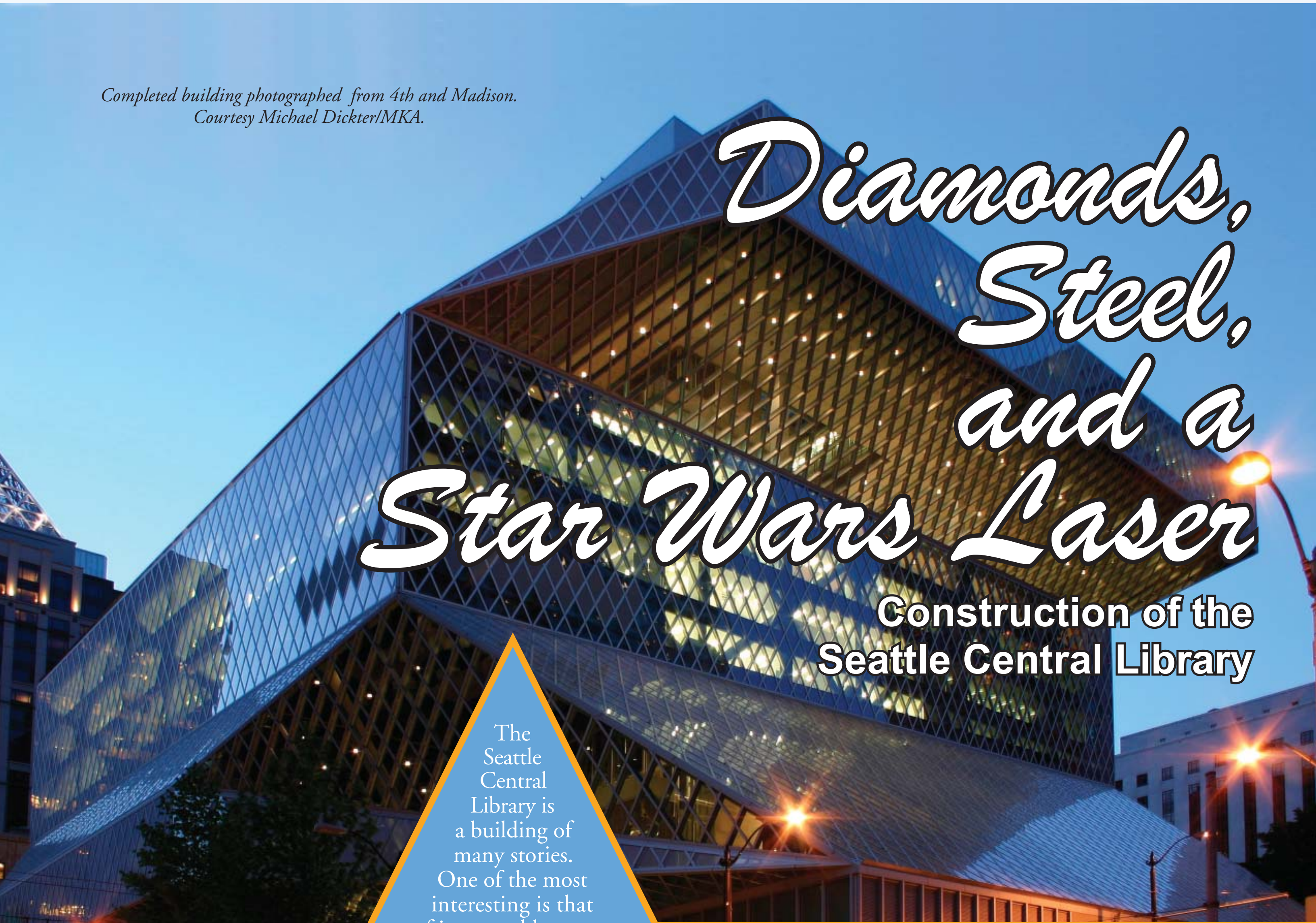


Completed building photographed from 4th and Madison. Courtesy Michael Dickter/MKA.

Diamonds, Steel, and a Star Wars Laser

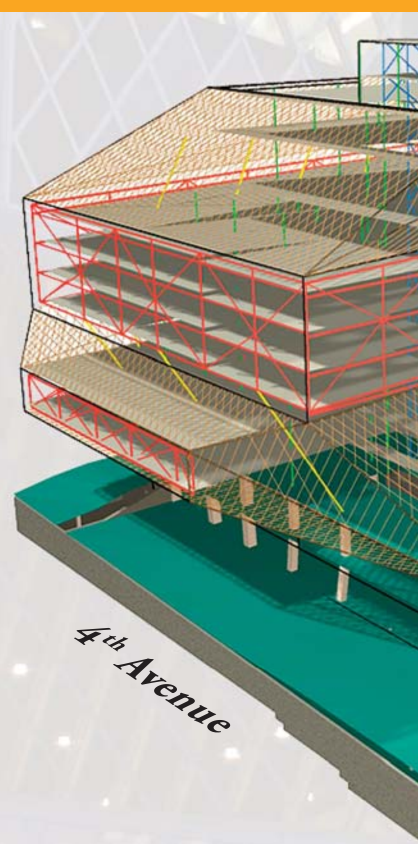
Construction of the Seattle Central Library

By Jay Taylor, P.E., and Dale Stenning

The Seattle Central Library is a building of many stories. One of the most interesting is that of its assembly, a saga involving 10,000 glass diamond panels, 4,644 tons of steel, 165,000 feet of aluminum mullion…and technology from outer space. To accomplish the feat, the architects, structural engineer, construction manager, and subcontractors undertook a complex process of design evolution that could not have been accomplished by any one firm alone.

Start with Floating Diamonds

A building like this had not been built before. The structure conceived by the architects (the Office for Metropolitan Architecture in Rotterdam and Seattle firm LMN, in a joint venture) and the structural engineers (Magnusson Klemencic Associates of Seattle, with Arup during schematics), was a 12-story, glass-clad, asymmetrical building with multiple cantilevers, sloping surfaces, and dramatic geometric angles. The glass cladding was shown in a diamond pattern, and the architects' desire was for a transparent building that floated with no apparent means of support.



MKA had envisioned two separate, layered structural systems supporting the structure (*Figure 1*). The first system, multi-story-deep perimeter platform trusses supported by carefully positioned sloping columns, would carry the building's gravity loads. The second system, a diamond-shaped steel grid exoskeleton, would resist wind and earthquake loads, interconnect the platform trusses, serve as the interior architectural finish, and support the glass curtain wall. Specially designed slip connections would allow the grid to stabilize the platforms against lateral forces without carrying gravity loads, thus eliminating the need for fireproofing (*Figure 2*).

A study was undertaken to determine the optimum diamond size and shape, both for constructability and cost. OMA/LMN and MKA worked closely with Hoffman Construction, the construction manager, and Seele GmBh, the curtain wall design/build subcontractor, to establish the optimum grid size and spacing for span, performance, fabrication, and aesthetics. Several variations of grid size and members were investigated and ultimately a 4- by 7-foot diamond grid was established.

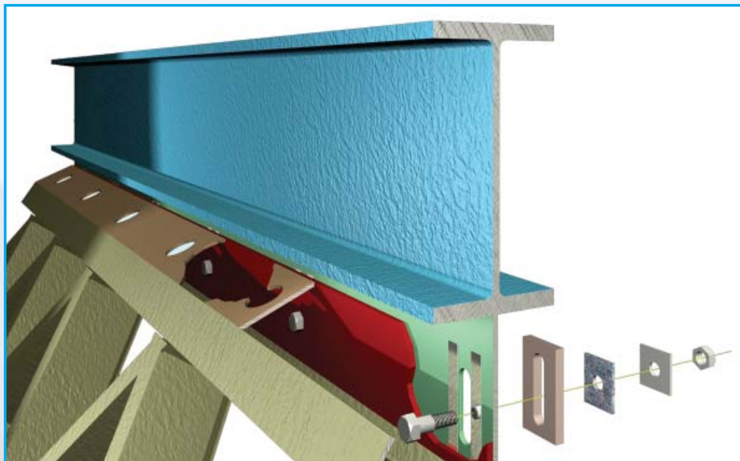


Figure 2: Perimeter truss to steel grid slip connection assembly detail. Courtesy Neal Luck/MKA.

Add an Alternate Frame of Reference

The next challenge was how to convey the building and its complex geometry to Hoffman Construction and subcontractors in 2D drawing form. As a start, OMA/LMN produced documents describing the basic geometry of the facades. These drawings illustrated cross-sections of the building's four elevations, with enough information to indicate primary geometry (i.e., offset from grid and dimensions to all building corners), including the dimensions of the geometry of the mullions on all faces of the building.

A nontraditional but strategic decision was made by Hoffman to have the curtain wall subcontractor take the lead on providing the 3D computer wire frame model necessary for the detailing and fabricating the structural steel. For a typical building, the curtain wall and steel are detailed in parallel. However, the Library's unique geometry and allowable steel fabrication and erection tolerances prohibited this approach, unless every single glass panel were detailed independently. Plus, the fold lines of the glass and the aesthetics of the diamond grid transition from one building face to the next were critical to the architects' vision. It was decided that if the curtain wall detailer proceeded first (working under a 3-mm tolerance), face-of-glass could be used to set building geometry versus face of steel. The steel could then be successfully detailed, fabricated, and erected *if* an incredibly tight cumulative tolerance of ½ inch was met. It would be possible, but it meant that the steel detailing tolerances had to be virtually *zero*, with very minimal material and fabrication tolerances, to save as much of the ½ inch as possible for erection.

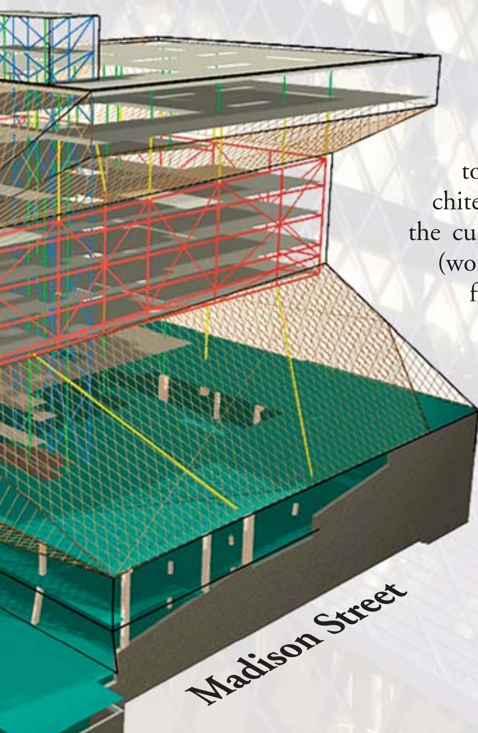


Figure 1: Computer rendering showing perimeter trusses and exterior steel grid. Courtesy Neal Luck/MKA.

One Piece at a Time

The next priority was to establish a common frame of reference, so that all involved parties were dimensioning to the same points. Since the diamonds were a standard size, OMA/LMN developed a "key diamond" approach, with the grid layout referenced from a single diamond on each face (*Figure 3*). Hoffman and Seele did modeling to array the grid geometry up each building face and across the folds, so the architects could select the optimal diamond grid relationships at the corners. The key diamond was set at a correlating location, with the grid lines and finish floor elevations providing the x,y,z coordinates.

Hoffman extrapolated that point into a uniform coordinate system (incorporating an x,y,z grid and CAD layering system) to create standards for transferring and sharing files. From this, Seele built a primary wire frame model which, after auditing and acceptance by the design team, was built into a 3D object model containing all the curtain wall components. The model provided back-of-mullion geometry and included production information for the computer numerically controlled fabrication equipment.

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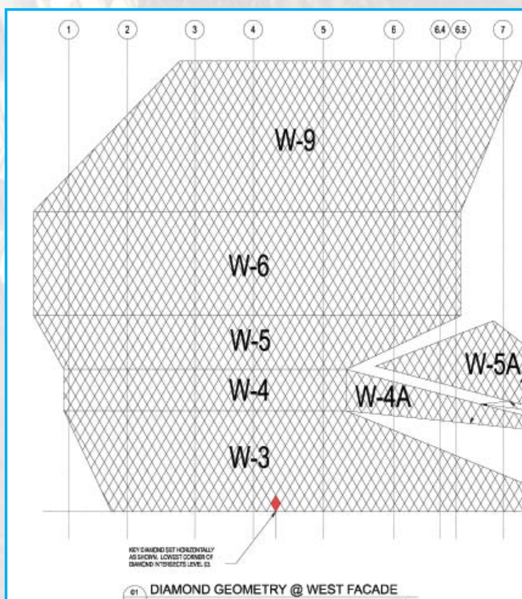

Figure 3: Exterior elevation drawing showing "key diamond" location. Courtesy OMA/LMN a Joint Venture.

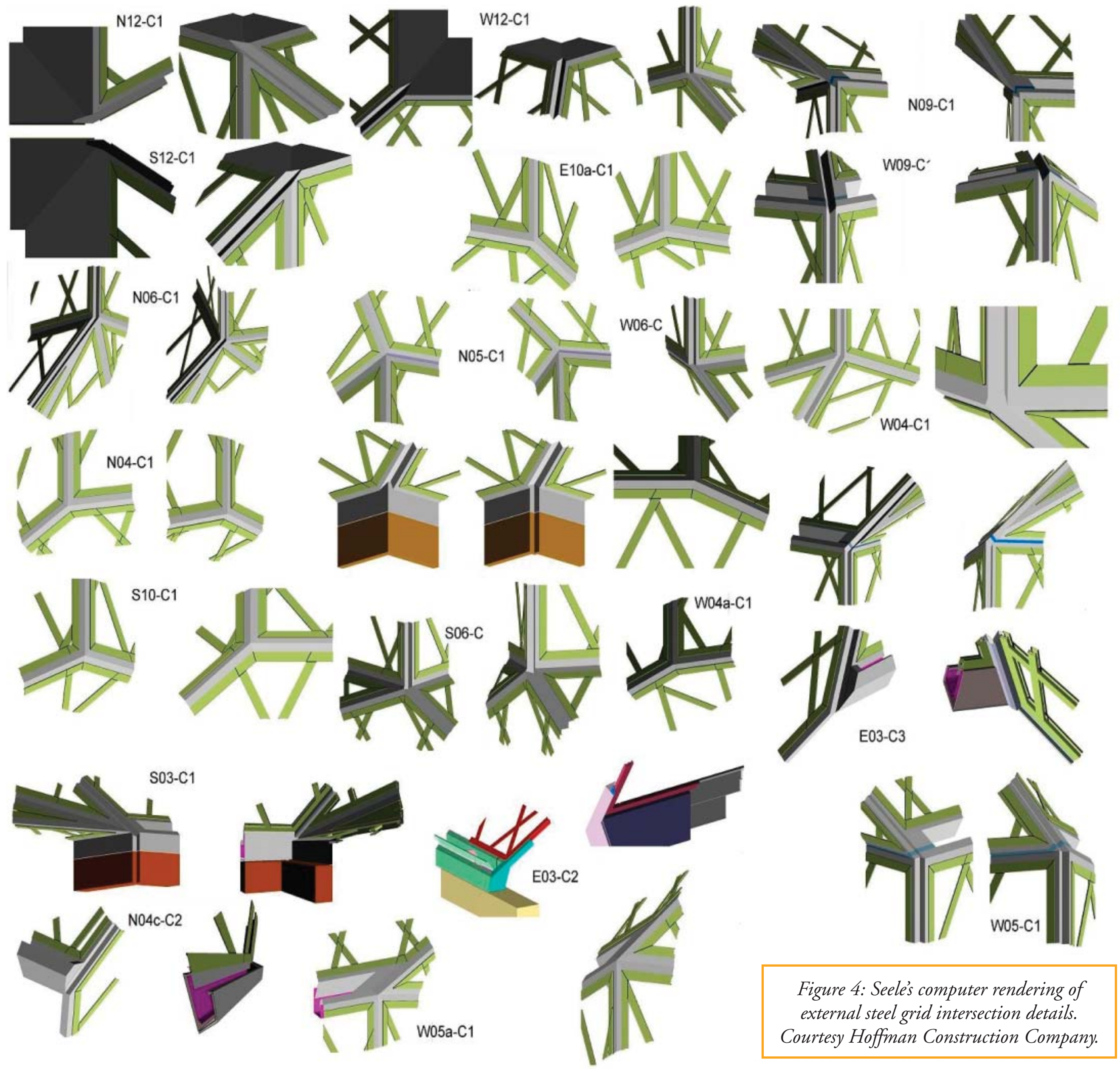

Figure 4: Seele's computer rendering of external steel grid intersection details. Courtesy Hoffman Construction Company.

Library Origami: The Art of the Fold

Looking at the planes and folds of the Library, the word "random" might come to mind. However, the fold transitions were anything but. At some folds, the architects wanted a gutter or "negative" fold to emphasize the edge of a face; in other places, a point was desired. No two folds were alike, due to the building's geometry and asymmetry, and every time a fold line was shifted, even very slightly, it changed the geometry of the entire building face.

Each fold decision also impacted the detailing, design, and construction of the various joins, including the steel connections. Seele developed details for every single condition of steel converging at the corners (*Figure 4*) for review by OMA/LMN and MKA. Ultimately, mockups were built of two of the most complex building corners, as well as many of the fold line conditions, for final architectural approval.

Six months later, Seele was ready to hand off their computer model to the steel detailers, a team of The Erection Company, Canron, and BDS. BDS used Seele's model and the information on the structural drawing sheets to create an Xsteel model, identifying top of steel, centerline of steel, and back-of-glass spacer.

Creating a "Kit of Parts"

Once the entire building was modeled and steel shapes assigned, MKA and Hoffman assessed constructability for all corner steel conditions. Instead of detailing every one of the thousand or more joints, MKA developed a "kit of parts" with individual details applicable to several conditions. The detailing team was told if they run into Condition A, B, or C, use Detail 1; if Condition D, E, or F, use Detail 2; etc., thereby covering a wide range of conditions with a relatively small set of details.

Tremendously helpful at this stage was Hoffman's development of a method to view exact building conditions without transmitting the Xsteel model back and forth or attempting to document the condition in 2D. The method involved generating .avi files from the Xsteel model, which were attached to and sent with RFI's. The avi's allowed the engineers to pan, zoom, and rotate the condition illustrated. In many cases, the engineers used a screen capture from the .avi to indicate the desired solution. The reduction in turnaround time, improved communication, and increased accuracy all contributed towards achieving required tolerance goals.

Once the detailing team had a partially developed Xsteel model (i.e., steel shapes extruded but not trimmed), the model was handed off to the M/E/P subcontractors. They incorporated the M/E/P routing and penetrations then gave the revised model *back* to the steel detailers, who trimmed the details around the M/E/P penetration points. MKA reviewed the model to compare actual penetrations with those originally anticipated and ascertain any structural impacts. A second "kit of parts" was developed by MKA for conditions requiring revision, with the detailing team again selecting and applying the appropriate solution.

Star Wars Laser Technology

And then the construction began. The steel erection sequence was complicated, as the seismic steel grid panels had to support the building not only upon completion, but also during erection. This meant the panels had to be hung and bolted off before the structure could advance upwards. The panels also had to accommodate building movement as construction proceeded, yet still meet stringent construction tolerances. The process called for ongoing and extremely accurate surveying. Hoffman turned to digital laser scanning, a cutting-edge technology developed by the military to link satellites under their Star Wars program.

A digital laser scanner is a bread-boxed size apparatus with a quickly spinning prism mirror synced to a pulse array of transmitted on/off laser pulses. Next to the transmitter is a receiver that reads the light reflected off any surface the laser hits. The scanner knows how to distinguish individual pulses and translates the pulses received into distance. Because the laser is spinning, the scanner also knows the exact transmitting angle of the light pulse and is able to locate an x,y,z coordinate. The groups of points captured, accurate to ⅛ inch in 100 meters, can then be translated into surfaces (*Figure 5*).

Hoffman "shot" every panel erected with the digital laser scanner from at least three separate points, then examined the graphical reports produced for areas where the Xsteel model and the erected surface varied by more than ½ inch (*Figure 6*). After quickly pinpointing these locations, Hoffman performed field adjustments by either pushing or pulling the steel into place. As might be expected, pulling on one corner of steel can impact the location of the entire piece, so adjustments were complicated. Once the steel was within acceptable tolerances, it was permanently bolted.

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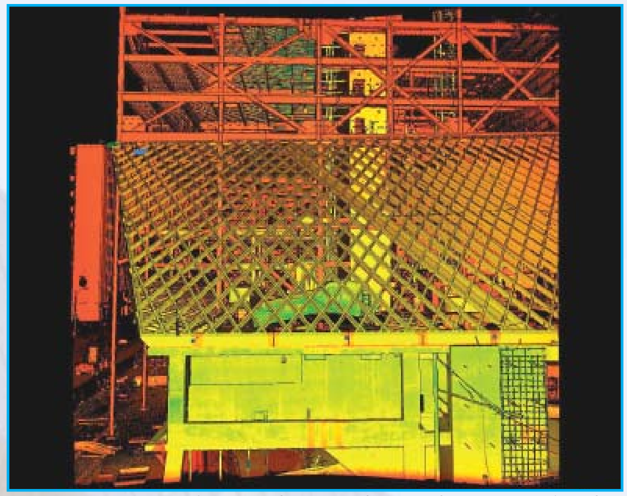

Figure 5: Digital image of "scanned" erected exterior steel grid. Courtesy Hoffman Construction Company.

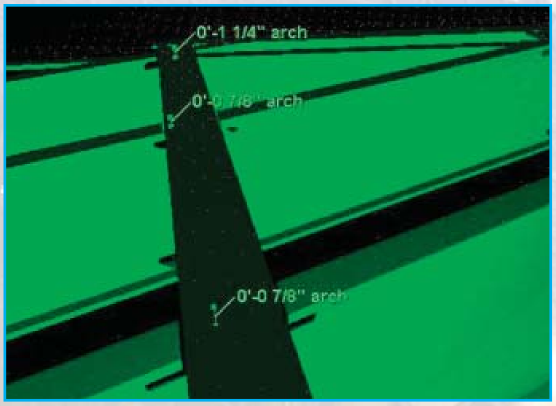

Figure 6: Enlarged digital image showing exact location of erected steel grid. Courtesy Hoffman Construction Company.

Hoffman quickly adopted a routine of hanging steel in the morning, laser shooting it in the afternoon, analyzing the reports in the evening, then reporting the results to the ironworkers the next morning. Any panels adjusted were "reshot" to verify location and determine any corresponding ripple effect. Due to the tight schedule and small construction staging area, the sequence of hanging, shooting, analyzing, adjusting, and reshooting had to be stringently followed.

4,644 Tons of Steel Settle Less than an Inch!

Tolerances were typically achieved the first time without adjustment. For a small number of steel-to-curtain-wall connections (primarily tight corners with small panel pieces), a custom connection was necessary. Hoffman developed its own "kit of parts" comprised of special brackets capable of achieving up to 1 inch of tolerance in a given direction. The brackets were employed on approximately 150 points of the 10,000-diamond grid.

Over 320 tons of temporary steel were used in an erection sequence developed by MKA and Hoffman. When the steel was removed, the building settled as expected, but less than half the amounts predicted. A final survey revealed that the structure had rotated just $\frac{7}{8}$ inch and settled $\frac{5}{8}$ inch.

The Library was extremely demanding from a construction perspective, due in part to numerous sight lines that absolutely had to be straight. There was little or no interstitial space where adjustments could be made; rather, the building envelope represents a single expression, from primary structure through seismic steel and culminating in the curtain wall.

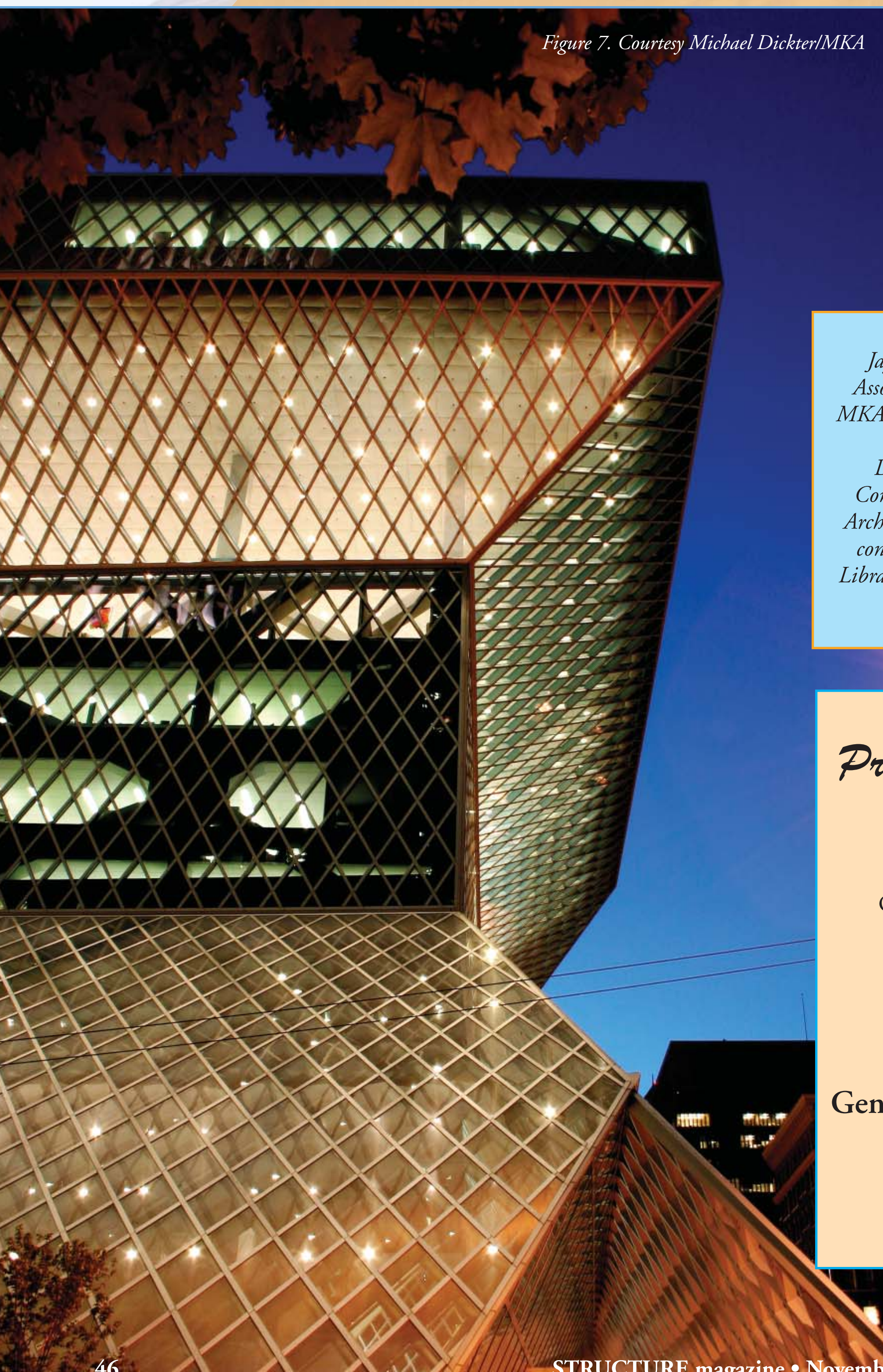

Figure 7. Courtesy Michael Dickter/MKA

Today, much of this construction story is hidden behind the dramatic folds and planes of the Library's glass exterior (*Figure 7*). (If only those walls could talk!) Yet those involved will not soon forget the collaborative experience and unique technologies used to create Seattle's newest landmark. Each day as many as 12,000 visitors pass through the library's doors, many drawn as much by the building's structure and architecture as they are the books!▪

Jay Taylor, P.E., is a Principal with Magnusson Klemencic Associates in Seattle, Washington. Jay is a senior member of MKA's Library/Museum Specialist Group and served as Project Manager for the Seattle Central Library project.

Dale Stenning is an Operations Manager with Hoffman Construction in Seattle, Washington. Originally trained in Architecture and Structural Engineering, Dale was the senior construction engineer for the Central Library. Prior to the Library project, Dale worked on the Experience Music Project, which was also engineered by MKA.

Principal Members of the Team

Owner:
Seattle Public Library (Seattle, WA)

Architect:
OMA/LMN, A Joint Venture (Rotterdam/Seattle)

Structural Engineer:
Magnusson Klemencic Associates (Seattle, WA)
with Arup during schematics

Mechanical/Electrical Engineer:
Arup

General Contractor/Construction Manager:
Hoffman Construction Company (Seattle, WA)

Development Manager:
The Seneca Real Estate Group (Seattle, WA)