Tension Arch Structure

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ABSTRACT

The Tension Arch structure is introduced and explained. The Tension Arch principle, when incorporated in an innovative bridge structure, has the potential for solving many of the problems that have plagued conventional bridge designs over the years. It offers more efficient use of materials; can be used with a variety of materials, including steel, concrete, and timber; can achieve lower construction costs through reduced design cost, mass production of compressive and tensile components, minimum shop and field custom fabrication, and reduced erection time and erection equipment costs; and provides a geometry that is relatively insensitive to a variety of support movements along any or all three axes.

Throughout the years the American bridge builder has made steady progress in designing and building bridges to serve an ever expanding federal highway system, as well as state, county, and municipal roadways. Many design innovations have been introduced and bridge building techniques have been refined. This has led to longer spans; higher load carrying capacity; and, in many instances, bridges that are aesthetically pleasing. Unfortunately, however, neither bridge maintenance techniques nor the funds required to maintain this bridge system have kept pace with these modern advancements.

Consequently, the highway bridge system has fallen into disrepair and many bridges are in need of major repair, rehabilitation, or replacement. In fact, it has been estimated that almost a quarter of a million bridges in the United States are structurally deficient or functionally obsolete (1,2). More than half of these are off the federal-aid highway system. The cost of rehabilitation and replacement has been estimated at roughly $50 billion, and the funds required for such a massive program of replacement and rehabilitation are simply not available. This is especially true at the local level where the needs are particularly acute.

In an effort to make the most of available funds, there has been a trend in recent years toward the use of improved bridge maintenance techniques and the rehabilitation of existing bridges, in order to forestall the need for full-scale bridge replacement (2-7). For those bridges that must be replaced, efforts have been made to devise standardized short-span bridge replacement systems that can be constructed more quickly and economically than can custom-designed bridges (8). In addition, FHWA has attempted to encourage highway agencies to strive to integrate bridge maintenance needs into preconstruction procedures (9,pp.100-135). Although these efforts certainly constitute a move in the right direction, for the most part they have not attempted to address one of the most fundamental and continuing problems embodied in the conventional design and construction of bridges in the United States. This is the tendency to design bridge systems that are costly to build initially and that contain features that make continued maintenance difficult and expensive.

For example, in the design of conventional highway bridge systems, the cost savings that can be achieved by making the superstructure continuous over the piers has long been recognized. In fact, in many states, a relatively large percentage of the multispan bridges are designed for partial or total continuity. However, in recognition of the fact that these continuous bridges may be more sensitive to differential settlements than simply supported bridges, the majority of states found these structures on piles, or other deep foundations, unless rock or some other hard foundation material is located close to the proposed foundation level (10). In many instances, the cost of these deep foundations may be substantially greater than the savings achieved by making the superstructure continuous. Consequently, it has been suggested that substantial savings may be achieved in some instances by designing bridges to tolerate the total and differential settlements to which they may be subjected (10).

Another frequent consequence of conventional bridge design practice is the occurrence of bridge deck joints and bearings that continually require maintenance in order to prevent deterioration of the bridge superstructure (11). Although considerable effort has been devoted to solving this problem, a substantial number of highway agencies have concluded that it is better to avoid the problem than to try to solve it. For this reason there has been a trend toward the use of integral-abutment bridges, which contain no conventional joints or bearings (9, 12). However, at present the behavior of these bridges is not well understood, and, to remove at least some of the uncertainties, there has been a tendency to also found these structures on piles or other costly deep foundations (12).

These limited examples represent only a few of the many technical and financial problems facing those who are charged with maintaining and upgrading the highway bridge system in the United States. However, even if solutions to these particular problems are found, the fact remains that most conventional bridge designs do not incorporate even a limited capability for handling long-term increases in live load stresses or temporary overloads without costly overdesign, rehabilitation, or retrofitting (13).

Consequently, there is a need to redirect efforts to the development of innovative bridge systems that attempt to solve these problems. The Tension Arch bridge described in this paper is the result of one such effort that shows promise of producing reduced initial construction costs, less maintenance, better capability to adjust to total and differential settlements, and the capability to handle limited increases in live loads without excessive overdesign or future costs for rehabilitation.

TENSION ARCH CONCEPT

It is a known mathematical principle that the arch and the catenary are the inverse of each other. The funicular shape taken by a chain subject to a given series of loads, a tensile structure, is the mathematical opposite of the arch formed by those same loads, the compressive structure (see Figure 1) (14, 15). On the basis of this, it may be said that a structure that supports a load through both tension and compression, such as the simple beam with a point load at the center, would tend to create a triangular funicular polygon of compression, such as the solid line shown in the beam in Figure 2. But it is known from photoelastic tests that a beam-type structure subject to a point load exhibits stress behavior as shown in Figure 3. So a dashed funicular polygon of tension (shown in Figure 2) also tends to occur in the beam.

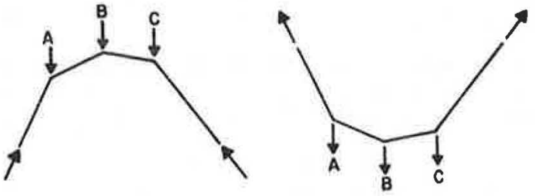

FIGURE 1 A series of loads, if supported by compression, will assume a certain funicular shape (left), and the same loads supported by tension will assume the inverse of that shape (right).

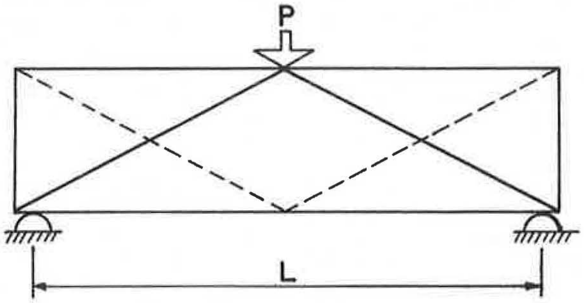

FIGURE 2 Simple beam funiculars of tension and compression.

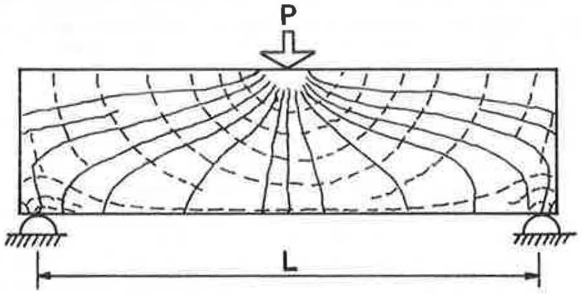

FIGURE 3 Simply supported beam showing photoelastic stress trajectories, with the tensile stress trajectories (dashed lines) curved upward, and the compression stress trajectories (solid lines) curved downward.

Concept of Moment

When a beam, an arch, or a truss is viewed as a moment resistant structure, this view has to do with the ability of the structure to transfer the energy created by the load's geometry, mass, and gravity to the earth. It is generally assumed that structures must be moment resistant to support loads. However, pure compressive structures such as segmental arches and pure tensile structures such as cables or chains are generally not considered moment resistant structures because they have no internal moment. They create rather an "external" moment. The resisting couple is internal to the geometry of the whole structure but external to the cross section. These structures support loads based on their overall geometry and stress resultants. For example, in Figure 4, $M_C = PL/4 = T_H \cdot Yc$, where T_H is the horizontal internal tension at the center line and Yc is the sag at that point. Moment resistant structures like beams or trusses, on the other hand, resist loads based on moment resisting properties of cross section, that is, area and moment of inertia. Any special overall shape geometry of a beam or a truss is a consideration only as it affects the moment of inertia.

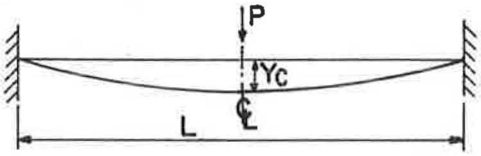

FIGURE 4 Parabolic cable with concentrated load.

The moment energy, PL/4, generated by the load, P, which must be supported and transmitted by the structure, is related to the overall geometric properties of the span and is based on the ratioed gravitational energy generated by the mass of P. PL/4 is not only the maximum moment of a simply supported beam with the load, P, at the center, but also the moment energy created by a load, P, midway between two points in space, L distance apart, supported by any structure.

CURRENT FREE-BODY DIAGRAM

From Newtonian mechanics and the theory of elasticity, an approach to analyzing structures using a tool called a free-body diagram has been developed. The usual free-body diagram cut through a simple beam is shown in Figure 5.

The three vectors shown in this free-body diagram represent mathematical abstractions. They represent reality as viewed from an orthogonal three axes system. However, they are visually inaccurate because the moment vector is the effect of a force acting at a distance and not itself a cause. Moments and forces do not really exist; they are symbols for reality. Engineering and science educators for many years have wrestled with communicating these abstract concepts, particularly moments, to students.

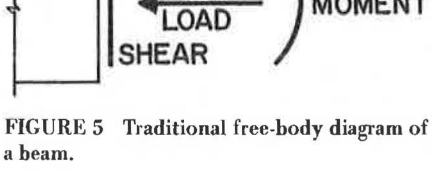

FIGURE 5 Traditional free-body diagram of a beam.

Through this free-body diagram (Figure 5), a mathematical abstraction is allowed to direct the approach to structural design. This free-body diagram is equated with basic structural behavior. One result of this is that the overall stress level efficiency of structures is not measured. In fact, structures are created, on the basis of the overall average stress levels in the materials used, that are grossly inefficient. For example, designing steel beams based on controlling maximum moment, generally at the center of the span, makes the rest of the material throughout the beam understressed, or half the concrete in a reinforced concrete beam is unused and merely supports the reinforcing steel. Prestressed and posttensioned structures are an effort to overcome this inefficiency. Trusses also are a more efficient use of materials. But due to the high cost of manufacture and construction their application has declined.

Let us view the energy created by a force P acting midway between two points L distance apart as PL/4. This is a mass-gravity geometric relationship independent of structure. The ability of a beam's cross section to transmit this energy could be described by M = f(I/c), where I and c are the geometric properties of moment of inertia and distance, and f is stress level, a material property.

However, a more holistic view of the beam describes its moment carrying capacity by the relationship M = K x d, where K is the stiffness and d is the deflection at the center due to the load P. K contains geometric properties including the length as well as the cross section and the material property of elastic modulus. In the current design paradigm one is prone to say M = PL/4 = f(I/c) = K x d, but only PL/4 is exact. The other relationships are based on a variety of simplifying assumptions and varying physical properties and conditions.

In Figure 3, the plot of stress trajectories in a simple beam, it can be observed that the compressive stress trajectories formed take an arching shape (solid lines) and the tensile stress trajectories formed take a catenary shape (dashed lines). With a view to these stress trajectories, a more visually accurate free-body diagram of a section through this structure would be the polar representation of Figure 6.

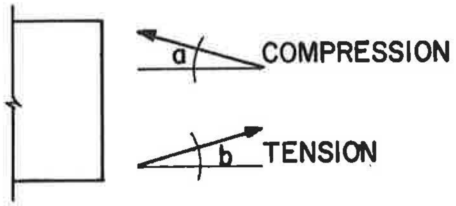

FIGURE 6 Free-body diagram of what actually occurs in a beam and in the Tension Arch.

Geometry

Structures are analyzed and designed on the basis of the fundamental assumption that the geometry of the structure remains unchanged while it supports the load (plane sections remain plane sections). This is true of suspension bridges, arches, beams, trusses, and everything in between. However, the suspension bridge without the stiffening truss, or other means of stiffening, is a dynamically sensitive string, a swinging bridge, or a musical string (plane sections do not remain plane). Roebling was among the first to realize this and to incorporate adequate techniques for stiffening into his designs. On the other hand, techniques for preserving arch geometry under load were first used perhaps by the Romans or earlier peoples and were later used by the modern French and the Swiss and then worldwide.

Modern suspension bridge builders are aware that the solution to the problem of dynamic sensitivities is based on the preservation of the original geometry, through stiffening trusses or beams or energy absorption techniques. Pure tensile structures such as ski lifts and aerial tramways are restricted by custom and standard to a ratio of hanging load to internal tension (16). For example, if the internal tension is 1,000 lb, the maximum hanging load is 50 lb (a ratio of 1:20). The ultimate purpose of this ratio is to ensure the geometry of the operating system. Thus the structure that will exist in the field is analyzed.

Structure as Energy Conduit

Structures do act as transmitters of energy. The moment energy, that is, the ratioed or levered gravitational energy created by the load in the span, can be thought of as analogous to electricity in the wire, with the load as a generator or dynamo and the wire as the structural section. The energy created by the load is transmitted by the structure to the earth. But the earth is a purely compressive structure with negligible tensile resistance. So each basic structural system must transform any inherent tensile energy to compression so that it can be absorbed by the earth. This occurs generally at or near reactions, or their direct extension from the earth. Thus beams and other structural systems whose reactions occur along tensile flanges or sections require longer bearing lengths or stiffeners. Figure 7 shows where these tension-to-compression transfers occur in a variety of structures.

Man and Tension

The ability of man to devise means and methods for resisting tension has been a vital part of his growth and of that of his civilization. This can be seen in his weapons, housing, structures, clothing, and almost everything that man has developed in the last 20 centuries. It is particularly visible in his structures or his shelter. The suspension bridge dates back to antiquity and is one of the ways that even primitive man used to span the chasm. But just what is tension? How does it originate? Where does it go? Let us consider the segmented arch, a pure compressive structure, and its funicular polygon. As load is increased above a certain level, the cracks in the arch open, and the funicular tends to move outside the structural cross section. Energy must be applied in opposition to the load to close these cracks and restore the funicular to its original geometry. If the original resisting structure was a funicular of compression, then the necessary opposing structure must be a funicular of tension. Thus tension may be defined as the energy component necessary to overcome a deficiency in compression.

With the development and understanding of tension resisting materials, man proceeded from wood to steel structures, to reinforced concrete, and ultimately to the skyscraper, which gets man higher and higher from the compressive earth. Finally the airplane with tensile structures as a vital part of its composition transmits its load to the earth through a form of compressed air.

The ability to resist tension is thus a vitally important part of the rise of human civilization. Today more than ever, a great deal of technical tal-

BEAMS
LOADS CONVERT TO TENSION AND COMPRESSION IN THE BEAM; TO COMPRESSION AT THE REACTION; AND TO COMPRESSION IN THE EARTH.

PRESTRESSED OR POST-TENSIONED BEAMS
THIS MAY BE SUPERIMPOSED ON A BEAM. EXTERNAL COMPRESSION IS TRANSFERRED TO THE STRAND IN TENSION AND THEN TO COMPRESSION IN THE P/S TRANSFER. EXTERNALLY APPLIED LOADS THEN ACT SIMILAR TO A BEAM.

ARCH
LOADS ARE CONVERTED TO COMPRESSION AND GO DIRECT TO THE EARTH AS COMPRESSION.

CABLE
LOADS ARE CONVERTED TO TENSION IN THE CABLE; TO COMPRESSION IN THE ANCHORAGE AND THEN TO THE EARTH AS COMPRESSION.

SUSPENSION BRIDGE
LOAD IS TRANSFERRED TO TENSION AND COMPRESSION IN STIFFENING TRUSS; TO COMPRESSION AT TRUSS REACTION WITH SUSPENDER; TO TENSION IN SUSPENDER; TO COMPRESSION AT REACTION WITH MAIN CABLE; TO TENSION IN MAIN CABLE; TO COMPRESSION IN THE TOWERS; TO COMPRESSION AT END ANCHORAGE TRANSFER; TO TENSION IN ANCHORS; AND COMPRESSION TO THE EARTH.

TRUSS
SIMILAR TO A BEAM

TENSION ARCH STRUCTURE
DEAD LOAD IS CONVERTED TO TENSION IN THE CABLE; CONVERTED TO COMPRESSION C_1 IN ANCHORAGE TO THE EARTH AND COMPRESSION C_2 INTO THE STRUCTURE AS SELF-POST-TENSIONING.

LIVE LOAD IS CONVERTED TO C IN ARCH AND T IN CABLE; C_3 GOES TO EARTH; C_4 ACTS TO COUNTERACT THE LIVE LOAD C_2 AND IS DIRECTED BACK INTO THE STRUCTURE. T IS CONVERTED TO C_1 TO THE EARTH AND C_2 BACK INTO THE STRUCTURE AS A SELF-POST-TENSIONING LOAD.

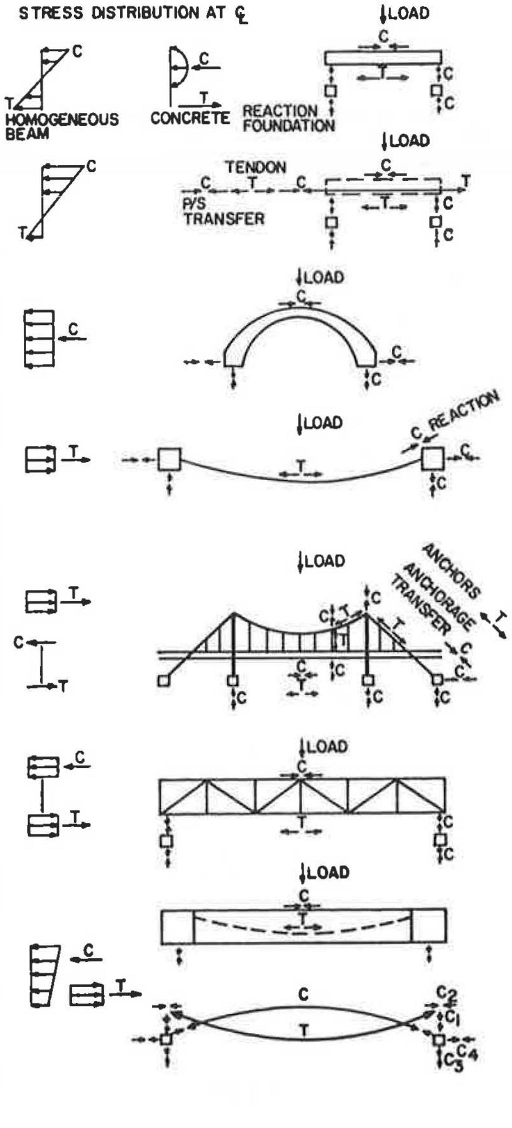

FIGURE 7 Tension to compression transfers in some typical structures.

ent is spent merely trying to resolve the question of how to resist tension--how it will be controlled, directed, and transformed into compression so that it can be absorbed by the earth.

TENSION ARCH STRUCTURE

The Tension Arch structure is a combination of the arch and the catenary. It is a structure that transports loads to the earth through segregated unbonded tensile and compressive structural components. It is basically a suspension structure whose horizontal tensile forces are resisted by a compressive strut. This strut or prop contains an internal saddle to preserve the parabolic shape of the cable or tensile component (see Figure 8).

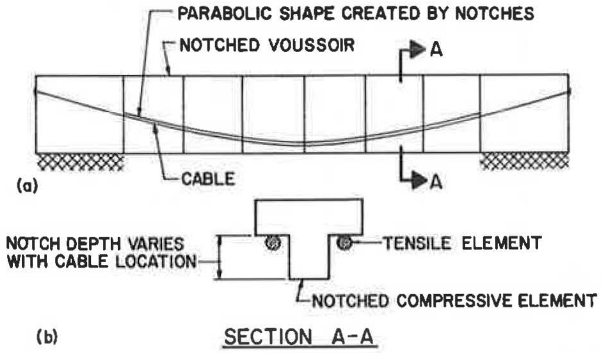

FIGURE 8 Typical Tension Arch structure in elevation (a) and section (b).

Compressive Structures

When considering pure compressive structures, we usually think of a Roman or concrete arch spanning between two points. There is something in the arch that strikes a personal intuitive chord. It is a structure that we somehow know is dependent on geometry and proportion to support its load. If the geometry fails, the structure is no longer a purely compressive structure and buckles and collapses. All beautiful arches exhibit a delicate sense of proportion; it is hard to imagine an arch that is not beautiful. But, due to the mass of most arch structures, we endow them with a certain degree of stiffness or ability to resist a moment-type energy, whether they have it or not. This is true not only of arches but also of prestressed and posttensioned segmental structures that are literally flat arches whose segments are compressed by external energy. The abstract concept of moments directs the approach to design, whereas tensile and compressive forces (i.e., directional energy components) alone or together transmit the load's energy to the earth.

Catenaries or Suspended Structures

When a purely tensile structure, such as a chain or cable, is considered, it is easy to understand that the applied load can change the shape of the chain and that the catenary geometry must be preserved to support the load effectively and efficiently. A chain or a cable is a structure that is obviously dependent on geometry and proportion working with axial stress resultants to support its loads. No internal moments can be supported because these structures can only resist tension. It was observed earlier that very specific ratios of hanging load to interior tension of the cable, as well as stiffening systems, are important to all tensile structures, from suspension bridges to aerial tramways, to ensure catenary or parabolic geometry.

But when we see an arch structure or a suspension cable, what do we see? Are we seeing just a structure or are we also seeing energy being transformed and transmitted? This is not so obvious with the arch, but consider the cable. In no structure is the concept of visible energy so apparent as in the pure tensile structure. A variety of catenary shapes, from utility lines to bridges, makes up our everyday environment. We have been taught that it is the shape of a cable that supports its loads through pure tension. However, the shape of a cable or chain is generally any shape we would like it to have. It will assume a shape based on a particular use, for example, around a wheel or over a saddle. What is seen in a suspended cable structure is the shape of the tensile energy that is transmitted through the cable to its supports, where it is changed to compression and transmitted to the earth. Change the tension in the cable and its shape changes. The tension inside controls the external geometric shape. The physical composition of the cable or chain is merely a visual characteristic of the material and is secondary to the structure's property as an energy transmitter.

Tension Arch = Arch + Catenary

A conclusion that may be drawn from these observations is the classical concept that structures tend to assume a shape based on the loads they support or the energy they transmit--the point made in the first paragraph of this paper. But, from another perspective, it is not the structures that tend to assume the shape but the tensile and compressive energy within the structures that tends to assume a specific shape due to its own nature. If structures are viewed from this perspective, a structure's behavior takes on a vitally different appearance.

With this as a basis, the Tension Arch structure combines (a) the stress-strain properties of materials as energy transmitters; (b) the geometric properties of levered or ratioed loads, that is moments; and (c) the geometric properties of the arch and catenary. This combination is a structure that will resist the external load's moment energy. The Tension Arch, in effect, takes two structures with no "moment resistive capacity," the cable and the segmental arch, and combines them to create a structure that can resist moment energy and preserve the parabolic geometry of the tensile element (see Figure 8).

The Tension Arch is both a cable-stiffened arch and an arch-stiffened cable. It is at once a suspension structure, which dissipates its horizontal tension through a flat arch or prop, and a flat arch structure, which dissipates its horizontal thrust through a parabolic shaped tensile tie. It may also be viewed as the mathematical inverse of a tied arch. It combines and displays the properties of posttensioned, suspension, and arch structures. The inherent geometry of the system makes it different from what is sometimes referred to as "tied" or unbonded concrete.

This structure further takes advantage of the energy created by the load itself to add to the ability of the structure to support that load. It does this by rerouting a portion of the tensile energy (the cable's horizontal tension component) back into the structure instead of dissipating it into the earth as do the ties on the traditional suspension bridge. This portion of the load, the horizontal tension, posttensions the structure.

For example, a cable that spans 100 ft with a 2 ft sag (a 2 percent sag ratio) creates an internal tension of 12.5 lb for each 1 lb supported by the cable at the center of the span. If the 12.5 lb of internal horizontal force per pound of vertical external load must be dissipated into the earth, massive anchorages are required, as with suspension bridges. However, if the 12.5 lb can be redirected back into the structure, in effect to posttension the structure, the mechanical advantage inherent in the cable's geometry can be used to support the load. This is what occurs in the Tension Arch. The horizontal forces generated by vertical load and the cable's geometric form are levered and used to assist in supporting the load.

Negative Moment Resistance at the Supports--Effect of Parabolic Shape

Figure 9 is a free-body diagram of a single-span Tension Arch structure in which the supports are restrained from rotating. Summing the forces in the Y direction yields

$$\Sigma F_Y \,{}^{+}\!\uparrow = C \sin \beta + T \sin \alpha - (w\ell/2) = 0 \qquad (1)$$

In this structure the angle α is known because the shape of the tensile element is formed on the inside of the compression component. The tension, T, is also known because it can be controlled and selected on the basis of loads and design parameters. That

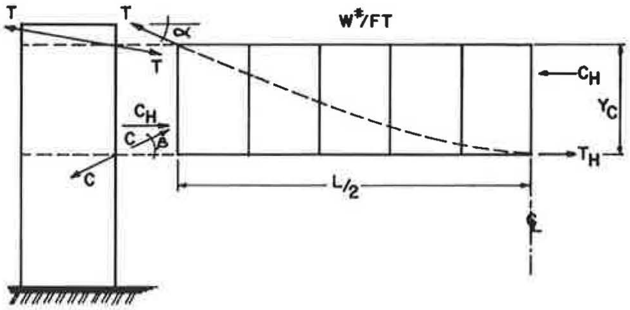

FIGURE 9 Free-body diagram of beam.

leaves C and β as the unknowns. Summing the forces in the X direction yields the following equation:

$$\Sigma F_X \overset{+}{\rightarrow} = -C_H + C \cos\beta + T_H - T \cos\alpha = 0 \tag{2}$$

because at the center line

$$|C_H| = |T_H|.$$

This gives

$$C \cos\beta = T \cos\alpha$$

The following expression can be generated from Equation 1:

$$C \sin\beta = (w\ell/2) - T \sin\alpha \tag{3}$$

Squaring Equation 3 yields the following relationship:

$$C^2 \sin^2\beta = (w^2\ell^2/4) - w\ell T \sin\alpha + T^2 \sin^2\alpha \tag{4}$$

Squaring Equation 2 and adding it to the preceding relationship yields the following equation:

$$C^2 = (w^2\ell^2/4) - w\ell T \sin\alpha + T^2 \tag{5}$$

It is known from basic cable theory (Figure 10) that for a symmetrically loaded structure Angle A = Angle B. If the shape of the cable is restricted to a parabolic shape, it is known that

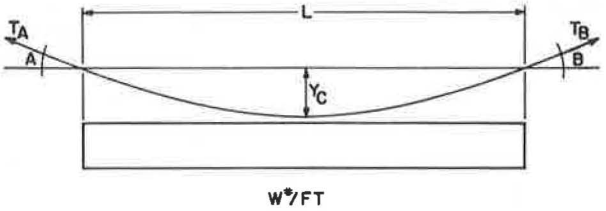

FIGURE 10 Parabolic cable with uniform load.

$$TA = TB = w\ell/2 \text{ tangent } A$$

It is also known that for small angles

$$\sin A = \text{tangent } A$$

and from the properties of the parabola that this equals $4Yc/\ell$. Therefore,

$$\tan\alpha = 4Yc/\ell = \sin\alpha \tag{6}$$

It is further known that the horizontal component of tension in the cable is

$$T_H = w\ell^2/8Yc \tag{7}$$

Substituting Equation 6 into Equation 5 yields the following expression:

$$C^2 = (w^2\ell^2/4) - 4 \cdot w \cdot T_H \cdot (Yc) + T^2 \tag{8}$$

It is known that C must equal T to preserve equilibrium. By inspection, in order for $C^2 = T^2$ the value of $T_H(Yc)$ must be equal to $w\ell^2/16$. But $T_H(Yc)$ is the "moment" at the center of the span resisted by the cable. It is only with $T_H(Yc)$ equal to $w\ell^2/16$ that this equality will exist and the system will be in equilibrium. It can be inferred that if M at the center is $w\ell^2/16$ then M at the ends is also equal in value to $w\ell^2/16$ and opposite in sign.

It is known that the end moments must vary between the limits of 0 and $w\ell^2/12$ and the center line moment must vary between the limits of $w\ell^2/8$ and $w\ell^2/24$. But $w\ell^2/8$ is a measure of the energy. The total moment value or energy to be resisted is the quantity in question when it is said that

$$|M_A| = |M_B| = |M_C| = w\ell^2/16.$$

What this simplified analysis implies is that half of the moment energy created by the load is carried by the cable and half of the load's moment energy is carried by the compression component. The analysis further considers the development by the Tension Arch of negative bending at the abutment regions as long as they are designed to dissipate it. With the existence of the $w\ell^2/16$ relationship, the implication is that the moment at the center line and the moment at the abutments are the same and these sections may be designed for precisely the same forces, only acting in different directions. The natural shape of the cable allows this to conveniently occur so that the design of this section at the center line yields the same section at the abutments.

The approach to designing the first Tension Arch structure has been to ensure that compressive stress distribution exists at all times in the compression component cross section. No tensile stress, or crack opening, is allowed. What this means is that the location of compression resultant is restricted by adding a small amount of additional posttensioning.

Design and Analysis

On the basis of the previous discussion it is assumed that for a single span, one-half the simple-span moment is taken at the center of the span and one-half is taken at the ends. This considers both dead and live loads. Early laboratory tests at West Virginia University indicate that the system behavior is similar to that of a partly fixed end beam on a series of spring supports. The laboratory structure also exhibited a sensitivity to the ratio of dead load to live load, a characteristic of most tensile structures. This information will be used in the design and analysis of the full-scale experimental project now being developed in conjunction with the West Virginia Department of Highways.

The analysis of the compressive elements is made using the traditional combined axial load and bending relationship:

$$(T_H/A_C) \pm (T_H \cdot E_C/I_C) \pm (M_L \cdot C/I_C) \tag{9}$$

where A_C, I_C, E_C, and C are geometric properties of the compression section. No tensile stresses are allowed in the compression element and additional tension is provided to ensure this condition. The resulting cross section for a bridge designed to span 100 ft is shown in Figure 11.

Erection--Dead Loads

The level of T_H during construction can be critical before the compression element is in place. Several erection schemes have been developed; the most effective one appears to be the arch crane. It will be used to support half of the dead load during construction with the other half supported by the tensile element. In this way the horizontal tensile

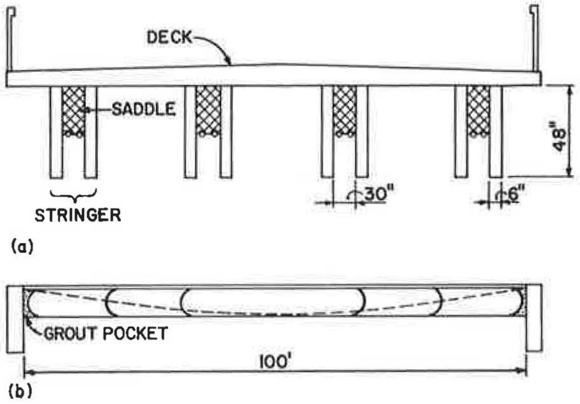

FIGURE 11 Schematic of an experimental Tension Arch structure that will be built by the West Virginia Department of Highways during 1984.

force T_H directed toward the center of the span is counteracted by a horizontal compressive force C_H directed away from the center (see Figure 12). Another obvious approach is for all of the dead load during construction to be supported by falsework from above or below.

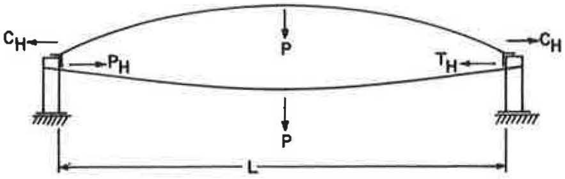

FIGURE 12 Compressive arch crane and tensile elements support dead load by both tension and compression.

Each stringer (see Figure 11) will be erected and completed before moving to the next if only one arch crane is used. A grout pocket is left at the end of each stringer and filled with chemically expanding grout. When the grout is set the stringers are post-tensioned to the appropriate energy level to receive the deck and other loads.

Movements and Deflections

Thermal loads are handled through the raising and lowering of the whole structure. This movement and other movements, such as differential settlement, are absorbed by the circular joints located at the center and at the abutments. These joints appear to be hinges; however, moment energy is transmitted across these joints, inasmuch as tension and compression both exist at these locations. The result is a structure that can withstand substantial movement through settlement and rotation and at the same time transmit moment energy within the framework of its original design geometry and assumptions. A temperature expansion or seismic load or settlement would all generally be experienced and handled similarly by this structure. Such movements would be viewed as a translation, a rotation, or a combination of the two at these joints.

Abutment Design

In the experimental project, abutments will be designed to resist lateral earth pressures. The negative moments resisted by this structure at the abutment interface are dissipated into the old abutment structure. What better way to make use of this energy dissipation than to use the structure behind the abutment? The Tension Arch structure geometry is designed to allow some abutment rotation to occur. Additional soil compaction due to lateral earth pressures will occur on the face of the abutment. The resulting minor rotations would not affect the overall structure's capacity to support loads. What the Tension Arch does is create a bent integral with the abutment. It simply makes use of the natural shape of the cable to build a structure that can resist positive and negative moment energy.

Origin of Concept

While viewing the natural shape of the cable as it appears in a ski lift (see Figure 13), one can observe that it is similar to the natural shape of tension in a continuous beam over several supports. For example, if one had to provide a single piece of reinforcing steel for a concrete beam continuous over several supports, it would assume a shape similar to this sinusoidal wave. Not only would this be appropriate for the moment energy involved, it would also be positioned for many of the basic shear problems that exist in reinforced concrete. By marrying with this ski lift cable a group of compression components with the inverted saddle shape of the cable incorporated into their cross section, it is ensured that the natural shape of the cable, the catenary or parabolic shape, will be preserved for all loads. When the last piece was mentally installed, a rigid structure ensued. Extensive patent searches indicate no similar structures. Literature searches had similar results and patents were applied for in the spring of 1982.

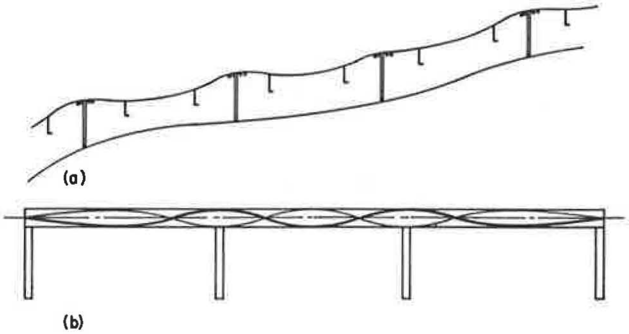

FIGURE 13 Natural shape of the tensile cable of a ski lift (a) reflects the natural shape of tension in a beam [solid line in (b)]; the natural shape of compression [thin line in (b)] is the opposite of this tensile shape.

CONCLUSIONS

The Tension Arch concept will potentially allow all types of structures to maximize the use of material at higher overall stress levels. Half of the concrete in a beam need not be used merely to position and bond the reinforcements necessary to withstand the tensile load. Nor will the midheight area cross section of beams be used at low stress levels. The concrete can all be devoted to compression. Wood beams could easily be made continuous with this system, inasmuch as they would no longer have to resist anything but localized tensile and bending stresses. Wood beams of 200 ft or more could be conveniently designed with this technique and assembled at the site from small modular pieces.

The only things that need to be continuous are the tensile elements. They can be wires, rods, plates, or anything that can conveniently be shipped to the site and made continuous.

Continuous tension is considerably different from continuous compression. It is easy to make a variety of materials continuous in compression; however, continuous tension must be handled selectively and only the highest quality materials can be used. Although at first the problem of deflections was considered serious due to the sensitive geometry, this has not proved to be the case. The ratio of dead load to live load is of more importance. An expression for deflection is available that is consistent with cable theory and virtual work, and reasonable deflection has been calculated and experienced (17).

This system can achieve construction cost reductions in structural systems of 20 percent or more as a result of (a) reduced design cost, (b) mass production of the compressive and tensile structural components, (c) minimum shop and field custom fabrication, and (d) reduced erection time and erection equipment costs. Finally, the Tension Arch is a structure whose geometry is relatively insensitive to a variety of support movements along any or all three axes.

The West Virginia Department of Highways and FHWA are currently considering the construction of the first Tension Arch structure. Testing will continue through West Virginia University during the construction of this project.

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