Getting Started with Cable-Net Walls

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While cable-net-supported glass walls remain an atypical design solution for exterior wall systems, their popularity is growing.

CABLE-NET SYSTEMS, WHILE CONCEPTUALLY SIMPLE, ARE STILL A SOMEWHAT EXOTIC SOLUTION FOR SUPPORTING GLASS WALLS, DUE TO THEIR MINIMAL STRUCTURE AND LARGE IN-SERVICE DEFLECTIONS. But since the first application of the planar cable-net concept in 1993, the practice has established a proven track record thanks to the completion of several major cable-net wall projects around the world.

The first cable-net wall, at the Kempinski Hotel in Munich, Germany, is 40 m wide by 25 m tall and was designed with the principal cable pretension installed in the longer-span horizontal direction. The 22-mm-diameter cables are spaced at 1,500 mm on center, and are pretensioned to limit deflections to 900 mm.

Following the Kempinski Hotel project, larger and more complex walls have been designed and constructed, representing an evolution of the original design concept. Two such projects include Time Warner Center at Columbus Circle in New York, with a cable-net wall 46 m tall by 25 m wide, and 28-mm-diameter horizontal and vertical cables; and the Beijing New Poly Plaza in Beijing, China, with a 90-m-tall by 60-m-wide cable-net wall consisting of 34-mm-diameter horizontal cables at 1,333 mm on center and 28-mm-vertical cables at 1,500 mm on center. Achieving these large spans required faceting the net by folding it across large-diameter cables (235 mm to 275 mm).

How They Work

Planar two-way cable systems support and stabilize glass façades through the resistance to deformation of the two-way pretensioned net. Gravitational loads from the glass elements are carried through the attachment nodes to the vertical cables, and up to a transfer structure in the base building above. Lateral deformations due to wind and seismic loadings are resisted by the tendency of each horizontal and vertical cable to return to its straight line configuration between supports.

The flexible nature of a planar cable-net under lateral loading means that the critical design goal is limiting deflection through adjusting axial stiffness of the cables, and the cable pretension. In-service deflection limits under a 50-year return wind loading condition are typically set in the range of $L/40$ to $L/50$ (with L corresponding to the shortest span passing through the considered point) to protect the integrity of the glass and sealants and to minimize a perception of movement by the building's occupants. Occupant perception of movement is often the controlling design criterion.

Service deflections of a cable-net wall can be significantly reduced by curving the wall in an anticlastic fashion, where cables running in the two principal directions are curved in opposing directions, creating a stiff grid of intersecting nodes. In this arrangement lateral deformations due to wind and seismic loadings are resisted with less deflection than that of a comparable flat net, because the wall has been built with a partially deflected form. This pre-curved configuration of cables avoids the softest portion of the non-linear lateral response of a planar cable-net: the undeformed, initial condition. When the anticlastic cable-net is subjected to lateral loads, only half of the cables resist the loads applied in each direction. The cable-net essentially behaves as two separate one-way cable-nets, rotated 90° from each other, with each optimized to resist lateral loads in a given direction. Because of this configuration the support points on each side of the cable-net must be able to resist half the total applied wind


Kempinski Hotel, Munich.


Time Warner Center, New York.

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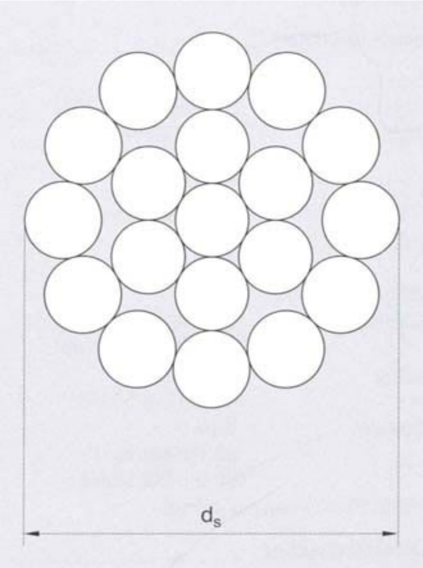
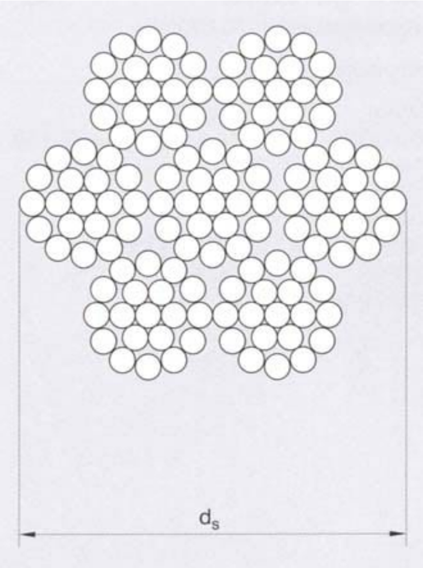


1x19 wire strand.



6x19 wire rope.

Swaged cable fittings.

loads on the gross area of the wall, necessitating strong boundary conditions on all four sides. Despite only half the cables being loaded for a given direction of wind loading, the cables that are mobilized offer such an increase in stiffness over planar cable-nets that curved cable-nets can efficiently be designed to deflection limits as high as *L*/120. They may also be designed in the range of *L*/40 to *L*/50 using less pretension than a comparable planar cable-net. As with planar cable-nets, occupant comfort and perception are often the determining factors in establishing the deflection limit.

Cables and Cable Fittings

The cable-net is made up of cables held together at their intersections by cable clamps, which also serve as the point of attachment for the glazing, typically supported only at its corners. Plain, threaded, turnbuckle, or eye hook terminations are swaged or speltered onto the ends of cables and anchor them to the base building structure. Swaging is a process in which a fitting is mechanically pressed onto the cable end. The less commonly used spelter socket connection consists of a cone-shaped termination into which the splayed wires of a cable are inserted and bound by a poured zinc or resin wedge.

Each cable is composed of individual cold-drawn wires twisted together in a variety of arrangements, the most basic of which is called wire strand. Strand consists of individual wires twisted about a central core wire. Wire rope is made by twisting strand cables about a central core strand. Cables are named for the number of strands and wires they contain: 1×37 describes one wire strand composed of thirty-seven individual wires; 6×19 describes wire rope consisting of 6 strands of 19 wires each. In addition to the standard strand and rope constructions, individual manufacturers also offer a variety of special "locked" windings designed to increase the construction's stiffness and improve its resistance to corrosion by making the surface less permeable. Cables are either galvanized or stainless steel, and untreated cable is not generally used in cable-net applications. In most designs, the cables are on the interior of the building, and corrosion is only an issue during construction.

Cables are specified and ordered pre-stretched with end fittings to meet or exceed 110% of the cable's minimum breaking load (MBL). Pre-stretching tightens the helical construction of the cable and significantly reduces creep (relaxation) after installation. The designer determines a cable's allowable working load based on the MBL and must apply additional strength-reduction factors based on the end fitting type and angle of deviation at saddle supports. These factors are based both on code requirements and on manufacturer recommendations.

Glass Attachments

Drilled glass bolt fittings or patch plates are typically used to fasten the glass to the cable nodes. These attachments must be designed to accommodate the environmental loads, in addition to the resulting deflections. For this reason rotational glass bolts are a common solution, allowing upwards of 10° of rotation between the glass and its support point. Patch plates are a more economical solution, because a single plate can take the place of four bolts, and the glass does not need to be drilled. The plate penetrates the glass joint to clamp multiple pieces of glass to a common node. Deflections and rotations are accommodated by a neoprene bearing pad between the glass and patch plate, and by localized deformation of the glass.

Glass Technologies

Glass can be annealed, heat-strengthened, or fully tempered. Heat strengthening and tempering are treatments in which annealed glass is heated, then rapidly cooled, placing its surface in compression and center in tension. This increases the strength of the glass, as higher applied loads can be resisted before the outer surface fractures. Concerns with heat treating include nickel-sulfide inclusion, roller wave, and bow or edge warping. Of these, nickel-sulfide inclusion is the only problem with structural implications: it can cause spontaneous breakage in fully-tempered glass. Heat-soaking after tempering will usually cause glass with inclusions to break, so the process is often specified in contract documents to reduce the likelihood of breakage after installation. Most cable-nets employ laminated glass as a safety measure against breakout. Heat-strengthened and fully tempered glass sheets have different breakage patterns, giving added strength after glass breakage to a laminated panel containing both.

Design Team Roles and Responsibilities

The design team for a cable-net structure tends to consist of a variety of entities who are involved in the design of the cable-net wall system, the base building structure, or both. For each portion an entity may be involved as the architect or engineer for the design phases and/or as the architect of record or engineer of record for the construction documentation phase. The principle roles in the design team are as follows:

- Design architect
- Architect of record (often the design architect)
- Design engineer
- Engineer of record for the base building (often the design engineer)
- Cable-net designer (could be the design architect, design engineer, associated designer, or design-build contractor)
- Engineer of record for the cable-net structure (could be the engineer of record for the base building, but more commonly is the cable-net design-build contractor)

Structural Analysis

For the simplest of cable-nets—one-way spanning planar systems—hand calculations can be performed to accurately calculate the behavior of the net under lateral loads. However, for more complicated conditions such as two-way nets, irregular geometries, curved nets, or nets with non-rigid boundary conditions, computer analysis modeling is required. Due to the highly non-linear response of cable-net systems under out-of-plane loading, an analysis program with full geometric non-linearity capabilities is essential. Additionally, an analysis program that has been specifically developed to include a "cable" element as an in-built standard element type usually offers a significant advantage. This allows cables to be modeled as single-line elements in the analysis model from "pin to pin." Some analysis models require that cables be modeled as a series of individual elements connected together in series, significantly complicating the analysis model.

It should be noted that due to the non-linear response of cable-net systems, linear combinations of analysis load cases are not applicable, and all individual load cases and load combinations must be analyzed in turn. Therefore, analysis of complicated systems subject to many load cases can result in very long analysis run times. This is especially true when the analysis of the cable system also includes an element of form-finding.

Interaction with Base Structure

A significant portion of the design of a cable-net wall is related to the design of the areas around the perimeter of the cable-net wall. Due to the parabolic displaced shapes typical of cable-net walls under lateral loads, the relative rotations between adjacent glass panes are small, but the rotations between the perimeter panes and support conditions are large. Therefore, the majority of architectural detailing considerations relate to maintaining suitable movement capacity at the perimeter to avoid glass damage as the cable-net displaces.

The structural design of both the cable-net and the base building structure is significantly affected by the loads that are transferred across and the displacements that occur at the perimeter of the cable-net wall. Cable-nets gain their out-of-plane stiffness due to the high levels of pretension applied to the cables during wall installation. These forces must be transferred to the base building structure around the perimeter of the wall. For larger cable-net walls these force levels can be a significant contribution to the overall design demand on the main lateral force-resisting elements. The engineer of record needs to consider the forces applied to the structure in the permanent condition (cable pretension) and the maximum cable force levels that occur during the design wind event. The design of the cable-net itself is also greatly affected by the structural solution employed at the perimeter of the cable-net.

There are two principal base-building characteristics that influence the design of the cable-net. The first relates to the stiffness of the perimeter boundary condition elements. The cable-net is a flexible structure, so the rigidity of the cable termination points is critical. The second important point is the careful consideration of the deformations of cables support points due to base building movement. This is particularly important for tall cable-net walls and those spanning between separate structures. Racking of the cable-net wall due to drift of the base building, and changes in cable tension due to supporting structures at either side of the wall moving towards or apart from each other, must be carefully considered in the design.

Construction Means and Methods

Because cable-nets are relatively uncommon, few installers have experience erecting them. Indeed, this is one of the primary reasons they are typically constructed on a design-build basis. The installation sequence and procedure are planned in tandem with the design of the wall. Clearances need to be allowed for the tensioning apparatus and provisions made for tension adjustment during the building's service life, should it be required.

Planning also includes determining the exact cable length to order, usually specified as a length at a specific load. Pre-stretched cables are used to minimize creep over their installed lifetime, but their effective modulus of elasticity varies by cable construction and batch. Also crucial to ensuring their fit is the base building engineer of record's estimate of deflection resulting from cable installation, and the position tolerance of that supporting structure. If cables are ordered after the support structure has been installed and surveyed, its tolerance need not be considered. Ordering cables at their service tension and having a reasonable estimate of the support deflection ensures they will fit properly. However, it is still important to know their approximate modulus of elasticity to ensure that tensioning is possible. A cable expected to stretch 50 mm during installation needs to have at least 50 mm of free thread by which to tension. In practice it needs far more thread than that to accommodate erection tolerance, jacking apparatus, and permanent connection hardware.

Temperature loads are a further factor to consider in planning an installation. Indeed, they must be considered throughout the wall's design. Typical operating temperature ranges for buildings are relatively well defined and controlled, but until construction is complete and the building is enclosed and occupied, the range can be quite large. This affects both the cable tension at time of installation as well as the installation sequence. If the site is very cold, the cables must be installed with a higher tension value than their service tension, since they will relax once the building is enclosed and conditioned. This can affect the tensioning sequence if the required tension exceeds the allowable temporary or permanent load for the cables, depending on the installation duration.

Installation Sequence and Tensioning

Layout and survey of the cable anchor positions are the first and arguably most important steps in the installation of a cable-net. Small changes in length or geometry can dramatically affect the cable tension, ability to properly tension the net, or the fit-up of the glass, so it is essential that the anchors are placed in the correct positions. The cable-net designer can make this first step easier by designing adjustable connection points and allowing an additional length of threaded cable end. Provided that the anchors have been properly located, the remainder of installation can be relatively simple. Cables are hung, tensioned, and clamped together. Selected nodes may then be surveyed and the glass installed and caulked.

Though the process is simple, it is important that the cable-net installer works with the building's general contractor to schedule and coordinate the installation. The base building engineer of record should be notified sufficiently in advance of the planned tensioning, to be able to plan a structural observation visit to the job site. Though the visit may be informal, its focus should be to ensure that the perimeter structure supporting the wall has been properly installed, necessary welds completed, and concrete sufficiently placed and cured. Because ultimate responsibility for proper installation rests with the general contractor, it is important that the cable-net installer educates him about the installation procedure and coordinates its scheduling.

Cable hanging and preparation for jacking may take just a few days or weeks, depending on the size of the wall, but when ready, the actual tensioning operation can take just a few hours. Hydraulic jacks are required to bring the cables to full tension for all but the smallest of walls. In a typical arrangement a hollow-core jack is mounted on a jacking chair that straddles the threaded cable end swage. On the swage are a permanent nut, the jack, and a temporary nut used during tensioning. The jack is extended, engaging the temporary nut and tightening the cable. The permanent nut is run down snug against the cable's ultimate bearing surface, and pressure is released from the jack, allowing it to be disassembled. Usually, jacks linked to a common hydraulic reservoir are installed on multiple cables and pulled simultaneously. In this manner the actual tensioning can be completed relatively quickly.

Installation is completed by affixing or tightening the cable clamps, which are often installed at the same time the cables are hung and glass is placed. Provided that the cable anchors were properly located and installation correctly planned, the glass often installs very easily. Here, again, the cable-net designer can do much to ease installation by detailing adjustable connections between the nodes and the glazing. This serves as further evidence of the advantage of using the design-build model to complete a successful cable-net project.

Post-construction Performance

Once construction is complete and the building is enclosed, the cable-net has relatively few requirements beyond occasional cleaning and tension monitoring. Cable tension is generally checked 100 hours after initial tensioning, and record tensions are taken once glass has been installed. The record tensions should be noted on as-built drawings submitted upon completion of the job. Typically, tension measurements are then performed after one year and every five years thereafter to ensure that the wall is working as designed and no significant creep or other factors have affected its capacity. MSC