Fine Art

By Paul Asp, P.E., S.E. and Joy Beers, P.E.

Unconventional framing provided the support solution for this Minneapolis art center's structurally challenging expansion.

The expansion of the Walker Art Center in downtown Minneapolis challenged the design team to develop creative solutions to a structurally challenging design concept. The Swiss architectural firm of Herzog and de Meuron developed a design employing cantilevered box forms, large frameless windows that wrap around corners, and sloped and folded walls, ceilings, and floors. Structural engineers from the Minneapolis office of Hammel, Green and Abrahamson (HGA) worked closely with Herzog to develop an equally unconventional framing plan.

Design Execution

The complexity of Herzog's design dictated that supporting structure could not always be located in conventional (and more economical) locations. During early phases of design, both architects and engineers worked with simple drawings and models to create the preliminary concepts for the structural system. In the final phase, the HGA architectural team created a computer model of the finish surfaces using a three-dimensional modeling program called Rhino (see sidebar). Sloping surfaces were described by identifying a sectional plane at a given elevation. The surfaces were located by using work points dimensioned from a grid system in combination with a specified slope.

The structural framing plans were further developed by utilizing the specified locations of architectural surfaces and their compositions. Sloped surfaces often dictated the locations of steel members so that flanges would not emerge through finishes. All structural geometric plan work was based on hand calculations and graphically compared to the Rhino model.

Several engineering software packages were used to help analyze and design the complex structure. RAM Structural System was used to design the steel floor framing while RISA models were used to model wind frames. RISA was also used in the preliminary stages to develop concepts for the cantilevering theater, but the final analysis used a three-dimensional RAM Advanse model extracted from RAM Structural System.

Framing Systems

There was no "typical" framing on the project. Office floors above galleries spanned 52′ with W21 beams spaced at 3′ on center to match ceiling ribs and HVAC and sprinkler piping distribution lay-

Paul Asp (far left) is an associate vice president with Hammel, Green & Abrahamson's Minneapolis Structural Engineering Department.

Joy Beers (left) is an associate with Hammel, Green & Abrahamson's Minneapolis Structural Engineering Department.

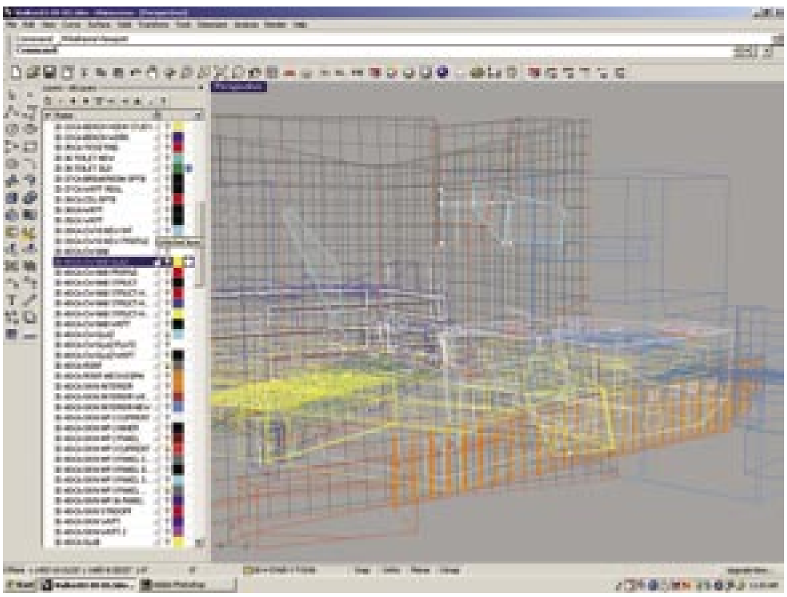
Rhino to the Rescue!

HGA architects used Rhinoceros (Rhino) software for 3-D modeling of the Walker Art Center's complex structural geometries.

Rhino, a product of Robert McNeel and Associates, is a free-form modeler that has been commonly used for industrial design applications. According to Scott Davidson, Rhino market development manager, architects and structural engineers have been using the software to determine the shape and components of curved forms and surfaces, advanced cladding, and structural and systems layout. Rhino can design, prototype, engineer, and manufacture buildings using any material, according to Davidson.

"[Rhino] was a good program for this project because it is flexible and can do NURBS modeling, and it can draw very accurately," said Tyson McElvain, HGA architect.

NURBS—non-uniform rational B-splines— are mathematical representations of 3-D geometry that can accurately describe any 2-D or 3-D shape.



"Rhino allowed us to take a number of sloping angle beams and columns, cut them at different elevations, and accurately display them in 2-D," McElvain said.

HGA used the software's surface modeling capabilities to offset surfaces, then locate and coordinate structural gridlines within the wall assembly. The building's skin is 18" thick from the face of the steel to the face of the skin, McElvain said.

"We modeled it with Rhino from the outside in," he explained. "We worked backwards to build each plane so we could start with the architectural concept."

Rhino is compatible with design, drafting, CAM, engineering, analysis, rendering, animation, and illustration software. It supports many file import and export types including DWG, DXF, STEP, Parasolid, ACIS, VDA, Viewpoint, STL, Adobe Illustrator, and over 30 flavors of IGES.

It can also read and repair DWG and IGES files so models can be used in all parts of the construction process, according to Davidson.

"Rhino was valuable in generating 2-D floor plans, ceiling plans, and elevations to give to the contractors," McElvain said. "We used the 3-D model to confirm everything once they were in the field." ★

outs. Composite lightweight and normal weight slabs were used on metal deck in 1.5, 2, 3, and 4.5″ depths, depending on location. Girders were often raised to the top of the metal deck to reduce total structure depth. For example, 4.5″ Epic deck was nested between W10 beams spaced at 17′ on center in some locations to create the shallowest structural steel framing possible.

Cantilevered Theater Element Structure

The structural concept that was developed to support the most prominent structure on the expansion—housing the theater, restaurant, and a special event space—required a search for any opportunity, no matter how obscure, to support the massive cantilevering form.

The architectural renderings clearly showed the theater projecting over the sidewalk, floating above the glass façade on the east wall facing the street. It was apparent that the design would not permit columns along more than half of the perimeter. The most recognizable opportunity for support was adjacent to elevator shafts along the west face in the form of a concrete shear wall. The north and south faces each had just one opportunity for a column extending to the ground hidden within interior partitions. Interior columns were not part of the main support due to the open nature of the theater.

The large expanse of solid walls at the perimeter of the theater created opportunities for deep wall trusses. Each face of the 95′ by 120′ by 60′-high box contains a full-height truss fabricated from W14 shapes connected to gusset plates with flange claw angles—angles that connect gusset plates to flanges perpendicular to the gussets.

Early in the design process, the north and south wall trusses cantilevered approximately 60′ past their single column support to carry the weight of the 120′-long east wall truss. Almost all of the building weight was supported on two columns, resulting in significant uplift forces at the back span.

As the design developed, an entry vestibule and an exit stair were added to architectural plans under the cantilever. This provided an opportunity to support east wall loads more directly. Two columns were added within the walls of the vestibule to relieve some of the load on the cantilever trusses, but these columns could not be in the same plane as the east truss. A pair vertical transfer trusses was integrated into the structure, and its diagonals would convey gravity forces from the east face approximately 12′ back to the recessed columns. The primary full-floor diaphragms at the base (one level above grade) and the roof were used to resolve the induced eccentricity. The cantilever of the box produces a pull at the top floor and a thrust at the lowest floor, resolved as shear in the concrete elevator core walls. The addition of these vertical trusses and recessed columns reduced the total steel tonnage significantly and helped to limit deflection without affecting the architectural impact of the cantilever.

Design evolutions created additional complexity. The south wall was sloped, and folds were added in the north and east walls that caused kinks in the wall truss members. All but a few diagonals and columns were relocated to avoid most of the folds and window openings. Floor diaphragm members were used to resolve the out-of-plane loads resulting from kinked members carrying up to 800 kips. Details using Williams high-strength post-tensioned threaded bars were used to transfer large axial forces from steel members to the shear walls.

The floors within the theater element were designed to deliver all gravity loads to the exterior wall trusses. Two interior hangers supported the inner edge of the upper balcony, which was framed almost entirely using W8 beams. HSS 5x3 hangers were located within a 4" sloped wall located at the re-entrant corners. The hanger size was minimized by detailing connections to minimize eccentric loading.

Theater Erection

The theater structure was designed with the assumption that the 12 perimeter columns not extending to the ground would need temporary shoring until the wall trusses and diaphragms were complete.

During the bidding stage of the project, the steel erector had evaluated several methods of shoring and removal and concluded that the best method of shoring was to extend the columns down to the ground and remove them one at a time after the structure was completely erected. The erector evaluated the possibility of simultaneously releasing the load on all 12 shoring points using 12 high-capacity jacks connected together. This idea was rejected because of complexity, high load capacity requirements for the 800-ton jacks, expense, and overall unpredictability of the system.

Due to the complexity of the structure, and to expedite the shoring removal design approval process, the erector enlisted HGA to analyze the shoring removal sequence using the already developed RAM Advanse computer model of the building. The model was analyzed a dozen times, beginning with the fully shored condition and then removing one shoring post at a time. Because of the highly redundant nature of the structure, the erector wanted to begin removing the most rigid elements (those with the least deflection) in order to transfer the loads to the main structure, which was designed to bear these loads in the earliest stages of shoring removal operations. The results of these analyses were compared with the original loads for each member affected by the shoring.

Even though member sizes did not need to be increased due to the shoring removal process, several connections needed enhancement because of higher loads. The shoring removal analyses also identified temporary unbalanced conditions during shoring removal that caused increased diaphragm stresses. Added shear reinforcing in the slabs and chord force enhancements in the steel connections were required due to shoring removal.

Prior to the shoring removal, the general contractor coordinated the project team to ensure the erection and inspection of the structure was complete. Contingency plans were developed for a number of potential risks. The six permanent columns and 12 temporary shoring columns were fitted with strain gages so that during shoring removal the changes in column load could be monitored in real-time and compared with predicted values. The displacement of each column at each stage of removal was surveyed, and inspectors observed slabs for cracking and connections for slip.

The erector devised a method to remove the temporary shoring columns by simply cutting away a pre-determined portion of the column flange and web near its base to bring the column cross-section close to failure. After the initial cut, the remaining steel was heated until smooth failure and load release occurred. The method worked flawlessly—by noon on the day devoted to shoring removal, all 12 columns had been cut. As

Twelve temporary perimeter columns were installed to make erection easier. They were sequentially removed after erection was complete.

In this photo, the erection columns have been removed from the lower level, transferring the structural loads into the multi-story trusses.

expected, the actual deflections were less than predicted, due to lower actual loads and higher member stiffness than modeled. The changes in column load were also lower than predicted. Overestimation of dead load, redistribution of load during erection to the primary columns, and alternate un-modeled redundant load paths contributed to these results.

Glass Wall Structure

Three glass walls connect interior public space with exterior gardens and terraces. The architectural design required the glass to be butt glazed and as open as possible to merge interior and exterior spaces. Columns placed behind the glass walls to support the roofs and public terraces above were not possible.

The final structural solution was to use structural steel mullions to support the roof as well as the wall. While this was a simple solution that appealed to the design team, it required overcoming several challenges familiar in architecturally exposed steel construction— how to keep mullions small, straight, and fireproofed.

Five inch by 3″ square-corner built-up tube columns spaced at approximately 6′ on center were designed to span vertically 24′ and carry both wind and gravity loads. By post-tensioning the anchor bolts to achieve base fixity and by loading each mullion with just a single roof beam, the required section could be made as small as a mullion designed only for wind. To achieve a steel fabrication tolerance compatible with that of the glass, tolerances were specified to be one-half of those required by AISC's definition of AESS. The curtain wall fabricator used special techniques and added internal stiffeners to maintain the shape and square corners of the welded shape. To achieve the two-hour fire rating required for the columns, an equivalent fire rating was developed using sprinklers adjacent to each column, thereby eliminating the need for spray applied or intumescent fire protection.

Despite complications in the building structure, dramatic impact was made possible by structural steel design solutions. ★

Owner
Walker Art Center

Design Architect
Herzog & de Meuron, Basel, Switzerland

Architect and Structural Engineer
Hammel, Green & Abrahamson, Inc., Minneapolis

Structural Engineering Software
RAM Structural System
RAM Advanse
RISA 2D

Detailer
Wasatch Detailing Corporation, Salt Lake City, AISC member

Detailing Software
AutoCAD

Steel Fabricator
W&W Steel Company, Oklahoma City, AISC member

General Contractor
M.A. Mortenson, Inc., Minneapolis