Design With Cables

By Paul Gossen

Historic Review

"Tension-only" members in structures have been used for decades: from canopies in Roman times to suspension bridges for crossing rivers and deep gorges by people in America, Asia and Africa. Common applications of tension-only members were in temporary structures such as tents and in construction equipment. The materials used in these structures were mainly woven ropes from hemp or vines.

With developments in the skills of black-smithing in the early Middle Ages, non-metallic tension members were replaced with chains and link bars such as ties in domes and arch structures. The introduction of the cable, formed from a twisted array of single wires, dates back to the industrial revolution where these cables were mainly used as running cables. Stationary steel cables in structures were used mainly as guys in towers and catenaries in bridge structures. The introduction of cables in buildings, mainly roofs, is relatively new and dates only to the 1930's.

Characteristics

The ability to design large spans with little self weight and high load capacities, as well as exploring new architectural expressions, made cable structures very popular, though their structural behavior is unique and unconventional compared to common structures.

Unlike the common design, where the strength of a member is derived from its section and material properties, the cable has an additional variable that influences its capacity: its geometry.

Because a cable has negligible bending strength, its deformation from loads follow its funicular curve. The funicular curve is the shape that produces only axial forces in the member for a given load configuration. A close approximation of the funicular shape is the outline of the moment diagram from the load placed on an imaginary beam. In the case of a cable, the axial force is tension only.

The above implies that when the load configuration changes, the shape of the cable must change. In addition, the strain of the cable, as well as movements at its support, influence its shape and thus its load carrying capacity significantly. Because the cable exhibits non-liniarities in its properties due to its construction, they are usually pre-stretched in structural applications to reduce the non-linearity. Thus, in analysis and design, it is generally assumed that their properties behave in a linear elastic manner. Today's design with cables is regulated through ASCE 19-96.

ASCE 19-96 defines the modulus as the slope of the secant to the stress/strain curve between 10% of the nominal strength and 90% of the pre-stretching force (See *Figure 1*).

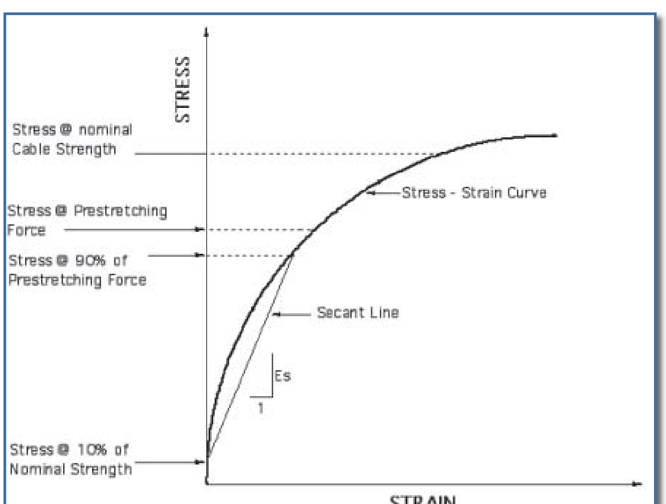

Figure 1: Stress-Strain Curve

Usually, cables are pre-stretched to 50% of their nominal strength, depending on their size. The modulus of elasticity of a cable varies with the type of its construction.

Unlike common structures, the load/deflection relationship of a cable system is not linear, but can be highly non-linear. To give a simple example:

A 200-foot "straight" cable under its own weight, with a stress of 10 ksi, has a sag of 2 feet. Moving one support ½-inch to shorten the span will increase the sag by 6 inches.

At 30 ksi, the same cable with the same movement at the support increases its sag by only 1.68 inches. *Figure 2* shows this nonlinear behavior.

The increase or decrease in sag, which can be the result of movements of the cable termination and/or the strain of the cable itself, influences the load-carrying capacity of the cable. In a cable network these effects are compounded since often the cable terminations "float", in other words, are held by other cables.

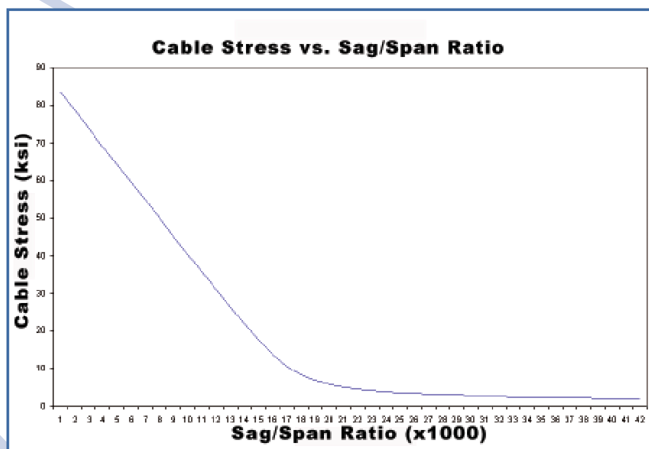

Figure 2: Sag vs. Span Graph

Effects of Pre-Tension in Cable Networks

To control deformations in a cable net, the cable system is pre-tensioned. This pretension is designed to elevate the cable behavior above the range in which the sag deformations become significant. The axial strain provides resistance to the movements of the cable ends. An analogy can be made in stating that the compression capacity of a cable is its initial tension. This means once the cable has lost its pretension, it goes slack and does not contribute to the structural system in terms of strength or rigidity. This implies that the pre-tension is in fact a structural property and must be modeled as such in any analysis. A guyed tower will illustrate this behavior. Initially the guys are pre-tensioned. The vertical force component from the guys is resisted by the mast. A lateral

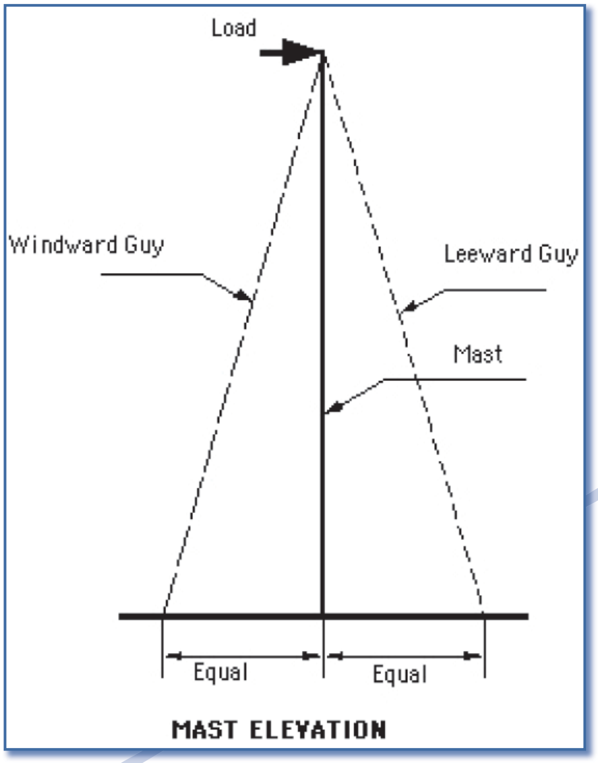

Figure 3: Tower Elevation

load is applied to the top of the tower. (See *Figure 3*) The force in the windward guy increases, while the force in the leeward guy decreases. Note that the force in the mast stays constant. As the force on the tower increases, the leeward guy loses all its pretension; the base to resist the overturning moment is now reduced to the depth between the mast and the wind ward guy (1/2 the original base). The force in this guy increases twice as rapidly, and the force in the mast also changes as rapidly as that in the guy. (See *Figure 4*) The change in this abrupt behavior is due to the change of the structural system, initiated by the loss of the pretension.

Cable-net structures behave in a similar way. Deformations and cable effectiveness can be controlled through the pre-stress initiated by the jacking of the cables. In some structures, pre-stress is introduced through the gravity loads. In the design, cable net structures are analyzed through non-linear programs. These programs work with iterations in the following way. Small incremental loads are applied to the structure. The deformations and forces are being used at each incremental step to form the basis of the new model for the next load step. This procedure is repeated until the total load value has been applied to the structure. Any cable that went slack is being eliminated from the structure as the analysis continues. The program reactivated the cable if it is tensioned again. In reality, a cable will never loose all its tension. The transition from high tension to tension that can be neglected in the analysis is not linear, as *Figure 2* shows. New programs can work with variable "modulus of elasticity" to simulate this fact. However, in most programs, multiple nodes in the cable are used to determine its segmental deformation and force. This technique will yield the deformation/force behavior within the cable span. These steps are possible through powerful computers and programs that can solve large deformations in structural models.

The response to the pre-stress in cables is not uniform. If a tensioned cable is loaded axially by increase in tension, the response is almost linear regardless of the level of pre-stress. However, if the tensioned cable is loaded perpendicular to the deformation, cable forces are a direct function of its material as well as its initial tension.

Implications on the "Factor of Safety"

One of the implications of the non-linearity of cable nets is in the assignment of "Factors of Safety" to this structure as well as its components. In Working Stress Design (WSD) the stress, force and deformation behavior are assumed to be linear, even beyond the service load. The nominal strength of the cable is reduced by a factor of safety to a "safe" cable working load level. This factor is meant to account for accidental overloads, material and fabrication imperfections. It does not determine to what magnitude or percent it covers an overload of the structure itself, and what percentage covers the material/fabrication imperfections. Thus, due to the non-linearity of the cable structure, the "Factor of Safety" against overload can vary wildly and stays indeterminate unless the structure is analyzed beyond the service load to a load level that incorporates the desired "Factor of Safety". A "Factor of Safety" against over stressing the cable (as it is done today) does not coincide with a "Factor of Safety" of overloading the structure.

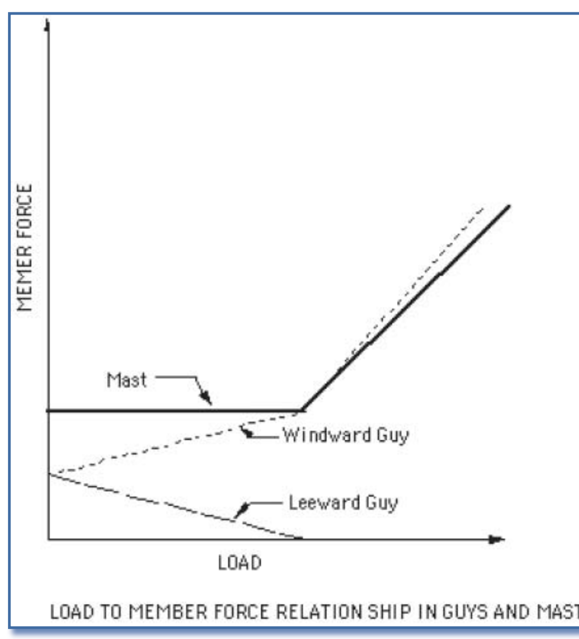

Figure 4: Force-Load Graph

It has been suggested that the "Load & Resistance Factored Design" (LRFD) approach be used, in which the service load is projected to an ultimate load level at which failure occurs. The material strength is modified by a resistance factor ø to account for material and fabrication deviations from the design assumptions. However, superposition of load effects with varying amplification factors is not applicable for non-linear structures, and thus the strict application of LRFD will give erroneous results. Furthermore, the ultimate load approach may result in individual cables stressed beyond their accepted level under service loads, while still satisfying the ultimate load design requirements.

It is apparent that the analysis and design of these structures can be much more laborious than what is common in the design and analysis of "conventional" structures. However, not all cable structures require extensive analysis. Enough structural behavior is understood beyond the service load limit to design a guyed tower or gravity pre-stressed cable system, such as the "Madison Square Garden" roof (it was designed by hand), that do not warrant extensive analysis for the design. The need for extensive analysis must be determined by evaluating the complexity of the cable net in concert with the cable pre-stress and applied loads.▪

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