with the contractor producing complete and exact 3D detailing and erection models of the structure. The model was created and maintained by the architect with a general-purpose 3D solid and surface modeling software called Form-Z, used primarily as a geometry and visualization tool. By importing all disciplines' work into the master model, the architect was able to achieve 3D coordination in a way that would otherwise not have been possible.

For structural design, the centerline planes of each wall were defined by the architect, and then a 3D wireframe model was developed and exported to structural analysis packages. Once the structural members had been designed, these shapes were manually "hung" onto the 3D wireframe model so that the actual member sizes, together with an allowance for fireproofing, could be coordinated with other disciplines. This 3D coordination was



Davis Partnership

particularly important for the mechanical ductwork, as it was also routed through the inclined walls and closely integrated with the structure.

The project's documentation consisted of 2D drawings together with the 3D model. The structural geometry was defined by a series of approximately 700 node points in 3D space, which were also identified on the 2D plans and elevations, so that the geometry, member sizes, and connections could be fully defined.

Structural Design

Due to the severely inclined walls and large cantilevers—including the "prow" of the building, which extends out over 13th Avenue—it was decided early on that the dead weight of the building would need to be minimized, thus making structural steel the material of choice.

The walls of the building generally lean outwards, so to some extent, the lateral loads balance each other. Thus the floors act as tension ties for the inclined walls, with the steel beams helping with

Jeff Goldberg/Esto, Courtesy of the Denver Art Museum

PROJECT FACTS

Area 146,000 sq. ft	Total Steel Weight 2,750 tons
Primary Steel Pieces 3,100	Bolts 50,000
Total Steel Pieces 16,500	Field and Shop Welds 28,500 lb

Column-free spaces inside the building led to the placement of large amounts of structural steel inside the titanium-clad inclined exterior walls.

Jeff Wells. Courtesy of the Denver Art Museum

tension and compression. However, where these forces are not balanced, they must be taken to ground through the building's lateral stability system. This requirement, together with the architect's desire for dramatic column-free spaces inside the building, lead to the decision to place as much of the structure as possible within the inclined walls.

The floor system consists of steel with a composite floor deck. The design of the floor system was complicated by the forces of the inclined structural walls, which create very significant in-plane forces under dead load. To deal with these forces, additional reinforcement was required within the concrete floor slabs. In areas of particularly high stress, the metal deck was replaced with a ½-in. steel plate welded directly to the beams. Similarly, a substantial amount of steel diagonal bracing in the roof plane was required to supplement the roof framing in areas where concrete diaphragms were not an option.

The main analysis of the structure was carried out in SAP2000 and eventually developed into a very detailed model containing every member in the building, including floor diaphragms. Several additional models were also required for the complex stair framing, which winds its way around the atrium space. The composite floor framing was modeled in RAM Steel, as the primary floor beams also carry significant axial loads from the inclined walls. The results of the global SAP2000 and RAM Steel analyses were combined into a spreadsheet to design these members.

The interaction of the steel-framed structure with the concrete floor diaphragms necessitated the inclusion of the effects of cracking, creep, and shrinkage of the concrete. This was accomplished by running several analysis models with a range of concrete stiffnesses and ensuring every member design was adequate for the forces from each of the models.

Connection Design

The design of the connections presented a particular challenge, with some connections requiring the joining of up to 10 structural members in three different planes. In addition, where the members in the walls also support the floors, they were generally rotated to be in a web vertical plane for bending efficiency, thus further complicating the connection design.

For the first few months, the preconstruction team debated erection concepts, various connection designs, orientation of members, and edge conditions. Eventually, the final connection design and detailing commenced. Input from the detailer and the fabricator was paramount throughout the entire process in order to assure that the details being drawn were not only possible to fabricate, but also as economical as practical for such an extreme structure. In many cases there were several interactive rounds of 3D details and connection designs going back and forth between Arup engineers, the connection designer, fabricator, and detailer until the final connection was solidified for a single condition.

At the request of the fabricator, the connection plans were revised to use bolted connections in the field wherever possible, except at the column splices. Eventually, a "structural claw angle"-type connection was developed for most brace members. A very unusual connection for the rotated beams in the walls was developed, using end plates in combination with double angles to connect to the massive inclined gusset plates.

In a project of this type, virtually every connection is unique, and there is no such thing as a "typical" detail. To address this problem the contractor initiated a predetailing request system, which clarified geometry connection design and fabrication concepts for every connection in the building prior to the start of actual connection detailing. The final connection design was then performed by Structural Consultants, Inc. of Denver, who designed each connection individually, eliminating wasted fabrication costs caused by conservative "grouping of the connections." Calculations were then submitted to Arup for review.

Substructure Foundations

The foundation system is typical for the Denver area, consisting of individual drilled piers with pier caps. Load-carrying capacity of the piers is developed from the bearing of the piers into the rock, plus the skin friction developed from the portion embedded into the very hard shale bedrock. All exterior bracing walls are supported on vertical planes, where they intersect the first floor (at grade). The building shear for the perimeter walls is transferred to the basement retaining walls to take loads to the foundation.

Construction

The preconstruction team met with Arup early in the design process to gain an understanding of the structural design concepts for the building and to start multiple dialogues concerning connections, interaction of steel and concrete, design concepts for pre-camber of the structure, shoring methods, building deflections, and interaction with construction means and methods.

The complex, leaning geometry results in several areas of the building deflecting significantly. For example, the tip of the structure, which extends out over 13th Avenue, deflects approximately 4 in. under dead load, and consequently some of the floors that it supports also deflect considerably. The two primary concerns in terms of deflection were levelness of floors and flatness of walls, whereas matching the exact geometry of such an irregular structure was a lesser concern. Early discussions between the engineers, architect, and owner resulted in an understanding of the deflection issues and realistic tolerances, which only required a few of the nodes in the building to be set in a pre-cambered position. This was accounted for in detailing and construction by simply setting the required nodes higher than the intended final geometry.

In a structure where the dead loads impose forces on the diaphragms and lateral load system, the construction sequence was critical. The timing of shoring removal relative to the placement of concrete slabs had a significant effect on the final stresses in the structure. To address this, the steel erector developed construction and shoring sequences in a 3D CAD model so that the intended construction sequence could be evaluated. Arup shared their SAP 2000 structural model with the steel erector, LPR Construction Co. LPR engineers then went to work dissecting the model and breaking it up into multiple stages of construction. Load cases included loads from wet concrete slab pours, cured concrete slabs, and partially erected portions of the structure, as well as various stages of shore removal. It became apparent that proper positioning of the shores was critical to assure that overstress conditions would not occur in the building throughout the multiple construction stages.

Given the complex geometry of the structure, conventional alignment techniques were not an option. A structural steel alignment plan was developed by the preconstruction team, that required incorporation of XYZ survey coordinates into the 3D Xsteel detailing model. All the primary columns (sloping and vertical) were then detailed and fabricated with shop-drilled "alignment control holes" designed to hold a surveyor's prism at a theoretical point in space. Spreadsheets including the XYZ survey coordinates were electronically transmitted from the detailer to the steel erector in the field, then into total stations to accurately determine the position and alignment of individual members.

The design and detailing of the shoring systems for the project also comprised an interactive process. In many cases the false-work shores had to be literally laced through the structure below to support upper portions of the building. The steel erector precisely modeled all 50 of the unique shores for the project using 3D CAD. These CAD models were sent electronically to the detailer to incorporate with the Xsteel structural model. Finally, the interfaces between the shores and the actual structure were developed through collaboration between the steel erector and the detailer.

Prior to the start of steel erection for each area, extremely detailed 3D erection procedures were developed and provided to the field, resulting in clarity that could not be accomplished with 2D illustrations or mere words. Xsteel viewers were utilized at the jobsite on a daily basis to help visualize the connections and scope of the work, clarify the erection procedures, and plan the daily operations. The final erection procedures were meticulously followed onsite with very few problems, and the structure was completed some three months ahead of schedule. **MSC**

Atila Zekioglu is the principal in charge of structural engineering and Edwin Shlemon is associate principal and lead structural engineer, both for Arup's Los Angeles office. Matt Jackson is a senior engineer with Arup's New York office, and Curtis Mayes is a director of pre-construction and engineering at LPR Construction Co.

The Denver Art Museum's Frederic C. Hamilton building is the winner of a 2007 AISC Presidential Award of Excellence in Engineering. This and other AISC IDEAS[2] award-winning projects will be highlighted in the May issue of *MSC*.

Owner
The City of Denver and the Denver Art Museum

Lead Architect
Studio Daniel Libeskind, New York

Executive Architect
Davis Partnership, Inc., Denver, Colo.

Structural Engineer of Record
Arup, Los Angeles

General Contractor
M.A. Mortenson Company, Denver

Fabricator
Zimmerman Metals, Inc., Denver (AISC member)

Erector
LPR Construction Co., Loveland, Colo. (AISC member)

Connection Design Engineer
Structural Consultants, Inc. - SCI, Denver (AISC member)

3D Modeler and Steel Detailer
(above ground level)
Dowco Consultants Ltd., Burnaby, B.C., Canada (AISC member)