Innovative Curtain Wall System Requires Integration of Architecture and Structural Design

ABBAS AMINMANSOUR
University of Illinois at Urbana-Champaign

WILL SHEPPHIRD, P.E.
Advanced Structures Incorporated

INTRODUCTION

Chicago may be regarded as the world leader in advancing architecture and building technology. The list of contributors to this progress includes such names as Louis Sullivan, Elisha Otis, Mies van der Rohe, Fazlur Khan and Helmut Jahn.

Rising from the ashes of the Great Fire, the members of the First Chicago School capitalized on three emerging technologies in conjunction with innovations in foundations that contributed to the birth of the skyscraper. They three were; the fireproofed steel frame, the passenger elevator, and the non-load bearing curtain wall. The last of these three has undergone a century of transformation from ornate terra cotta claddings to dematerialized glass membranes.

THE PROJECT

One North Wacker Drive is a 51-story multi-use office building under construction at a prime location within the Chicago Loop. The building bounded by North Wacker Drive to the east, Madison Street to the south, and North Franklin Street to the west rises over 653 ft. above the street level (Fig. 1).

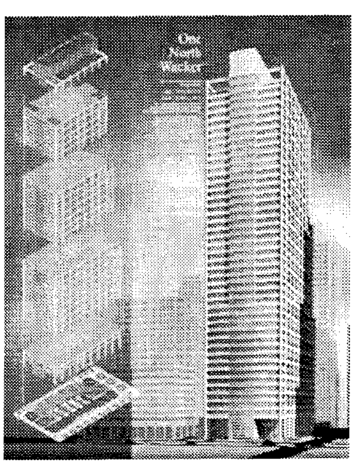

Fig. 1: Rendering of One North Wacker (courtesy of Lohan Associates)

One North Wacker Drive offers about 1.7 million sq. ft. of leasable space in the busy downtown Chicago, making it the largest office building under construction in the United States. In addition to office space, the building will house a conference center, restaurant, and about 230 parking spaces.

The building is owned by The John Buck Company and developed by Lend Lease Real Estate Investments, Inc. Morse Diesel International (now called AMEC, as its parent company) is the general contractor. Construction is expected to conclude by June, 2001 with an estimated cost of $250 million.

THE ARCHITECTURE

The architect, Lohan Associates, utilized a postmodern stainless steel curtainwall as well as the latest telecommunications and other technologies to design a building ready for the challenges of the twenty-first century. Lohan Associate's Design Principal Jim Goettsch led the design.

The building's many innovative features provide tenants increased productivity and lower operating costs. Constant temperature control, air quality monitoring, and high-speed elevators with curved glass cabs, are among features that make this building stand out.

One North Wacker is divided into four zones. The lobby consists of retail and restaurant space. Extensive use of glass in the east, west, and south walls create a very transparent lobby (Fig. 2). Originally, the developer wanted stone cladding at the building base. However, Associate Principal Steve Nilles of Lohan Associates, felt that the modern stainless steel curtainwall and stone cladding would not be a good match. The designers opted for transparent walls that draw the passerby's attention to the granite and marble interior core wall, without the use of stone at the building's exterior base, blurring the distinction between inside and out in what Mies called "beinahe nichts," meaning almost nothing.

The developer wanted the building to have floor sizes flexible enough to accommodate the varying needs of the tenants. Therefore, the tower consists of three zones above the lobby level with 38,000, 33,000, and 29,000 sq. ft. floor areas. This led to a stepped tower design.

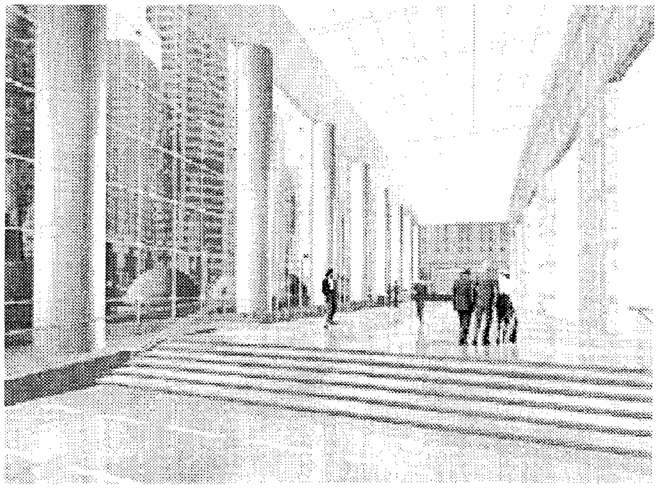

Fig. 2: Rendering of the lobby area and the south wall (courtesy of Lohan Associates)

THE NET WALL

For the transparent lobby walls, Goettsch and Nilles specified two alternate designs during the bid stage. The first scheme presented a cantilevered glass fin solution with point fixings supporting the glass panels. In contrast, the second scheme presented a non-drilled glass solution by combining a flat, prestressed cable net with specialty nodes supporting the glass panels. After requisite interviews, technical assistance, real time animations, and full scale rapid prototypes, Trainor Glass of Alsip Illinois and Advanced Structures, Inc. (ASI) of Marina Del Rey, California were awarded the design-build contract.

A very innovative net wall system used on the east, west, and south walls of the building lobby utilizes an extensive amount of glass (Rothrock, 2000). But don't expect to see any mullions in this lobby. One North Wacker is the first building in the United States to incorporate this innovative two-way cable net enclosure concept.

The net wall system uses 3/4 and 7/8-in. pretensioned stainless steel cables to hold up 5 X by 5 ft. panels of glass (Fig. 3). According to Nilles, "To enhance the net wall transparency, Lohan specified water-white low-iron non-reflective coated glass manufactured by Schott Corp."

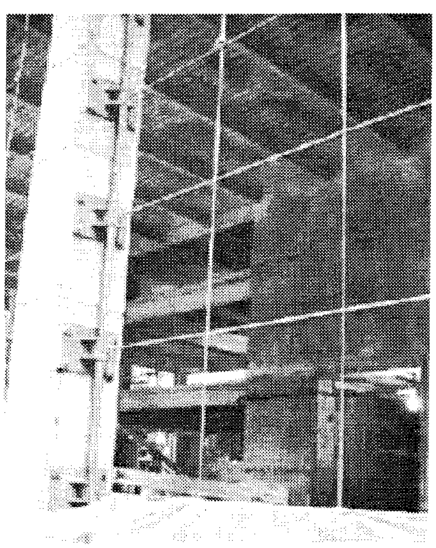

Fig. 3: Pretensioned cable grid in the south wall (courtesy of Joshua DeYoung)

Patrick Loughran of Lohan Associates, the Project Architect for the curtainwall, says, "In the past, cable net wall facades have been the focal point of the buildings which incorporate them such as the Kempinski Hotel in Munich (Figure 4)." He adds, "One North Wacker uses this enclosure technology to elegantly connect the street with the main lobby."

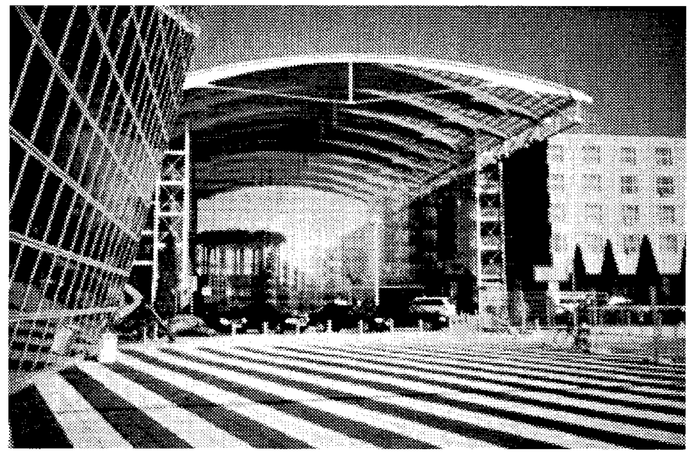

Figure 4: Kempinski Hotel in Munich with the first net wall system (courtesy of ASI)

The south wall of the lobby consists of seven bays, each 30 ft. wide and 40 ft. high. The east and west walls each measure 45 ft. wide and 40 ft. high. Loughran points out, "Multiple bays of cable net wall enhance the interior space without dominating it." All bays have monolithic glass panels supported at their corners via a custom made stainless steel node (Fig. 5). Each node is clamped to both the vertical and horizontal cables at their intersection. The nodes are manufactured from investment cast stainless steel and polished to a high sheen.

As shown in Figure 3, each cable is fixed to a carbon steel connection box via a threaded end swage. The steel connection boxes are site-fixed to the boundary structure either by field welding or bolting. The entrance portals located at the east and west elevations, pivot at their base to accommodate the differential wall deflection.

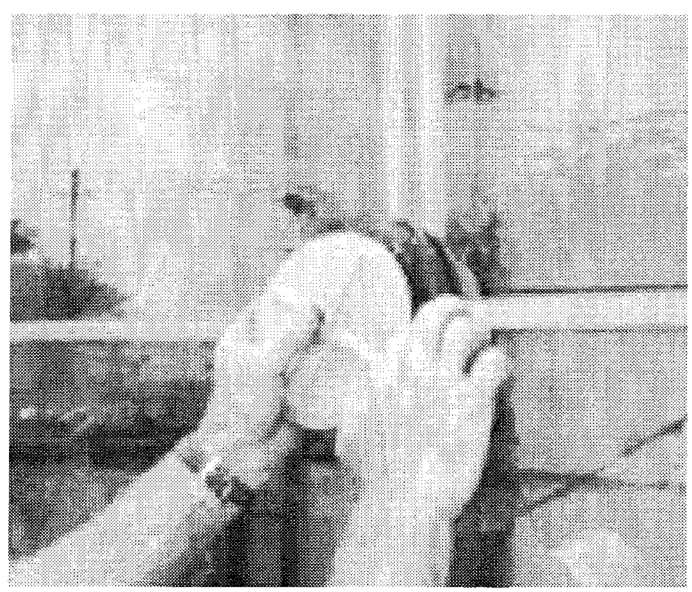

Fig. 5: Installation of a mock-up node in the net wall (courtesy of Lohan Associates)

THE CABLE NET STRUCTURE

Conventional curtain wall systems resist out of plane forces such as wind pressures in addition to their self-weight through beam action. A typical design includes vertical and horizontal mullions with adequate cross sectional properties, designed as pin-roller bending members. Building Code standards limit the deflection of glass-supporting members to 1/175 of their largest span.

Often, glass-supporting systems are designed to include concealed steel structural members. A conservative span to depth ratio limits the maximum depth that such systems can span without steel back up members. Structural principles governing glass fin systems do not vary greatly from aluminum mullion designs. A narrow beam is restrained against rotation and lateral buckling at certain intervals between supports. Many point-fixed strategies exist to support the glass panels on the glass flexural members.

Structures supporting glass walls often reduce transparency. Even with the introduction of glass as the beam element, reflections and glass fixings decrease the overall wall transparency. Both systems referenced above provide structural solutions that limit the deflection of the glass rather than focus on material efficiency.

The net wall system uses very stiff pretensioned cables instead of mullions to support the glass. It is designed to deflect more than the Code stipulated maximums and actually increases in stiffness with larger deflections. As noted earlier, the system was first used in the lobby of the Kempinski Hotel, in Munich, Germany, designed by Murphy/Jahn and Schlaich Bergermann and Partners. While the bay spans are significantly less for the One North Wacker project, the concept, detailing, and system components remain the same.

The flat cable net technology relies on the initial conditions for the tension members rather than shape, as in doubly curved (anticlastic) membranes. The design of this class of structure requires the use of "large-deflection" non-linear structural analysis programs. ASI utilized both in-house non-linear program DR and SpaceGASS proprietary program. Hand calculations supplemented the computer calculations.

A simple analogy can be drawn between the cable net wall system and a tennis racket. Just as the energy of the incoming ball is absorbed by the deflection of the racket strings, the energy embedded in the wind forces causes a deflection of the cable net. In both instances, the energy is redirected to a much stiffer boundary structure. Regardless of scale, each cable net seeks return to the initial position due to the prestress within the tension members. This translates into shape recovery for the flat systems. Considering that the glass panels warp to different degrees during the deflection of the cable net, proper engineering review is required for the glass panels. Until recently, flat cable net projects have utilized monolithic glass panels due to the high local forces at the support conditions and the panel warpage under design loads. ASI is currently investigating the use of cable net technology with insulated glass panels and anticlastic surfaces.

As with any tall building, the design of the wall system had to take into account the building's movement without causing any damage. Franz Safford, a principal of ASI says that a hinged U-shaped steel portal was used at the entrances to accommodate wall displacements without impacting the performance of the entrance doors.

COLLABORATION IN DESIGN AND CONSTRUCTION

Clearly, this type of innovation requires collaboration between everyone involved in the design and construction of the system. Architect Nilles highlights the challenges involved in the design of this innovative wall system by pointing out that the architect, structural engineer, wall system designer, and the glazing contractor had to work very closely to ensure proper design and construction.

Safford emphasized the "critical collaboration" that his team had to have with the structural engineer to ensure that the boundary structure supporting the cable net structure was adequately designed to support the significant loads at the cable anchors.

Thomas Poulos, Project Manager of Thornton-Tomasetti Engineers states, "Columns were designed to support the 5 ft. grid of high-strength cables which support the elegant transparent net-wall glass system at the lobby." He adds, "the composite column design allowed an unbraced length of 45 ft. without increasing the section of the original steel column design." For a more comprehensive description of the building structure see (Aminmansour, 2001).

MOCK-UP TESTING

New and innovative curtain wall designs are often tested under laboratory conditions for air and water infiltration and to observe their behavior under design wind pressures. The design used at One North Wacker was no exception. In order to address life safety concerns expressed by the City of Chicago and performance warranties for the owner, a mock-up test procedure was undertaken at Construction Research Laboratory (CRL) in Miami, Florida.

A full size test rig was constructed and fitted to a testing chamber (Figure 6). Steel truss members and wide flange steel sections simulated the boundary stiffness. A 25 ft. wide by 37 ft. tall aperture, with 4 vertical cables, 7 horizontal cables, and 28 nodes represented the average job site condition. To ensure that the mock-up rig would closely match the real project, ASI prepared a full engineering report and detailed design. Apart from the leakage testing, a topic of greater concern was the expected deflection under maximum design pressures.

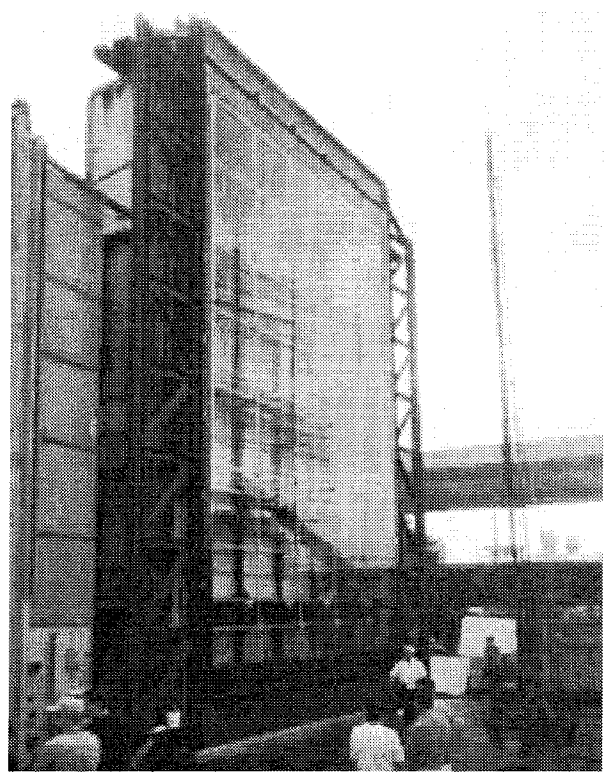

Fig. 6: Mock-up testing a net wall (courtesy of Lohan Associates)

To mitigate any occupant discomfort, a maximum deflection threshold of 7 in. over a 35 ft. span was established by the A/E and the building owner. Once calibrated and tested to ASTM standards by the CRL staff, the mock-up rig was tested for both air and water infiltration. The mock-up met the requirements for both criteria.

Structurally, the cable net deflected less than the pre-established limit and to within 10% of the theoretical value. After passing all of the required tests, the specimen was tested to destruction. Suction pressures exceeding 150 psf, equivalent to approximately 250 mph wind speed, failed to damage the system. No glass lites were broken and no cables ruptured. Additional vacuum pressure was not possible as a non-structural silicone perimeter seal failed.

At peak test pressures, a noticeably large deflection of approximately 16 in. was observed (Figure 7). Upon release of the pressure, the wall returned to it's original flat position with no permanent set in the wall. At the request of Trainor Glass, additional mock-up testing was performed on the typical glass panels.

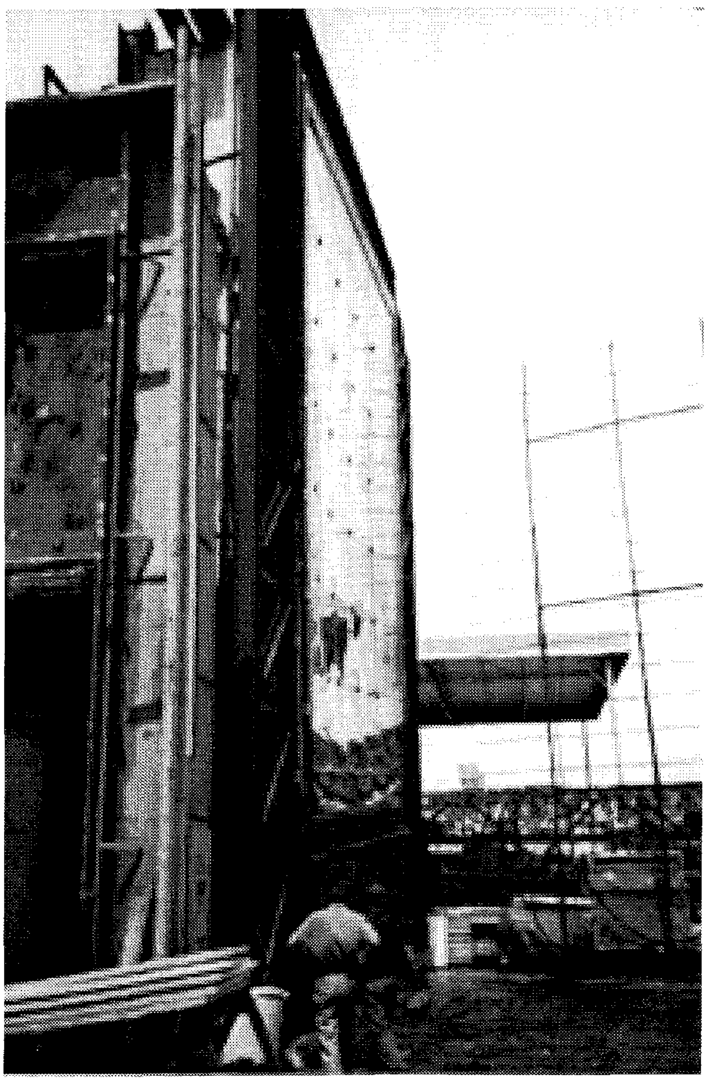

Figure 7: Test specimen exhibiting large deflections without failure (courtesy of ASI)

The panels that would experience the maximum warpage due to the support conditions were chosen for study. A testing apparatus was designed to model the free corner point load for the glass panels. Full instrumentation, provided by Smith-Emery of Los Angeles, California, was used to record the glass stress using Rosette strain gauges versus the load and deflection. For the 5'-0" x 5'-0" x ½" monolithic glass panels, sustained deflections up to 9 in. were recorded with the maximum glass stresses remaining below that of the allowable values for tempered glass. Additionally, a pull test to verify the cable swage breaking strength and the connection box was performed, but did not cause any failures. The mock-up testing of the cable net system and the individual components provided the A/E/C team with great confidence in the design of the system.

INSTALLATION

All glass structures require tight tolerances for fabrication and installation. For cable net walls the tolerances are even tighter. Because the location of the cable intersections determines the node locations and subsequently the glass support, the correct installation of the cable connection boxes was crucial. A precise inquiry was undertaken to determine the proper location of the shop fabricated connection boxes. Minor adjustments were necessary to correct the boundary conditions when they were determined to be out of the system tolerance. All cable centerline locations were located to within 1/8 in. in any direction. This assured a proper fit up for the glass supporting nodes. In addition to their proper location, all of the cables within the system were required to be prestressed to a pre-established value provided by ASI. The field superintendent supervised installation and prestressing of cables closely as determined by ASI. The overall installation process was problem free as demonstrated by the ease of glass installation by Trainor Glass.

CONCLUSION

A modern approach to materials and sophisticated engineering techniques achieved the maximum transparency and sleek appearance of the curtain wall for the lobby walls of One North Wacker. This project represents the first ever designed, tested, and installed flat cable net curtain wall in North America. The project also demonstrates the significance of the collaboration among different disciplines in the conception and implementation of successful and innovative curtain wall designs.

While the desire to dematerialize the membrane that separates the outside from the inside might look back to the early stages of modern architecture, the technique has been perfected as is demonstrated by this and other examples of world architecture. Chicago continues to be on the forefront of emerging architecture and building technology.

ACKNOWLEDGEMENTS

The authors thank Lohan Associates, Thornton-Tomasetti Engineers, Advanced Structures, Inc., and their staff for providing valuable input and information in the preparation of this article.

REFERENCE

Jenni Rothrock, "One North Wacker Drive: Anatomy Of A Glass Building," *Glass Magazine*, June 2000, pp. 52-54.

Abbas Aminmansour, "*High-rise with Cable Net Facade for the 21st Century!*," *CTBUH Review* Special Feature, March, 2001, pp. 65-68.