Design Considerations in Cable–Stayed Roof Structures

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ABSTRACT

Cable supported structures have inspired and fascinated people for many decades. Today's cables structures are recognized as unique and innovative structural solutions, which create new and dramatic forms while enclosing large spaces and providing new design opportunities. This paper presents several unique aspects of cables and cable-stayed structures, and some of the unique design considerations that should be evaluated by structural engineers.

This paper also includes a case study on The University of Chicago Ratner Athletics Center, a recently completed cable-stayed structure that celebrates 150,000 square feet of health, fitness, and sporting activity space. The $51 million state-of-the-art athletics facility includes a competition gymnasium, an Olympic-sized natatorium, and a myriad of other spaces that accommodate virtually any athletic activity. Designed by internationally renowned architects Cesar Pelli & Associates, and engineered by OWP/P Structures in Chicago, the project features a first-of-its-kind asymmetrically supported cable-stayed system that gracefully suspends S-shaped roofs that float over the large volume gymnasium and natatorium spaces. This innovative structure utilizes 10-story tall composite masts and a series of splayed cables that support shallow curved steel roof members. The thin roof framing is cold-bent to shape, and delicately suspended over the 160-foot spans. The tapered masts are stabilized by back-stay cables anchored in place by massive concrete counterweights that counteract the weight of the roof.

DESIGN CONSIDERATIONS IN CABLE-STAYED ROOF STRUCTURES

Figure 1 – Olympic Roof Project, Munich, Germany

Cable-supported roof structures have inspired and fascinated people for many years. However, cables systems still represent a relatively new form of roof construction. Prior to the 1950s, steel cables were used primarily for long-span bridge structures, not buildings. In the 1950s appreciable advancements were achieved in the understanding and analysis of cable roof structures, culminating in significant building structures like the Olympic Roof project designed for the 1972 Olympics in Munich, Germany. Today, cables structures are recognized as unique and innovative structural solutions that create new and dramatic forms, while efficiently enclosing large volume spaces and providing new opportunities for transparency and natural light.

There are several types of cable-supported structures, but they can generally be sorted into two categories, cable-suspended and cable-stayed structures. In *cable-suspended* structures, the draped cables are the main supporting elements of the structure, and their curvature is a major factor in the load carrying capacity of the system. In *cable-stayed* structures, cables stabilize vertical or sloped compression members (usually called masts or pylons) and serve as tension-only members. This paper focuses primarily on this second type of cable-supported structure, cable-stayed structures. This paper also includes a case study, which outlines the design considerations and challenges of a recently completed and award winning cable-stayed roof structure, The University of Chicago Gerald Ratner Athletics Center.

The load carrying capacity of cable-stayed roof structures is not dependent on the curvature of the cables themselves, which are virtually straight with the exception of a small amount of sag due the cable's self weight. Various cable configurations can be incorporated into cable-stayed structure layouts, including "fan" profiles, "harp" profiles, and hybrid profiles that are a combination of the two (see Figure 2). The axial compressive members (masts/pylons) that support the cables can be designed as solid elements or open elements that are designed like tied-column elements. The axial compressive members can take on different profiles, and can be oriented as vertical elements or sloped elements. Symmetry of the structural system, architectural preferences, as well as how the cable loads are applied to the masts, are factors in the final shape and orientation of the supporting axial compressive element.

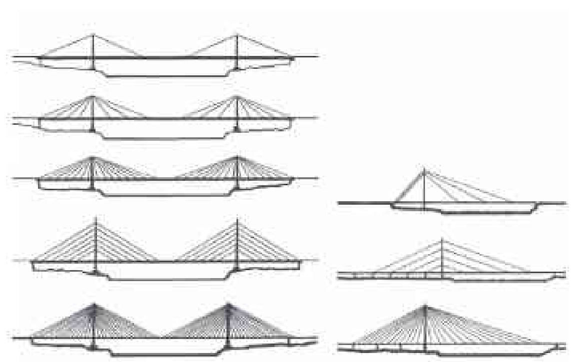

*Figure 2 – Various Cable Configurations**

The term "cable" is generically used to describe a flexible tension member consisting of one or more groups of wires, strands or ropes. Steel cables are distinctly different than steel rods. Steel rods consist of a solid circular cross section of mild steel, typically available for building applications in yield strengths of 36 or 50 ksi. The properties of steel used for cables is typically much stronger than the steel used in rods, allowing cable assemblies to have a tensile strength approximately 4-6 times greater than steel rods. Cables usually have yield strengths of approximately 240-270 ksi. Cables are also inherently redundant members. Since cables are comprised of dozens or hundreds of wires, the failure of a single wire is not significantly detrimental to the load carrying capacities of the cable. The loads in each individual wire has the ability to redistribute load to the remaining wires if one wire breaks or is eliminated. A "wire" is a continuous length of steel that typically has a circular cross section, and is cold-drawn from a small diameter steel rod. A "strand" is an assembly of wires formed helically around a central wire in one or more symmetrical layers (see Figure 3, picture 1). A wire "rope" is made from multiple wire strands that are twisted about a central core, which is typically comprised of another wire strand or rope (see Figure 3, Picture 3). Wire ropes are frequently used in cable-suspended structures because ropes are more flexible than strands.

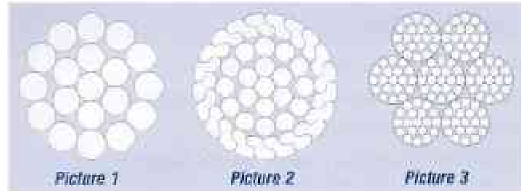

*Figure 3 - Wire Strands and Rope***

Not all strands have wires with a circular cross section. Some cable manufacturers make a unique cable cross section called a full-lock or Z-lock cable, which consists of Z-shaped cold-drawn or cold-rolled wires at the perimeter of the strand (see Figure 3, picture 2). Full-lock cables are designed to reduce water infiltration in the cable assembly, reducing the potential for corrosion of the wires. Some cable manufacturers produce a proprietary full-lock cable with a zinc-rich powder that fills the small inner voids between wires, providing additional protection and prolonging the life of the cable. Since cable technology is relatively new, the life expectancy for cables in exterior building applications is not yet well defined. Many factors influence the life expectancy of cables, including climatic conditions, cable material properties, coating systems such as galvanizing and stainless steel, and use of cable sheathing and high performance paints. However, by selecting an appropriate cable assembly and adhering to a regularly scheduled inspection program, many cables have the potential to last as long as the structure they support.

Cables are elastic, yet they exhibit a nonlinear behavior when loaded. The degree of nonlinearity varies with the cable structure as well as how the cables are loaded. The nonlinear effects of cables are generally less dramatic in cable-stayed structures than in cable-suspended structures. Two types of cable nonlinearities exist, geometric nonlinearities and material nonlinearities. A draped cable supported at two points in a horizontal plane will follow the catenary curve of the applied load and will undergo large geometric deformations, particularly when the load is concentrated or unsymmetrical. Geometric nonlinearities, therefore, occur in loaded cables regardless of whether or not the cable material is elastic. It is also important to note that significant elongation of the cables and deformation of the supported structure must be taken into account in the design of cable-stayed roofs. A nonlinear analysis should be performed if it is determined that the magnitude of cable displacements is such that the equilibrium equations for the structure should be based on the geometry of the displaced structure.

When cables are initially manufactured, they are not truly elastic. As a result, cables are often prestretched. If the cables are not prestretched, they will stretch inelastically as the cable is tensioned and individual wires settle into their final positions. Prestretching cables to a high percentage of their minimum breaking strength allows the wires to find their final position, with well-defined elastic characteristics. As helically wound cables are stretched, they will also try to twist. To assure that cables are properly installed and that the cable length has not changed i.e. they have not been twisted from their initial prestretched orientation, it is advisable for the designer to specify cables be shipped and installed with a removable longitudinal stripe on the cable that clearly defines the proper cable installation orientation.

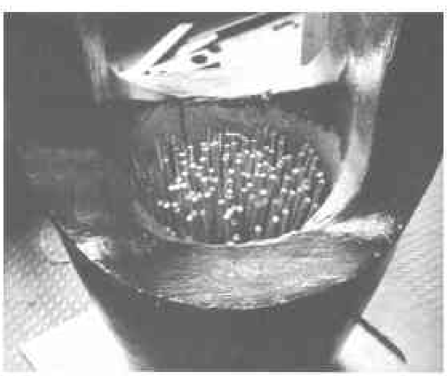

*Figure 4 - Broomed Cable at Cable and Socket Joint****

To ensure the cables arrive at the project site in satisfactory condition, cables should be shipped on reels with sufficient diameter to prevent bending and loss of prestretching effects. Cables should also be protected at the site and handled in a way that will prevent kinking or other damage to the cables.

As cables are handled at the project site, they should be brought into place and handled by their termination fittings. There are several types of cable termination fittings available that "grip" the cable and allow the cable to be attached to the primary structure. The application of the termination fitting, clamped, swaged, or socketed is typically how the fittings are classified. For example, a cable is inserted into the *swaged fitting*, which is placed in a die block of a hydraulic press. The softer steel of the fitting is hydraulically pressed such that the fitting's steel flows plastically around the harder steel wires of the cable. A swaged fitting is designed to develop the full strength of the cable, and is used with smaller diameter cables (less than approximately 1 ½" diameter). *Sockets* are typically used for large diameter cables. Sockets are cast or forged steel shapes that are fully tested and provided by the manufacturer along with the cable. The end of the cables is pushed into the socket, which has a wedge-shaped void that receives the end of the cable. Once the cable is in the socket, the cable wires are spread and separated within the wedge-shaped socket void, such that the cable end has a similar appearance to a stiff broom (see Figure 4). The socket void containing separated wires is then filled with molten zinc, or resin. When the cable is tensioned, the cooled wedge bears against the inside surface of the socket, transferring the cable load to the socket. Socket connections are available in two profiles; *open sockets*, which have an opening to receive a single connection plate, located on the structure (see Figure 5), or *closed sockets*, which have a single end connection that is knifed between two connection plates on the structure. The cable fittings are designed such that they are stronger than the cables themselves. The termination fittings are typically designed to develop an ultimate strength of at least 110 percent of the cable strength.

Figure 5 - Example of Open Socket Connection

Several books are available that provide excellent guidelines and commentary for the design of cable-stayed structures. However, governing building codes typically do not address specific design criteria for cable-supported structures. To provide guidance for the design of cable-supported structures, the American Society of Civil Engineers (ASCE) has developed useful standards through their publication ASCE 19-96, Structural Applications of Steel Cables for Buildings. The ASCE 19-96 publication touches on several topics including recommendations for design drawings and specifications, unique design considerations, material properties, fittings, protective coatings, and fabrication and erection of cable structures.

ASCE 19-96 indicates that temperature effects on cables, vibrations, deflections, and erection analysis must be evaluated for cable structures. The ASCE standard also states the minimum breaking strength of cables shall always be at least twice the maximum cable design loads, including the envelope of loading combinations of cable self-weight, structure dead load, cable prestress forces, and live load and environmental load combinations. Cables should also maintain a *minimum* tensile force under all loading conditions to minimize visible cable sag and potential for induced cable vibrations. Maintaining minimum cable tensions is also critical in achieving the required stiffness necessary to stabilize the axial compressive masts and other components of the structure. Cable-supported structures, which are generally lighter structures, must also be designed to account for the dynamic effects of individual cables and the overall structure.

The construction documents for cable-stayed roof structures will typically provide information not shown on projects with more conventional structures. Cable-stayed documents define specific coordinates and parameters of the cable structure, including diameter and required cross sectional area of the cables, which can vary depending on size and shape of wires used in the cables. The documents and specifications should clearly indicate any requirements for wire coatings, unique material properties, and specific testing procedures. They should also identify acceptable tolerances for the final geometry of key coordinates of the erected structure, as well as ranges of acceptable final cable tensions at a defined ambient temperature.

In addition to defining geometry tolerances and cable tensions, the design documents should also provide parameters or recommendations for the erection sequence of the structure. While it is the erection engineer's responsibility to establish the erection sequence required to achieve the final geometry and associated cable tensions of the structure, the design engineer is most familiar with the final structure, and can provide valuable information to the erection engineer particularly regarding issues of load flow and structural stability. The design engineer should be aware that the erection sequence might require cable forces not originally analyzed for the completed structure. When cables are initially tensioned, they are frequently not be tensioned to their defined design tensions. Unless all the cables are tensioned simultaneously, the magnitude of cable tensions will change as subsequent cables are tensioned. As a result, some cables are initially over-tensioned and others under-tensioned to ultimately achieve the correct final tensions at the end of the tensioning sequence.

The University of Chicago Gerald Ratner Athletics Center – A Case Study in Cable-Stayed Roof Structures

PROJECT OVERVIEW

The prestigious University of Chicago is in the midst of its largest capital development program in the University's 114-year history (est. 1890). The University is investing over $500 million in new facilities, as well as significant renovations to existing facilities. One reason for the improvements is to attract new undergraduate students that have the academic credentials to choose from the best universities in the country. The University of Chicago is augmenting their exceptional academic program with new and renovated facilities that provide opportunities for academic excellence, and allow students to maintain a balance between mind and body. One of those facilities is the new Gerald Ratner Athletics Center.

The University of Chicago Gerald Ratner Athletics Center is a $51 million state-of-the-art athletics facility that celebrates 150,000 square feet of health, fitness, and sporting activity. The project includes a competition gymnasium, an Olympic-sized natatorium, and a myriad of other spaces that accommodate virtually any conceivable athletic activity.

Consistent with their reputation for exceptional academics, the University is interested in exceptional architecture on their campus. To achieve their goal, the University selected Cesar Pelli & Associates to design the new athletics facility. Cesar Pelli & Associates teamed with OWP/P, one of the largest architectural engineering firms in

Chicago, because of their extensive experience with athletics facilities, as well as their ability to provide a strong local presence for the project. OWP/P served as the architect of record for the project. OWP/P Structures, a division of OWP/P, who also has extensive athletic facility experience, was selected as the structural designer and structural engineer of record for the project.

The Ratner Athletics Center is particularly unique because it is the first asymmetrically supported cable-stayed building with multiple levels of splaying cables in Chicago, and possibly the country and beyond. The innovative structural solution allows large volume spaces (over 20,000 square feet) to be enclosed with structural steel members that are only 33 inches deep. The asymmetry of the structure is dictated by site constraints along with architectural preferences. The unique athletics facility structure proved to be an extremely complex engineering challenge, and required a high degree of structural analysis. One of the primary goals of the engineering team was to develop the best and most efficient structural system that met unique architectural design objectives for the project.

The architectural design objectives for the structure, developed collectively by the architectural and engineering team, included four primary considerations:

- *The structure needs to be appropriate for its use*
  Even though unique and inspirational architecture was important, it was also important to develop an appropriate structural system that met the programmatic needs and budget constraints of the project.
- *The structure needs to be honest*
  Since a cable-stayed structure was selected for the project, all the cables needed to be functional and carry significant load. Cables or cable layout were not embraced solely to achieve an architectural image or dramatic appearance.
- *The structure needs to be true to the material*
  The most appropriate structural material was selected to resist the loads i.e. concrete was not used where steel could resist the load more effectively or at a lower cost to the project.
- *The structure is the architecture, and needs to be detailed accordingly (within the limits of the material)*
  The structure would be exposed, but the expectations of the finished product were in alignment of what could be expected from the material i.e. the team accepted the imperfections of the rolled steel process, and was not expecting the structure to have the refinement of a handrail, or other highly finished product. The "pinned base" detail illustrates a detail that literally communicated the structural performance of the connection, while doing so in an attractive exposed fashion (see Figure 6).

Figure 6 – Pinned Base Detail at Mast

STRUCTURAL SYSTEM OVERVIEW

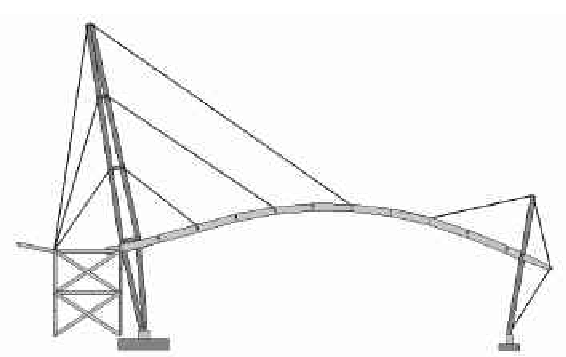

Figure 7 – Gymnasium Section

While cable-supported structures are not new, the three-dimensional configuration of this structural system with multiple levels of forestay cables that splay and support loads in three opposing directions makes this structure the first of its kind. The structural system for the gymnasium and natatorium space is a masted cable-stayed roof system of composite masts that are sloped, tapered, and stabilized by 15 cables (nine fore-stay cables and six back-stay cables), which in turn support S-shaped roof girders (see Figures 7 and 8).

From the interior of the building, the system achieves the architectural designer's vision of a delicate and uniform roof structure with minimal structural depth. The unique structural system allows column free spaces of 160' x 125'

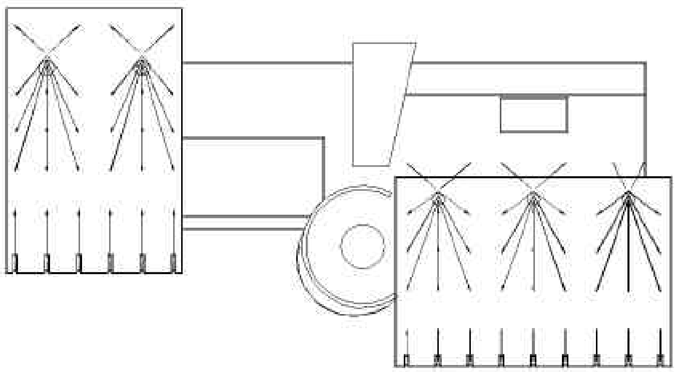

Figure 8 – Ratner Athletics Center Roof Plan

in the gymnasium, and 130' x 200' in the natatorium. Both spaces have a similar system of primary masts spaced at 75' on center, which are opposed at the other end of the structure by smaller masts located at 25' on center. Each of the primary masts supports three curved roof girders, with the mast located on axis with the center girder. The cables splay outward from the mast, and support roof girders located 25' to either side of the central girder. The cables are connected to the primary mast at three distinct elevations: top of the mast, approximately 25' below the mast top, and at approximately 50' below the mast top. Each of these levels has three forestay cables that reach to one of the three supported roof girders. Each level also has two backstay cables; each reaching to a tie-down connection located 25' on either side of the mast. The backstay cables transfer load to steel tension columns, which in turn anchor to massive concrete foundations resisting the overturning forces from the weight of the roof. Smaller secondary masts opposite the primary masts are located at each girder line. A single cable from the top of this mast supports a portion of the roof girder. Two back cables in a bow configuration help resist the flattening tendency of the arched roof. The overall result is a series of roof girders supported at four points by cables, effectively reducing the girder span and allowing the girders to be only 33 inch deep wide flange sections.

The asymmetry of the gymnasium and natatorium structure is a result of site constraints and architectural design preferences. The overall asymmetry of the structure results in an unbalanced horizontal thrust delivered to a truss located in the roof plane behind the primary masts through axial load in the curved roof girders. The horizontal truss transfers load to the building's vertical braced frames, thus the lateral system is essentially a component of the gravity system.

With each of the primary masts supporting three separate roof girders, it is critical to balance the load supported by each mast. Therefore, the girders located at the exterior walls on each side of the structure must also be supported by the mast and cable system, and not by the perimeter columns located directly below the end girders. The columns at the exterior sidewalls of the spaces offer no vertical support to the roof structure, and are connected to the roof only with vertically slotted connections. The sidewall columns are primarily vertical beams, which resist wind loads from the 50' tall exterior walls. However, the perimeter columns are also components of the lateral system and thus the vertically slotted connections are able to transfer horizontal loads from the roof diaphragm. The roof is in essence a curved floating plane suspended only by the cable system. The roof moves approximately 3.5" up and down at mid-span under the envelope of loading conditions across the 160' span of the gymnasium, and 3" up and down across 130' span of the natatorium.

The masts are inclined at 10 degrees from vertical for aesthetic reasons as well as to maximize its effectiveness in the asymmetrical structure. In order to maintain the mast as a predominantly axially-loaded member, the base of the mast is modeled and detailed literally as a "pinned" base in the direction of the span, such that the slight rotation of the mast under various loading conditions do not induce moments at the base of the mast. Additionally, the W33 that is in line with the mast, which carries axial horizontal thrust to the roof truss located behind the masts, is detailed as a collar that passes load around the mast, minimizing any bending in the mast. Each mast in the gymnasium transfers over 1700 kips of vertical load from the roof through the cables to the foundation.

Since the large volume gymnasium and natatorium spaces could not be interrupted with interior columns or tie-down system, a thin layer of concrete topping was added to the long span roof deck to provide sufficient dead load to offset uplift forces from gusting winds. The roof deck is a 7 ½" deep, long span deck with 2 ½" of lightweight concrete topping, and spans the 25' spacing between the W33 roof girders. The roof deck acts as a lateral diaphragm in the direction perpendicular to the span of the W33's, transferring load to high strength diagonal bracing rods at each end of the gymnasium and natatorium spaces.

COMPOSITE MASTS

Figure 9 – Composite Mast

The soaring 10-story tall masts are one of the most dramatic features of the structure (see Figure 9). They are comprised of three 18" diameter hollow structural steel sections arranged in a triangular, tapering form and tied together with 12.75" hollow structural steel sections at elevations of cable attachment, as well as at the point where they pass through the roof (roughly 30' above the base of the mast). At their widest, the composite masts of the gymnasium are 7'-6" across, and 5'-9" across at the natatorium. The secondary masts are 54-foot tall, single hollow structural steel sections of the same diameter. Each of the 18" diameter structural sections is filled with 10,000 psi high-strength concrete acting compositely with the steel to resist the large compressive loads delivered from the cable-stayed roof. The composite masts use new engineering knowledge, designing composite columns with greater lengths and using an innovative pumping technique to fill the masts with concrete. The contractor chose to place the concrete in a single concrete cast through "ports" located at the building roof level. A high-slump cast-in-place concrete was allowed to free-fall 30 feet to the base of the mast, then was pumped *up* the remaining height of the in-place masts, reducing the possibilities of air pockets and voids that might have been created around the internal stiffeners located at each point of cable attachment. This in itself was a constructability challenge and required special attention to specifying an appropriate mix design. The procedure was further complicated by the fact that the mast concrete was significantly placed in the heart of the Chicago winter, during conditions of at or near freezing temperatures, and particular attention needed to be paid to appropriate cold weather concreting procedures to ensure the integrity of the concrete.

The hollow steel masts were fabricated by LeJeune Steel in Minneapolis, and shipped in one piece to the project site, where they were lifted into place by a high capacity crane. In early design, the engineering team researched availability of large diameter hollow structural steel sections and found that 18" diameter, half-inch wall section of ASTM A500B material was available from select producers, and proceeded with design. However, at the time of material purchasing for fabrication, available quantities of this material section was not sufficient, and a substitution was made to use the more readily available API 5L x42 line pipe. Additionally, cable connections to the mast were required to be designed for the cable's minimum breaking strength, not merely the cable design load. The cable breaking strength is at least twice the maximum allowable cable design load, and therefore, in some cases a heavier wall (.812"), higher strength (65 ksi) section was spliced into the mast at cable connection points to reduce local stresses on the walls of the HSS. In other cases, a system of internal stiffeners was designed to adequately transfer the cable loads to the composite mast.

CABLE DESIGN CONSIDERATIONS

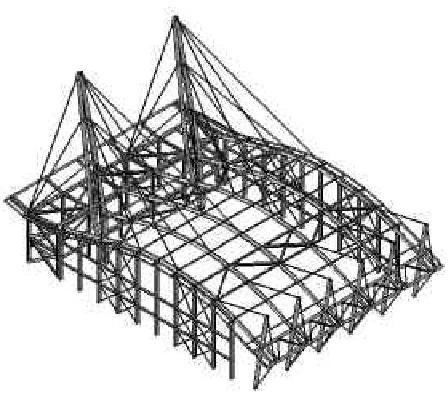

Figure 10 – Gymnasium Model

It was critical that under all loading conditions, the cables maintained a minimum amount of tension to mitigate any noticeable sag, to minimize any detrimental vibrations, and to provide stability to the masts. Cables were pre-stressed to ensure that they would always be in tension. Cable tensions under numerous loading conditions including snow loading, snow drifting, and wind uplift and downward forces were analyzed. Additionally, thermal impacts throughout the full range of climatic temperature variations on the structure, ice loads, and predicted long-term settlement of the mast bases were also critical components of the analysis that impacted initial cable tensions. Risa 3-D and Robot structural analysis software was used to develop three-dimensional structural models to investigate the numerous load combinations and to account for any non-linearity of the structure. The final gymnasium model had 450 nodes, 800 members, and 48 cables, and the natatorium model had 560 nodes, 1000 members, and 72 cables (see Figure 10). Numerous iterations adjusting cable pre-stressing tensions to optimize cable sizes, member sizes, and initial structure geometry were investigated. The goal was to achieve tensions that fell within the desired envelope to meet minimum serviceability tensions, not exceeding maximum allowable cable tensions under all loading conditions throughout the life of the structure. Per the applicable cable standards, maximum cable tensions should not exceed 45% to 50% of the cable design strength. Galvanized cables were used on the project ranging in size from 36 mm to 66 mm in diameter, with minimum breaking strengths of 286 to 978 kips.

In order to help minimize the maintenance and increase longevity, full-locked cables were specified to reduce water infiltration and subsequent corrosion of the cable wires. The helically wound cables include two to three outer layers of interlocking Z-shaped wires, specifically designed to inhibit water infiltration, surrounding a circular wire core. Full-locked cables are not currently domestically produced, and consequently all of the cables were imported from Germany.

MAST STABILITY ANALYSIS

The composite masts are critical compression elements and were the subject of complex stability considerations and analysis. The masts are not symmetrically braced about their vertical axis, and are braced at multiple levels by tension-only elements (cables) of varying stiffness. The spring braces of varying stiffness are provided by the cables tied to the foundations behind the mast, and the cables connected to the W33 girders, which are themselves spring supports. This presented several complex stability and buckling issues for the masts as well as the W33 girders (which also resist axial loads) not directly addressed by current design codes. References including published engineering standards and engineering papers by experts in stability analysis were used in addition to consultation with stability experts to establish an appropriate analysis procedure to calculate axial capacities and critical buckling loads of these members. Each composite tied-column mast has varying axial load along its length and between each of three distinct legs, as well as biaxial moments. Structural analysis software aided in determining spring stiffness at each cable connection level, which were reduced by the calculated spring stiffness of the W33 girders. This information was used to determine brace forces and compared to required brace forces to determine k-values for each segment of the mast. Ultimately, axial capacities and moment capacities of each segment were calculated to evaluate actual maximum loads to ensure satisfactory design of each mast.

REDUNDANCY

Since the City of Chicago Department of Buildings reviewed the project for a building permit shortly after the catastrophic events of September 11th, 2001, the City required the structural engineers to closely review the redundancy of the structure. Since clear redundancy criteria for this type of tensile structure does not have precedent, the City established their own criteria, requiring the investigation of instantaneous cable failure, and the associated effects. The structural design, including stability of the mast with a missing cable, was evaluated based on the City's criteria, and deemed satisfactory.

REVERSE CURVED ROOF GIRDERS

The architectural design called for the large, voluminous spaces of the natatorium and gymnasium to be enclosed by curved S-shaped roofs. Each of the W33x169 roof members, 160' in the gymnasium, 125' in the natatorium, is cold bent about its strong axis with reverse curves to multiple radii, using the latest steel bending technology. Segments of W33 up to 100 feet long were fed through a series of rollers to achieve the specified radius in mere minutes.

WIND TUNNEL TESTING AND ANALYSIS

The reverse curvature of the gymnasium and natatorium roofs present unique challenges when applying code provisions for wind and drifting snow. Current engineering codes and standards do not specifically address wind loading and drift criteria for the unusually shaped roof. Wind tunnel and water flume tests were performed to provide design parameters for the cable-stayed structure. Having an accurate measure of the drift and wind loading patterns allowed the building design to be further optimized. It also identified heavily loaded areas that are not intuitive or addressed by the governing code. For example, the water flume test identified a snowdrift configuration

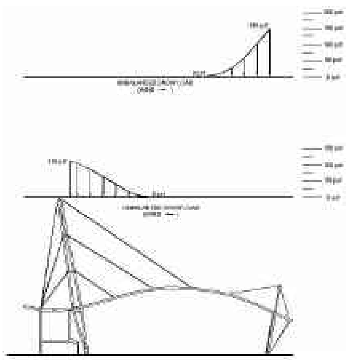

Figure 11 – Critical Snow Drift Load Case

that could form on the downward sloping portions of the roof near the eave (see Figure 11), which was a critical loading condition for the long-span roof deck and the overall structure.

Further complicating the matter is the cable structure's sensitivity to unbalanced loading conditions as well as its dynamic response to lateral loads. The wind tunnel test results provide the means to ensure a clear and reliable understanding of the structure's response to unbalanced loads. A dynamic analysis of the structure verified that the building's fundamental frequency does not align with the frequencies of the individual cables, minimizing concerns about harmonics within the structure.

MAST AND TIEBACK FOUNDATIONS

The behavior of the cable-stayed structure is extremely sensitive to settlement of the supporting foundation, particularly at the base of the masts. Excessive settlement of the mast foundation could reduce cable tensions below the envelope of acceptable tensions previously discussed. Therefore, selecting the appropriate foundation system for the mast and tieback columns is critical. The soil profile at the site consists of a top layer of sand approximately 15 feet deep. Below the sand is 15 feet of soft clay underlain by stiff clay. The relatively high bearing strength of the sand allows for a reasonably proportioned conventional shallow foundation at the masts. However, due to the magnitude of the mast's sustained loads, the soft clay could experience long-term settlement of undesirable magnitude, if not accounted for in the design. Since the foundations for the other elements, such as the secondary masts resist substantially less sustained load than the masts, conventional shallow foundations were deemed appropriate for the remainder of the structure. The challenge was to find an appropriate mast foundation system that would be compatible with the long-term anticipated settlement of the rest of the structure. Large differential settlements between the masts and the rest of the building could cause the cables to lose tension and experience visible sag (see Figure 12). Traditional deep foundation systems were explored and deemed not to be cost effective. At the recommendation of the geotechnical engineer, a soil improvement method called triple tube jet grouting was implemented to limit the long-term settlement of the mast foundations to one-half inch. This technique uses a mixture of grout, water, and air injected under high pressure to create "columns" of a soil-grout mixture. These columns transfer the loads from the foundation directly into the stiff clay layer (see Figure 13).

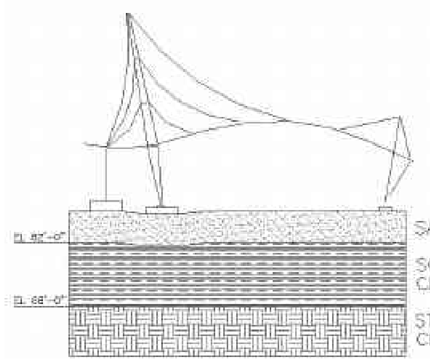

Figure 12 – Settlement Effects on Cable-Supported Structures

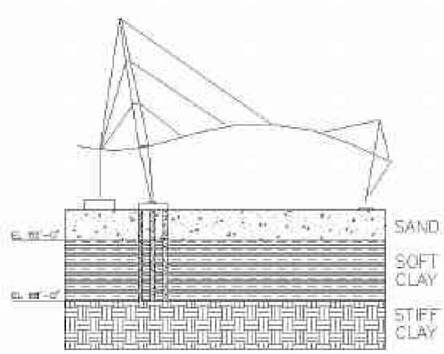

Figure 13 – Jet Grout Soil Improvements

The asymmetry of the cable structure results in large uplift reactions at the base of the tieback columns. Deep foundations that rely on friction or soil weight were explored as alternative solutions, but were determined not to be appropriate or cost effective. Concerns with deep foundations included long-term upward settlements having an adverse impact on the behavior of the cables, as well as highly tensioned elements in the ground that could possibly be disturbed in the future. In addition, several of the tieback columns are closely spaced such that the areas of influence overlap. These considerations directed the design team toward the system that was ultimately implemented; reinforced concrete counterweights buried below grade that utilize their self weight to resist the uplift forces from the cable-stayed tension elements. The system ensures a foundation with no upward displacement over time, and a system that will not be impacted by future removal of the surrounding soil. The long-term ground water level limits the depth of these foundation elements to approximately ten feet below grade. If the concrete counterweights extend below the water table, the hydrostatic pressure on the bottom of the footing produces additional upward forces. As a result, the counterweights are large in plan relative to their depths. In some cases, the depth restriction forces two tie-back columns to anchor to the same counterweight foundation, with footings that reach sizes of 25 feet x 50 feet x 8 feet deep.

CABLE-STAYED ROOF ERECTION PROCEDURE

ASCE 19-96 Structural Applications of Steel Cables and Buildings suggest the contract documents show a recommended erection procedure for the proposed structure. During the design phase, erectors were consulted to discuss erection procedures to determine an appropriate and constructible procedure for the erection of the cable-stayed structures. The challenge is to get the final structure to the specified geometry and cable tensions knowing that each stage of the erection sequence will impact the geometry and cable tensions. These discussion helped shape the recommended procedure documented on the structural drawings. The original concept on this project was to fabricate the structure to a specified geometry at a defined ambient temperature. Temporary shoring towers at each cable attachment location were to be used to keep the structure in the required geometry prior to cable tensioning. Once the entire structure was erected and supported by the shoring towers, the cables were to be tensioned simultaneously, lifting the structure off the shores and resulting in the intended geometry and cable tensions. This approach has been successfully implemented on other projects, including the cable-supported fabric roof at Stuttgart Stadium in Stuttgart Germany.

Figure 14 – Hydraulic Jacking System Used to Tension Cables

The general contractor for the project had also consulted multiple erectors, and had their own ideas about how to erect the structure. Once a fabricator and erector were awarded the project, the erector began to investigate alternate erection scenarios. They were interested in erecting the structure in stages, reducing the need for simultaneous jacking. The project specifications required the contractor to hire an "erection engineer", a structural engineer licensed in the state of the project, to model the structure and the erection procedure. Since the erection engineer elected to erect the structure in stages, the erection engineer's responsibility was to model the erection procedure using staged non-linear analysis techniques to ensure the final specified geometry and cable tensions were achieved. This independent model was of critical importance, particularly as they pursued erection methods that deviated from the design engineer's recommended procedure. The erection engineer considered implementing an erection procedure where all the cables were attached to the mast, and the roof girders would be hung directly from the mast supported cables – eliminating the need for temporary shoring. However, that scenario induced unacceptable horizontal thrusts on the masts from the roof girders. Ultimately, a concept that used a single temporary shoring tower near the mid-span of each roof girder emerged as the contractor's most favored approach. In this solution, the roof girders are erected, using only a single shoring tower near the midpoint of the long-span roof. Once the structure is erected, cables are connected to the mast and roof girders and are tensioned in stages, starting at the lowest level of splayed cables. The same procedure was implemented at the adjacent masts before the crew moved up and began tensioning cables at the next higher level of each mast. Cables were tensioned with the use of hydraulic jacks. Two jacks pressurized in parallel were attached to the two threaded rods on each socket. Pressure gauges on the hydraulic jacks allowed the erector to covert pressures and determine the exact force in each cable (see Figure 14).

CONCLUSION

Cable-stayed roof structures are complex structural systems that require unique design considerations. They use flexible tension-only members to resist large and varying roof loads. Cable-stayed systems can also be used to create dramatic and inspirational structures that enclose large volume column-free spaces, and still provide unique opportunities for architectural design freedom.

The University of Chicago Gerald Ratner Athletics Center is a unique and innovative cable-stayed structural system that creates a dramatic architectural experience from both the interior and exterior of the building. The structural solution reduces the depth of the roof members and overall project cost by using cables to suspend the structure. The roof system also serves as the building's finished materials, eliminating the need for costly ceilings and other cladding materials. The cable-stayed system allows 20,000 square feet of large volume column-free athletics space to be efficiently and cost effectively enclosed. The cable-stayed solution also creates a thin structure that "floats" over the interior spaces, and allows natural light to penetrate the spaces through continuous clerestories located along the roofline.

REFERENCES

ASCE 19-96 Structural Applications of Steel Cables for Buildings, 1997.
Krishna, Prem, *Cable Suspended Roofs*, McGraw-Hill, Inc. 1978.
Scalzi, J.B. ;Podolny, W. Jr., Teng, W.C. *Design Fundamentals of Cable Roof Structures*, United States Steel Corporation, 1969.
* Image from page 242, Krishna, Prem, *Cable Suspended Roofs*, McGraw-Hill, Inc. 1978.
**Image from Pfeifer Catalog, 2000
*** Image from page 11, Harris James, Pui-K Li, *Masted Structures in Architecture*, Butterworth Architecture 1996