

## Denver Art Museum

*The Denver Art Museum's new addition – the Frederic C. Hamilton building – won a Presidential Award of Excellence in the American Institute of Steel Construction's 2007 Innovative Design in Engineering and Architecture with Structural Steel (IDEAS<sup>2</sup>) awards program. The award recognizes outstanding achievement in structural engineering. Visit [www.aisc.org/mscdam](http://www.aisc.org/mscdam).*

The sharp angles and complex geometry of the Denver Art Museum's Frederic C. Hamilton building emulate the jagged peaks of the surrounding Rocky Mountains. The addition more than doubles the museum's size, creating a dramatic new gateway into the museum's art collection. Sheathed in 230,000 square feet of titanium shingles, the building's

*Sharp angles characterize the Hamilton building's complex geometry. Photo by Jeff Wells. Courtesy of the Denver Art Museum.*

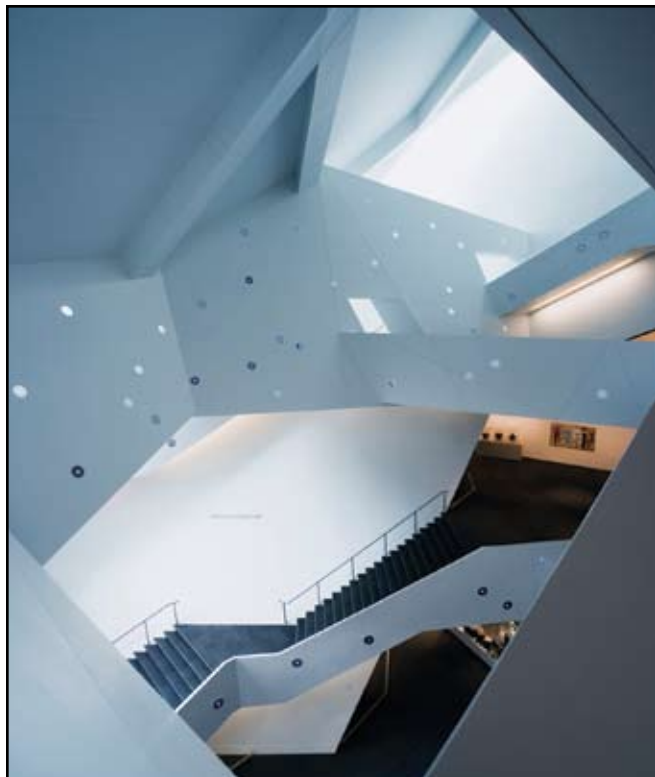
exterior skin shields from view a work of art in its own right; the building's structural steel skeleton. The 2,740-ton steel superstructure is an interwoven cluster of leaning braced frames and trusses. More than 3,100 pieces of steel are contained by 20 sloping planes that define the structure. A 194-foot prow extends out 167 feet over and 100 feet above the avenue below. None of the planes are parallel or perpendicular to one another.

The structure is testament to the power of integrated teamwork and 3-D Building Information Modeling (BIM), through which the design and construction of the building was made practical. 3-D modeling software (SAP2000, Tekla Structures) and BIM were keys to understanding the spatial relationships and detecting conflicts prior to construction. This approach enabled "virtual construction" before the first workers arrived on site and before the complex components were fabricated.

The architect used Form-Z to create a coordination model that allowed 3-D coordination of all disciplines. After the planes of each wall were defined, a 3-D wireframe model was developed, and exported to structural analysis packages. Once the structural members

were designed, these shapes were manually hung onto the 3-D wireframe model, so that the actual member sizes could be coordinated with other disciplines. The geometry and visualization tool was particularly important for the mechanical subcontractors who were routing ductwork through the inclined walls. Computerized design information was fed to automated fabrication and machining equipment to ensure proper fit-up in the field.

A desire for dramatic column-free exhibit space dictated that the structure be self supporting within the inclined walls, and did not allow for a vertical gravity system. The massive structural steel frames and trusses hidden within the walls shared the combined task of supporting the weight of the cantilevered overhangs while also resisting the lateral loads for wind, earthquake and additional gravity loads generated by the unusual geometry. Many of the opposing exterior walls lean away from the center of the building and tend to balance each other. The lateral loads that do exist as a result of the dramatic design were taken to the ground by the sloping columns and braces, resulting in substantial forces resisted through anchorages to the floor slabs, basement walls and foundations. The tension, compression and shear loads resisted within the floor system had to be resolved with the inclined braced frame loads, adding another level of complexity to the connection designs. Additional reinforcement and drag struts were required in the concrete floor slabs, and steel diagonal bracing was added throughout the many roof planes to manage the unusual lateral loads within the structure.



*Integrated Building Information Modeling made the project practical. Photo by Jeff Goldberg/Esto. Courtesy of the Denver Art Museum.*



*None of the building's planes are parallel or perpendicular. Photo by Jeff Goldberg/Esto. Courtesy of the Denver Art Museum.*

The wireframe was loaded into Tekla Structures to refine and reshape the model into an exact virtual replica of the entire structure, including every structural member, plate, bolt and weld. Nearly two months was dedicated to detailing the connections specifically to ensure an accurate advance bill of materials. Scores of connection points had

as many as nine members from multiple planes converging to a single point. To handle all loads and solve connectivity issues, the team fabricated columns with massive clusters of gusset plates designed to efficiently receive the field bolted beams, braces and struts. Structural bolt holes were oversized in all plies, allowing for the use of full-size fit-up pins during erection, which provided greater flexibility during assembly.

In order to analyze the complex structure, steel assembly

was separated into 18 distinct construction sequences. A 3-D CAD model established precisely where shores would be needed to support the massive cantilevers and overhangs during construction.

Multiple structural members were assembled on the ground, forming a single module, then hoisted in one lift. The most complex module was comprised of 28 individual members. Custom rigging was engineered for each module to suspend it at its final slope and tilt, allowing for safe and efficient connection to the emerging structure, while also reducing potential safety hazards, accelerating the schedule and increasing the structure's alignment accuracy.■

### Project Team

**Owner** – Denver Art Museum

**Lead Architect** – Studio Daniel Libeskind, New York

**Executive Architect** – Davis Partnership, Denver

**Structural Engineer** – Arup, Los Angeles

**Connection Design Engineer** – Structural Consultants Inc., Denver

**Steel Fabricator** – Zimmerman Metals Inc., Denver (AISC member)

**Steel Erector** – L.P.R. Construction Co., Loveland, Colo. (AISC member)

**General Contractor** – M.A. Mortenson Co., Denver

**Software** –

- SAP 2000
- Tekla Structures
- Form-Z

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