Data Flow and Communication in the Design of Complex Architectural Forms

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INTRODUCTION

The success of complex projects is contingent upon the effective transfer of information between the parties involved. Recent advances in architectural and engineering technology have opened the door for complex architectural expression in today's built environment. When pushing the envelope on geometric complexity, architects and engineers must begin a dialogue early on in the design process and communicate effectively throughout. Using digital models for communication, visualization, and analysis creates additional digital information that may need to be shared. Middleware provides interoperability between different software packages and facilitates the exchange of information. However, this does not exempt the partners from maintaining traditional lines of open communication.

This paper will discuss the importance of open communication and demonstrate a strategy for sharing digital information. The case studies that will be presented are taken from design projects whose geometric complexity required close partnership between design team members. Effective communication will first be discussed in the context of three sculptural concept designs. Second, the interoperability of digital models will be discussed through a case study of a complex, faceted super-tall high-rise tower.

1 CENTRAL COVE

Architects and engineers are often creatively constrained by the perception of economy in conventional designs. For a development called the Central Cove, the client envisioned a community unlike any other. This mandate freed the design team to grow sculptural expressions into paradigm-shattering building concepts. Figure 1 provides renderings of the three individually sited concepts advanced within the architectural team: Matrix Gateway Complex, Crystal Center, and Wings Museum.

Figure 1 Central Cove Renderings

(Matrix Gateway Complex) (Crystal Center) (Wings Museum)

Each structure would be large—up to three million square feet of occupancy and over 20 stories tall. The programming for each project varied, but multi-use was expected. The Matrix Gateway Complex would provide residents a full 3-D city experience, featuring suspended platforms linking modular housing and community venues. The Crystal Center would be one of many structures in a radically re-envisioned Arts Center. Finally, the Wings Museum would offer the highest quality hotel and museum experience within a structure, and appear to skim over the sea like a bird in flight.

Once the basic sculptural forms were realized, structural engineers were invited to evaluate the designs and propose means of structural support. In a familiar rectangular building with load-bearing columns and walls, structure is fairly well understood by architects and engineers alike. However, the proposed designs challenged the conventional wisdom by omitting instinctive means of support and lurching the building to an unprecedented length of cantilever. Despite the conceptual differences, three issues remain paramount in the mind of the structural engineer: providing a rational gravity load path, resisting applied lateral loads, and ensuring complete system stability.

The team members recognized that engineers and architects approach building design challenges with a different hierarchy of concerns. Through the schematic phase of such projects, the work of engineer and architect proceeds along parallel lines that converge toward a viable solution. A failure by either party to communicate changes results in divergence of the lines. Furthermore, in the schematic design phase, revisions happen very quickly. There is a time lag between architectural information being sent to the structural consultant and actionable information being returned to the architect. When structural advice is ready, the architecture has already changed.

New software tools help to close the gap. Interoperable model formats help communicate changes in form and reduce the delay between the sending and receiving of comments. In each of the Central Cove projects, the engineers were able to generate analytical models directly from the architect's models. However, shared software tools demand an open dialogue and a set of ground rules, especially when defining complex shapes with splines and arcs or when setting control points. Ultimately, the team must work together to find effective solutions.

2.1 MATRIX GATEWAY COMPLEX

Designed as both an urban gateway and a self-sustaining city, this 42-story prototype would be one of the greenest, most aesthetically striking and technologically innovative mixed-use buildings in the world. A 180-meter cube designed on an 18-meter grid, the prototype contains many of the components of a great urban center: a hotel with fitness and conference centers, retail and office spaces, cultural and religious facilities, and waterfalls surrounded by lush green terraces. Each component would take the form of a moveable module, connected to one of five central cores, all of which would be visible from the outside through a semi-transparent exterior skin.

The initial concept required that the entire structure be supported on four concrete cores. Columns on the grid would not extend down to a foundation, and beams were expected to span 18 meters. The engineers recognized that finding an effective load path would be the principal concern for the design of the structure.

Figure 2 Matrix Gateway Complex Interior

Early expectations were that the entire structure could act as a gravity load-resisting moment frame—meaning that the column to beam connections would provide stiffness. The structure would cantilever away from the cores. Hand calculations indicated that the span of the beams was too great to permit this concept. Instead, the engineers proposed including large hat trusses in the top stories of the structure (intended for mechanical and energy generation equipment), from which the rest of the structure would hang. To address the engineers' initial comments, the architects revised the program density of the building, moving more units toward clusters around the core. They also shared the Rhino model containing the floor plate layout. With this data, the engineers could accurately assess the distribution of the floor loading. After a few data conversions, the information was uploaded to an analysis program and several schemes were quickly evaluated.

As initially suspected, the moment frame concepts yielded unacceptably large steel sections. However, the hat truss concept was found to be viable. In the end, a combination of moment frames, hat trusses, and inter-story trusses was proposed to facilitate a stable load path for the structure. The final structural hurdle involved the asymmetrical layout of the cores. Both teams compromised on their initial schemes, resulting in the inclusion of an additional steel core that would support a corner of the cube from below.

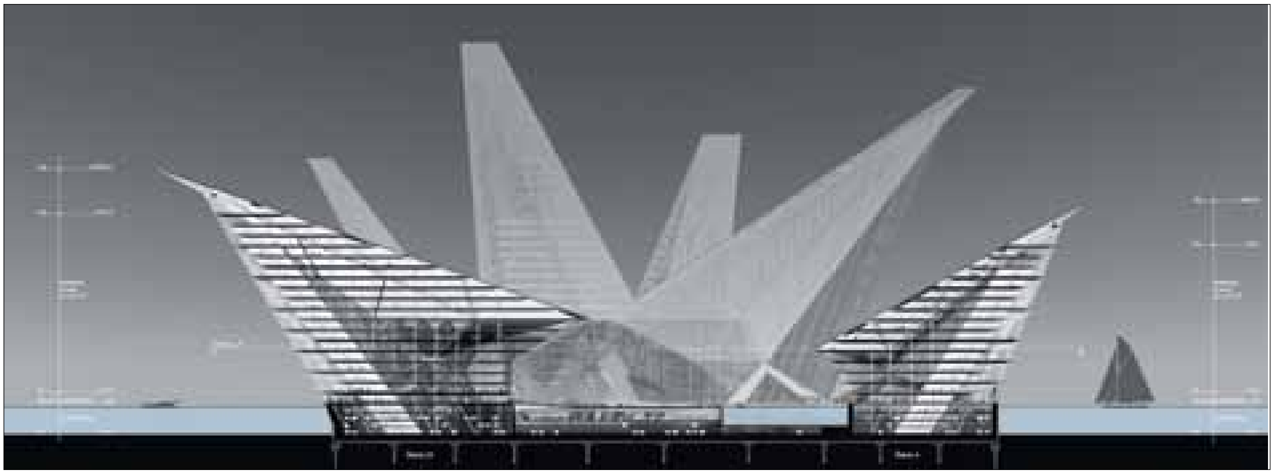

Figure 3 Crystal Center Section

2.2 CRYSTAL CENTER

If a tectonic shift in an undersea geological formation sent giant crystals thrusting up through the water's surface, it might look something like this dramatic arts center prototype, positioned in a lake or a harbor. Eleven jutting, crystalline structures of varying size—with cantilevers of up to 230 feet over the water—are joined at a base largely concealed beneath the surface.

Inside the structures, the cantilevers create stunning interior spaces from which occupants will enjoy extraordinary views, while experiencing a sense of being suspended above the water. The cantilevered roofs also allow the building to shade itself in a hot climate, which, in turn, allows for greater transparency in the glass curtain walls beneath.

Initially, the Crystal Center concept appeared to be the most straightforward structurally. Despite its challenging geometry, a rational framing plan using standard members was anticipated. The intent was to support the cantilevering point of the structure with a prop that extended down to the foundation. Chord members (top or bottom members of a truss) would run along the major facets, forming a shell-like structure that defined the top of the tapering shape. Several rows of columns would be hung from the exterior truss, while other columns extending to the foundation would lean up to meet the superstructure.

After considering lateral wind and earthquake forces, the structural system was reconsidered. The engineers were concerned about not only general stability, but also the amount of movement that would occur at the point of the form. The level of uncomfortable sway was estimated by first computing the period of the structure, or the time it would take for one complete cycle of swaying movement. A damper would be required in the structure to mitigate the motion.

Working within the basic architectural form, the engineers suggested near-horizontal trusses in the top exterior facets. At lower levels in the building, an internal braced frame (x-braces) was also recommended to link the floor diaphragms to the exterior trusses, as well as to assist in torsional resistance. These systems complement the unique inclining concrete core.

2.3 WINGS MUSEUM

Standing 40 stories tall and boasting a wingspan of 300 meters, this structure would be counted as a wonder of the modern world. Inside, visitors would be treated to multiple cascading levels of museum space and extravagant accommodations. Each gallery would be five stories tall with a continuous light-well extending the full height of the building. Hotel corridors would ring the high atriums at intermediate levels between the galleries.

The form was developed through a progression, from sketches to clay and paper models to graphical renderings using Rhino. When the engineers were first invited to review the concept, the architects were curious about how a structural system would be derived. Considering the most efficient means of supporting the sweeping cantilevers, the engineers recommended an exoskeleton design. Such designs have recently been utilized at the Hearst Tower in New York and 30 St. Mary's Axe (The Gherkin) in London. In each of those cases, closely spaced floor-to-floor members that intersect diagonally form an exterior tube. The result is a continuous grid of diamond-shaped segments known as a diagrid. This concept is very efficient because it combines gravitational and lateral structural systems. This also provides a more column-free interior. From an aesthetic standpoint, the diagrid uniquely allowed for a fluid expression of the structure at the façade.

SOFTWARE

Developing the diagrid layout requires close coordination between engineers and architects. On this project, the architectural team took ownership of the diagrid. Early schematic models showed the visual effect of a diagrid but lacked the precision necessary for structural analysis. Grasshopper, a graphical algorithm editor tightly integrated with Rino's 3-D modeling tools, was used to assign the parameters and automatically generate a more rational mesh from the sculpturally modeled forms. Figure 3 provides an illustration of the Grasshopper algorithm.

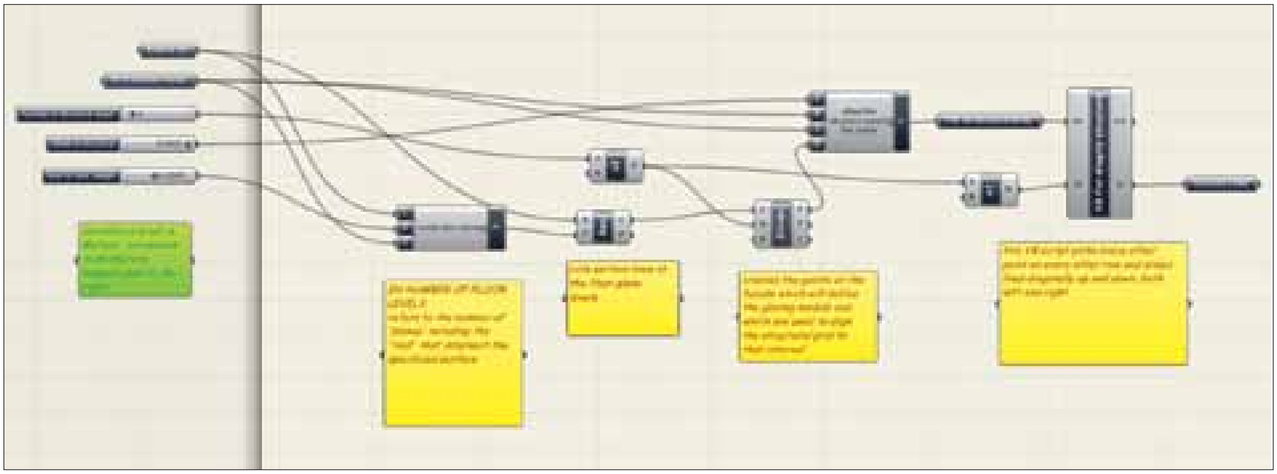

Figure 4 Wings Museum Grasshopper Algorithm

After generating a suitable diagrid mesh, the architects shared their wireframe Rhino model with the engineers. Since care had been taken to make sure that all of the members intersected at discrete nodes, the model parameters could then be directly imported to Finite Element Analysis (FEA) software for structural analysis with minor modifications. Although the initial FEA model ran successfully, results indicated that member sizes had become disproportionately large and uneconomical.

Based on the large member sizes and programmatic constraints, the architects proposed alleviating some of the floor loads by opening up large portions of the floor plates. Multiple-story tall atria were introduced. Implementing the changes in Rhino allowed the engineers to quickly asses the structural impact. The required size of the exterior columns had improved but still did not provide the optimal design. Through a series of iterative analyses, the engineers recognized that the diagrid members were not sufficiently braced against out-of-plane bending and buckling.

Lateral and gravitational loads induce horizontal forces in the diagrid; therefore, the diagrid needed to be braced at each floor. The magnitude of this outward force increases proportionately to the load carried in the diagrid, so greater resistance is required near the base of the structure. The floor slab diaphragm frequently provides adequate bracing stiffness. However, the large interior atria planned in the Wings Museum resulted in slender horseshoe-shaped floor plates for four out of every five floors.

This concern was immediately discussed with the architectural team. They pointed out that the demising walls between the hotel rooms could be utilized structurally. Taking advantage of this opportunity, the engineers proposed buttress trusses to span vertically between the gallery floors. Similar in concept to the buttresses used on Gothic cathedrals, these trusses carried the horizontal force components from the diagrid to the stiffest floors. Deep atrium trusses and ring beams stiffened the gallery floors. The atrium trusses served a dual purpose: providing column-free spans up to 250 feet and linking opposite edges of the floor plate. The ring beams resisted the net horizontal tension conveyed from the diagrid, much like the ring beams used at the base of large domes. Tension forces are the greatest where the angle of change in the floor plate is greatest.

The final piece in the structural puzzle was dealing with the sharp changes in geometry that occurred at a few principal edges of the floor plate. Members placed at these corners became collectors for load. Consider a single continuous line of diagrid members: They track diagonally across the building, shedding little load until intersecting a collector. The collectors receiving compressive forces were naturally the largest members in the design. To moderate the size of these members, a second, smaller diagrid was specified on the interior side of the hotel floors.

This progression of advanced structural concepts took place at an exceptionally accelerated pace. Though each of the concepts is individually well understood and had been applied with precedent, this specific application was only realized through a series of analytical models. The engineers were able to hit the ground running early in the project because of the verbal and digital communication facilitated by Grasshopper, Rhino, and SAP 2000—from concept to graphic model to analytical model. To close the circle, Revit structure was used to graphically illustrate all the structural systems.

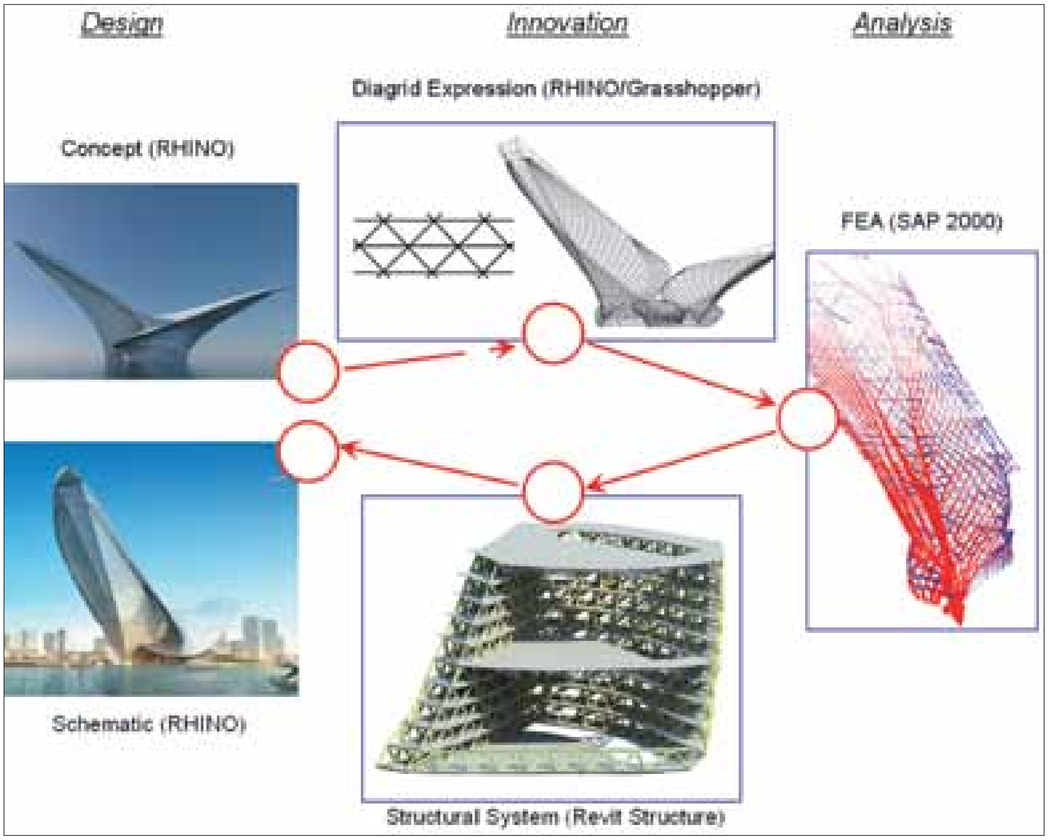

Figure 5 Illustration of Wings Museum Data Flow

3 FACETED HIGH RISE - MERAAS TOWER

The design of super-tall high-rise towers provides many unique challenges for all disciplines involved. Most notable is the coordination and communication between all design professionals. In today's fast-track design industry, communication of information needs to be efficient, but most importantly, it needs to be interoperable. As mentioned in the other case studies, architects and engineers work on different software platforms throughout the life of a project. The most important aspects of the communication between consultants are efficiency of data transfer, reliability of data flow through different software platforms, and informed decision making. Software and procedures in this case study demonstrate the flow of communication in the schematic design phase.

Like a prism, the 112-story super-tall tower has a series of faceted surfaces that increase light and air travel through the building. The faceted shapes maximize energy generation, balance natural light, and offer 360-degree views. The architectural form also creates natural atrium spaces as the building ascends. These atriums allow for the creation of naturally lit sky gardens that activate the tower's form. Vertically segregating the tower program gives the illusion that the structure is composed of four smaller towers stacked on top of one another, creating a "vertical city." The connection zones between vertical segments house the fuselage openings that contain wind turbines and air vents that pass through the body of the tower. Figure 6 provides a rendering of the tower.

Through early collaboration, engineers and architects proposed a tower system that utilized the faceted architectural skin geometry to create an external structural megacolumn and diagonal-brace framing system. This system is comprised of a highly efficient assembly of steel and concrete elements to achieve the stringent design requirements of a super-tall tower. In addition to the planar faceted tower skin, the fuselage openings have an impact on the structural solutions proposed.
The architectural form was massed in Rhino. This software platform allows architectural forms to be rapidly adjusted to present the best and most current design intent. For the architectural form to become the structure for the tower, geometric rationalization was performed to establish the relationship between external geometry and internal structural elements such as columns, slabs, and the interior core. Grasshopper, as the additional interface of Rhino, was used to develop this parametrical system. This interface allows the relationship of the geometry to structure, exterior skin faceting, tower height, and updates to the numbers of tower floors to be parametrically editable per design needs. Figure 7 shows an illustration of the geometry variations per different program needs.

Rationalization processes were developed to establish the key control media. Key control media are constraints set in the parametric algorithms. These constraints, such as facet line relationships to the structural system, control the way the tower geometry is updated. Control media–driven geometry updates provide an efficient method for coordinating changes between the architect and the engineer.

Figure 6 Meraas Tower Rendering

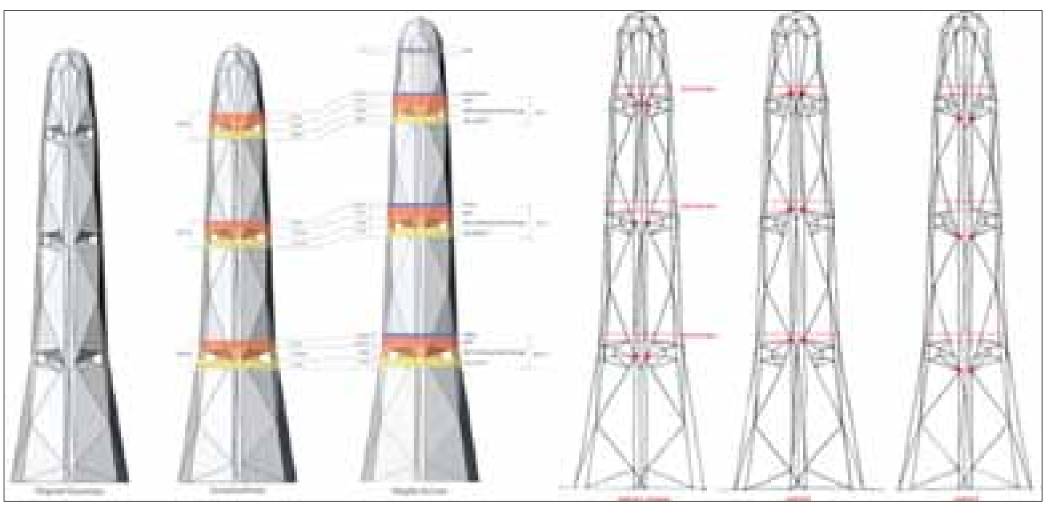

Figure 7 Tower Variation in Geometry

(Tower Height Change) (Adjustment of Exterior Faceting)

For Meraas Tower, a series of the control points was selected and became the control media to generate the architectural form, as well as to be easily transferable to the engineer's information modeling platforms, Revit and FEA software. This information is then used to (re)create/model structural components utilized in the finite element analysis for lateral and gravity load design. Figure 8 provides an illustration of the geometry rationalization outline of the Rhino-Grasshopper interface. Different projects would develop different control media, such as cross-section profiles, plan paths, etc., to provide optimal design control. Appropriate and wise control media are key aspects for design interoperation, both within each discipline and between architects and engineers.

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Software that allows live data to be transferred is also paramount for improving efficiencies in communication between consultants. Both the architect and the engineer can then perform more efficiently and give appropriate direction for the project.

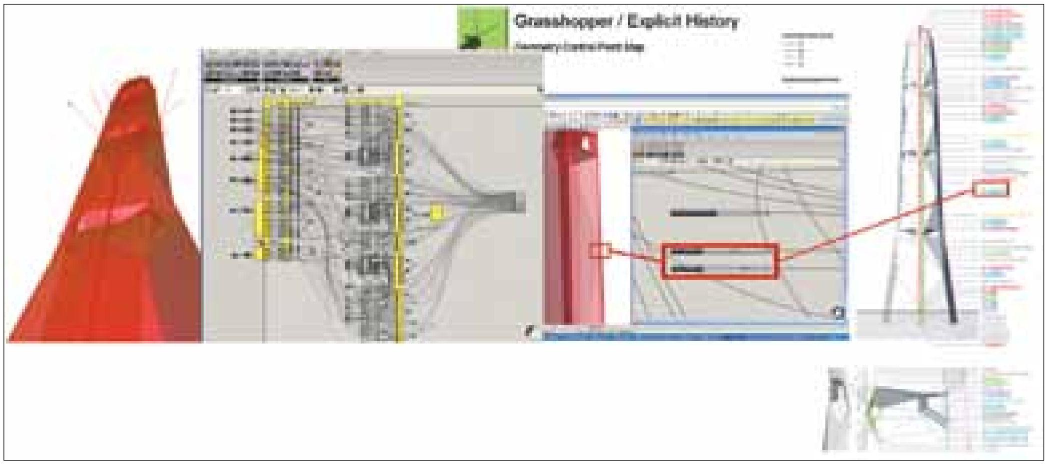

Figure 8 Illustration of Rhino-Grasshopper Interface

Structural engineering for the tower is predicated upon the concern for overall strength and stiffness in resisting lateral loading, both wind and seismic. As previously mentioned, an exterior diagonalized frame, over multiple stories and connecting a limited number of composite steel/concrete megacolumns, which extend along the entire height of the tower without interruption, provide resistance to lateral load. By utilizing the entire exterior dimension of the tower envelope, a highly efficient system is potentially realized. Diagonal and inclined vertical members of the perimeter system are organized along the facet lines of the architectural surfaces. A system of reinforced concrete core walls is oriented about the elevator and stair shafts in the center of the floor plate. These core walls provide local resistance to the global multi-story perimeter structure, as well as additional shear and torsional stiffness to the tower as a whole. At the three fuselage openings through the body of the tower, minor intermediate steel columns along the perimeter are interrupted. A continuous perimeter steel belt truss is provided at each of these locations in order to facilitate the intermediate steel column erection and further stiffen the perimeter structure. One of the challenges was to adjust the architectural faceted form to maximize the structural system efficiency while maintaining the aesthetics.

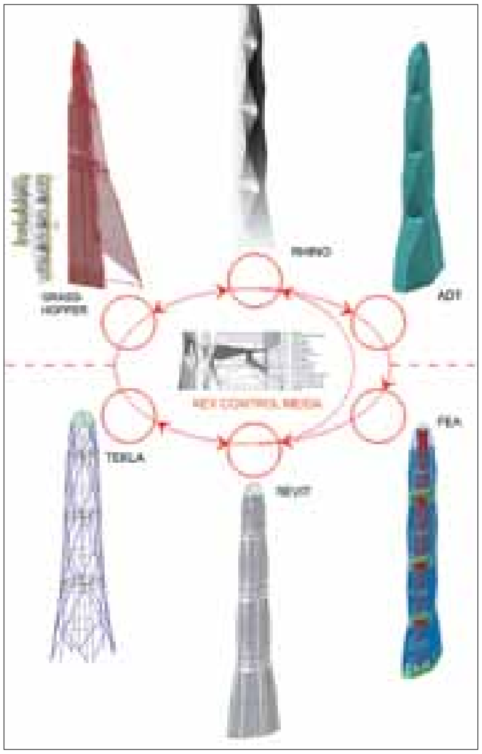

Figure 9 Illustration of Meraas Tower Data Flow

An alternate structural system with exterior concrete megacolumns at near vertical facet lines, interconnected by exterior concrete moment frames along the perimeter, was also investigated. Typical office and hotel floors are framed in structural steel beams, with composite steel deck and cast-in-situ concrete slabs. The floor beams are designed in composite fashion, with the deck slab through conventional headed shear studs. For the hotel floors, floor beams are spaced at 4.5 meter centers to match the room widths and partition lines. In the all-concrete structural system, a mixture of concrete beam and one-way slabs and two-way flat plate slabs were utilized for the floor framing. The tower megacolumns and core wall system are supported on a piled raft foundation. Piles are high capacity, straight shaft, large diameter bored reinforced concrete piles.

The integration of these structural systems into the architectural expression was critical to the overall design of the tower. Communication of the geometry was conducted through multiple software platforms. Figure 9 provides an illustration of the building information data flow through different software packages.

The communication of advanced building information is critical for accelerating project design, constructability, and the construction schedule. Being able to visualize complex three-dimensional building components like the connection of the steel diagonal braces to the concrete megacolumns before structural detailing starts is paramount. Figure 10 provides an illustration of critical structural connections detailed in TEKLA.

Figure 11 shows a study of the geometric transformation for the tower megacolumns at fuselage levels. These are complicated and critical design details for interior space planning, exterior wall geometry, and structural efficiency. After architectural parameters are transferred into the structural model, analysis data would be used to design and define the actual three-dimensional structural elements.

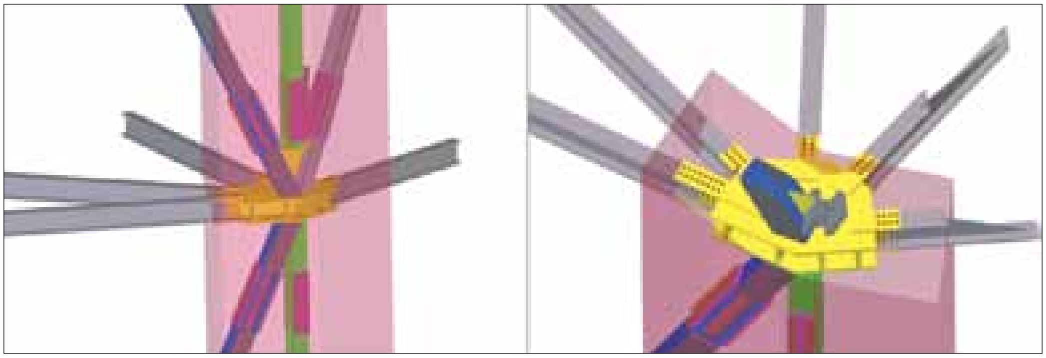

Figure 10 Steel Diagonal/Megacolumn Connection (TEKLA)

(Elevation) (Plan-Section)

Figure 11 Concrete Megacolumns at Fuselage (Opening) Levels

(Fuselage – Zone 2) (Fuselage – Zone 1)

CONCLUSIONS

Software cannot make the final decisions. However, communication through the live transfer of data between software needs to be at the forefront of the design process in order to make timely decisions and to give key direction for a project with geometric complexity. Once this direct link in communication has been established, managing and organizing the data flow is critical. This is accomplished by establishing key control media that is appropriate for the project, and that is understood between all design professionals. Efficient communication also requires an understanding of the advantages and disadvantages of different software platforms, so that the appropriate platform for different design issues at different design stages can be utilized. In short, design professionals must close the circle.

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