The Prestressing of Structures: a Historical Review

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INTRODUCTION

Prestressing means deliberately inducing a self-equilibrated state of stress in an object or structure before it is placed in service. Prestressing may be essential for the functionality or the stability of a structure. It may simplify connections and improve performance by increasing stiffness or limiting cracking. Prestressing may also preclude stress reversals under normal load conditions and thus allow use of tension-only or compression-only elements. It is often useful for rehabilitation, for strengthening or stabilizing a structure by providing confining forces. The concept has been applied throughout history and to most construction materials including fabrics, wood, masonry, metals and concrete. It has been used both for common small-scale objects and for large structures.

In this paper the principal objective is to present and explain structural issues that arise in the design and construction of prestressed systems. This is done by citing and discussing specific relevant prestressed structures. First the common techniques or processes for prestressing are briefly discussed and some examples given.

PROCESSES AND APPLICATIONS

Casson (1971) and Torr (1964) discuss and illustrate Egyptian boats, built approximately 3500 years ago, in which the hull, posts and ropes formed structures to prevent "hogging," or negative curvature in hulls. These boat structures were prestressed by twisting ropes, as shown in Fig. 1. The same technique is used to prestress the blade in a traditional bucksaw. Smaller tensile forces may of course be applied directly, as done for tensioning tents or tensioning stringed or membrane-type musical instruments. A preload may also be induced by using wedges, as was done for tightening chains girdling some of the great masonry domes (Benvenuto 1991). Another prestressing technique involves tightening nuts or turnbuckles on threaded rods. This was done for the Howe truss (Gasparini and da Porto 2003) and is commonly done to pretension spokes in conventional bicycle wheels.

Prestressing may also be effected by straining materials thermally. For example, Thomas J. Rodman invented an improved process for casting gun barrels (Rodman 1847). By circulating cooling water within a pipe along the axis of the barrel, he was able to initiate solidification at the inner radius first, thus inducing a compressive prestress there as the solidification progressed radially outward. The compressive prestress at the inner bore increased the life of a cannon by a factor of between ten

and twenty. An analogous thermal process is used to prestress the faces of tempered glass in compression. An intriguing example of prestressing is the tiring of wooden wagon wheels by heating the iron tires. This technology is wonderfully described within the social context of England by Sturt (1993) and in the US context by Peloubet (1996) and Kinney (2004). Prestressing was not only applied for tiring the wheel but, for some types of wheels, it was also applied to set the spokes in the hub.
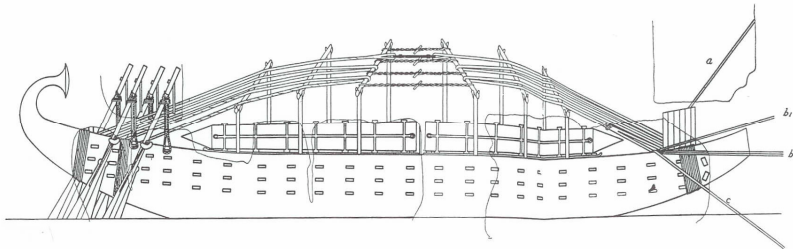

Figure 1. Egyptian barge prestressed by twisting ropes (Casson 1971)

Added weight has also been used to create a beneficial prestress. Heyman (1995) notes that the weight of pinnacles in Gothic cathedrals helped prevent sliding failures in buttresses. Heyman also notes the use of a weighted central rod or wooden pendant along the axis of spires to stabilize spires under lateral loads. An unusual prestressing technique involves using buckled elastic struts, utilizing the fact that the axial load increases slightly above the Euler bifurcation load with increasing axial deformation. This principle was used for a design of the deployable mast to support the solar panels for the international space station (AEC-Able Engineering 1993). Today, hydraulic jacks together with very high tensile strength materials and special anchorages are generally used to create very large preloads.

VISCOUS BEHAVIOR AND LOSS OF PRESTRESS

Wood, masonry, concrete and other materials are viscous; their stress-strain behavior is time-dependent. In addition, wood changes dimensions as a function of moisture content. Such behavior creates a prestress state and can decrease prestress levels to zero. The Long, Howe and Pratt wood and wood-iron trusses built in the US in the 19th century were all designed to be prestressed (Gasparini and da Porto 2003). The designers understood that periodic retightening was necessary. Time-dependent behavior can now be predicted using linear viscoelastic constitutive models. For example, Gasparini, Bruckner and da Porto (2006) used the three-parameter-solid linear viscoelastic model to predict the behavior of a prestressed Howe truss. Response time histories showed that forces and displacements have very different time rates of change. In the context of prestressed concrete, Freyssinet recognized that, given the actual viscous properties of concrete, a permanent prestress could be achieved if very-high-strength prestressing materials, stretched to large elastic strains, were used.

Engineering knowledge on modeling time-dependent behavior was not developed until the 20th century. Moreover, even the superposition of linear elastic effects of prestressing on those of dead and live loads, which generally requires analyses of hyperstatic sytems, was not widely used until the 20th century.

GEORGE FERRIS' WHEEL AND THE STRUCTURAL ANALYSIS OF THE PRESTRESSING ACTION

In an effort to outdo Eiffel's tower built for the 1889 Paris Exposition, George Ferris designed and built a great wheel of 76m diameter for the 1893 World Columbian Exposition in Chicago (Fincher 1983). The wheel had thirty-six cars, each designed to carry sixty persons on a leisurely, two-revolution, twenty-minute ride. The great wheel was prestressed by tensioning the cable spokes. Viewed as a plane truss, the wheel is hyperstatic to the first degree. In the third edition of the book, *The Theory and Practice of Modern Framed Structures,* J. B. Johnson, C.W. Bryan and F.E. Turneaure (1894) present a correct analysis for the effects of the actions of prestressing, self weight and full vertical live load. They did not use a direct Maxwell-Mohr analysis but rather an elegant argument based only upon symmetry and superposition. Their approach is depicted in Fig. 2.
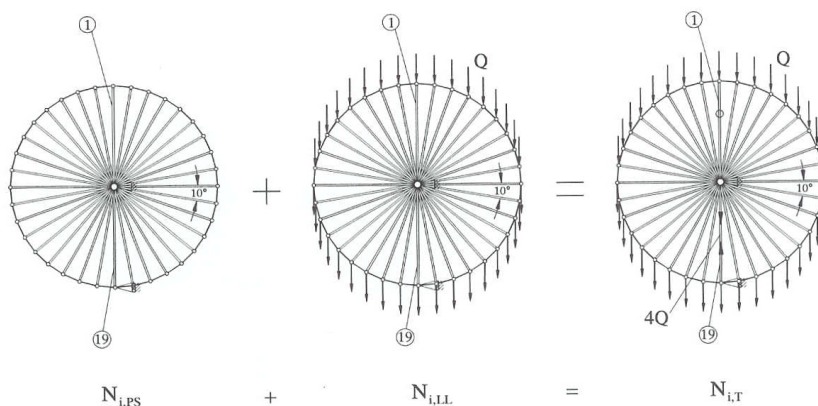

Figure 2. Ferris wheel analysis by Johnson, Bryan and Turneaure (1894)

The authors note that the dead and full vertical live loads are antisymmetric about a horizontal diametrical line whereas the prestressing action is symmetric. They then let the total force from the two actions be zero in the spoke extending vertically above the centre and, using statics, they compute the total force in the spoke that extends vertically down from the centre. Then, invoking symmetry and writing two superposition equations, they determine the required prestressing force in the spokes and the antisymmetric forces in the spokes from the dead and full vertical live loads. Their analysis maybe the first time that the preload required to preclude slackness in a prestressed system was determined analytically by US engineers.

Between approximately 1860 and 1880, procedures for analyzing statically determinate trusses became common engineering knowledge in the US. It is ironic that the hyperstatic, prestressed versions of the Howe and Pratt trusses, which had performed so well, were abandoned by civil engineers in favour of their statically determinate forms. Enthusiasm for prestressed trusses did not re-emerge in the US until the 1960's, when computer programs for structural analysis became widely available. However, prestressed trusses enabled the emergence of another revolutionary technology.

THE FLYING PRATT TRUSSES OF WILBUR AND ORVILLE WRIGHT

The structures of all the Wright flyers were three-dimensional versions of Pratt trusses with timber vertical compressive struts and wire X-bracing. There are two restored Wright flyers in the US. The one at the Smithsonian Institution in Washington DC is said to be a restored version of the Wright flyer used for their historic first powered flight on December 17, 1903. The other flyer, the third built by the Wrights and flown extensively in 1905, is on display at Carrillon Park in Dayton, Ohio, the home town of the Wright brothers. The restoration of the flyer on display at Dayton began in 1947 under the direct supervision of Orville Wright. Edward A. Deeds, a Dayton industrialist who financed the restoration, noted "Mr. Wright, in characteristic fashion, spared no pains to insure its authenticity in every detail" (Crouch, 1985). Neither the flyer restored under Orville's direction nor the Smithsonian flyer has turnbuckles on the diagonals for prestressing the structure. However, an image of the 1905 flyer during restoration, shown in Fig. 3, clearly shows turnbuckles on the diagonals.
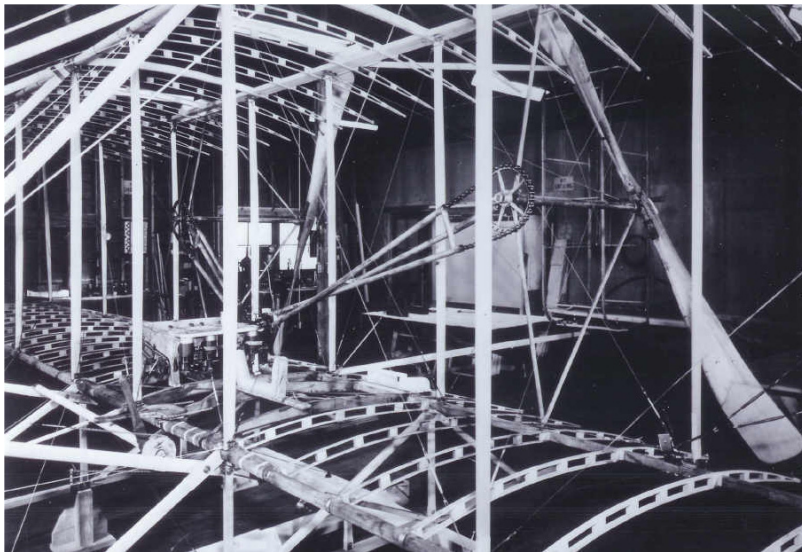

Figure 3. 1905 Wright flyer under restoration at Dayton in 1947. (Smithsonian Institution)

Turnbuckles are also evident in other images of the biplanes, taken with prominent "guests" aboard. Therefore there is uncertainty regarding whether/how the Wrights prestressed their flyers. It may be conjectured that turnbuckles were used during construction and for prestressing but then usually removed by the Wrights, perhaps to enhance performance or appearance. If the Wrights did not prestress their flyers, the stiffness of the structural system would have been significantly reduced, since only one diagonal in each panel would be active.

PRESTRESSED CONCRETE AND THE USE OF HIGH STRENGTH MATERIALS

The contributions of Freyssinet, Magnel and other European engineers to the development of prestressed concrete are well-documented (Iori 2003, Marrey and Grote 2003, Radelet-de Grave 2005). US developments are described in a series of papers published in conjunction with the 25th anniversary of the founding of the Prestressed Concrete Institute (Zollman 1978) and more recently at an American Concrete Institute (ACI) symposium (Russell and Burns 2005).

An early US patent for prestressed concrete was filed by Richard E. Dill on 7 February 1925 and granted on 18 September, 1928 (Dill 1928). Dill's patent focused on post-tensioning using undeformed asphalt-coated bars, tensioned by tightening nuts. Dill's patent clearly expresses that shrinkage and other long-term deformations in concrete can decrease the prestress to zero. In an amusing way, he states: "A further advantage in the use of my invention consists in the utilization of hard steel, or steel of high elastic limit and high ultimate strength." It is uncertain how far Dill developed and implemented his concept. The most common early use of prestressed concrete in the US was for the construction of cylindrical storage tanks. The evolution of prestressed concrete tank design is described by J. M. Crom (1936, 1943), who began constructing prestressed tanks in 1931 and later became vice-president of The Preload Company of New York. Tanks were generally prestressed both vertically and circumferentially. The principal evolutionary changes occurred in the strength of the wire and in the prestress magnitudes used. In 1936, wire with a yield stress of 413.8MPa was in use, prestressed to 275.9MPa. By 1943, wire with a yield stress of 1276MPa was in use, prestressed to 1034.6MPa. Regarding other structural applications of prestressed concrete, Rosov (1938) described European developments and potential uses. The discussions of his paper, however, were lukewarm and sceptical.

A principal driving force behind the rapid post-war development of prestressed concrete in the US was the John A. Roebling's Sons Company (JARSCO), which manufactured high strength wire, rope, strand and anchorages. They embraced prestressed concrete as an important post-war market for their products. The company began experimental research on prestressed concrete in 1943. The first large-scale application of prestressed concrete by JARSCO was on the Rio Paz suspension bridge between El Salvador and Guatemala, completed in 1949 (Reeve, 1950). Both the roadway and the sidewalk were prestressed concrete. The 6.4m wide roadway was formed by placing 53.4cm wide, 30.5cm deep and 6.6m long precast box beams adjacent to one another. Each box beam was

post-tensioned using two parabolic 16mm galvanized bridge strands. The entire length of the roadway was formed by 224 adjacent box beams, which were in turn post-tensioned together longitudinally using eight 32mm galvanized bridge cables. The prestressing strand and cable, the anchorages and the two-way pressurising system were Roebling developments, completely different from the systems of Freyssinet and Magnel.

JOHN A. ROEBLING'S SONS COMPANY AND THE SAN MARCOS BRIDGE

In response to the collapse of the Tacoma Narrows suspension bridge in 1940, JARSCO initiated an experimental research program on alternate systems for stiffening suspension bridges. The program was supported by the US Army Corps of Engineers as part of the war effort. A prototype design was under contract for construction by 1945 but was not built because of the end of the war. The system that was developed was eventually realized in the San Marcos Bridge over the River Lempa in El Salvador, Central America. Roebling's bid for design and construction was submitted in 1948 and the bridge was completed in 1952. The bridge, shown in Fig. 4, had five suspension spans, the largest
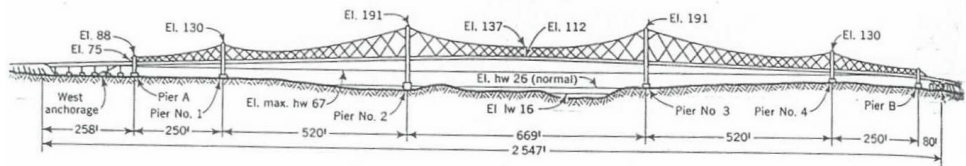

Figure 4. San Marcos Bridge over the River Lempa, El Salvador, completed 1952

being 204m. The bridge did not have a conventional stiffening girder or truss; rather it was pretensioned with horizontal cables at the level of the deck. The diagonal elements between the top and bottom chords formed a continuous "all-cable" truss. The design is described in Engineering News-Record (Birdsall 1953) and in a series of articles in Civil Engineering magazine (Birdsall et al. 1954). The design was based on measurements of a physical model. Stresses and displacements due to live loads and temperature were determined using strain gauges on a 1:20 scale model. A feature of the design was that the prestressed lower chord cables were "self-anchored" into the concrete deck of the bridge. The concrete deck, which was detailed to allow sliding over the steel floor framing, in effect formed a 658.5m long prestressed concrete slab. Unfortunately, this innovative bridge was destroyed by guerillas in October, 1981.

HYPERSTATIC AND HYPOSTATIC PRESTRESSED SYSTEMS

A hyperstatic system is one that has a non-singular linear stiffness matrix and has more discrete force unknowns than discrete nodal equilibrium equations. A non-singular linear stiffness matrix

means that the system can satisfy equilibrium in the undeformed position for any arbitrary applied loads. Such systems allow states of self-stress or prestress. If a system has a non-singular linear stiffness matrix and a number of discrete force unknowns equal to the number of discrete nodal equilibrium equations, then the system is statically determinate and cannot be prestressed. For simplicity, we can denote as *hypostatic* a system with a singular linear stiffness matrix; that is, a system that cannot satisfy equilibrium in the undeformed position for any arbitrary loading. Calladine (1978) discusses the Möbius-Maxwell necessary-but-not-sufficient criterion for categorizing trusses as hyperstatic, statically determinate or hypostatic. He also examines hypostatic truss forms that allow states of self-stress and whose initial tangent stiffness is proportional to the magnitudes of the prestress forces. In general, such systems may be used as structures but they require some type of geometrically non-linear analysis for design. Both hypostatic and hyperstatic prestressed systems have been built. David Geiger's Tropicana Dome (Rosenbaum 1989) and Ove Arup's roof for the reading room of the Phoenix Central Library (Ishler 1994) are examples of prestressed hypostatic forms. Matthys Levy's Georgia Dome (Levy 1991) and JARSCO's San Marcos Bridge are examples of hyperstatic prestressed forms. But the San Marcos Bridge could have been prestressed if only vertical elements had been used to connect the chords, which would have produced a hypostatic form. Structural engineers can often choose to design either hypostatic or hyperstatic prestressed forms. If a hypostatic system is chosen, the designer accepts and relies on geometrically non-linear behaviour of the system. A structural assessment of the relative merits of hypostatic versus hyperstatic prestressed systems must consider ease of erection and prestressing, static stability, stiffness and strength as well as dynamic behaviour. Gasparini and Gautam (2002) examine these issues for hypostatic and hyperstatic forms of a planar prestressed truss analogous to the truss of the San Marcos Bridge. The two forms carry moving vertical loads on the lower chord in completely different ways.

STABILITY OF EQUILIBRIUM OF PLANAR PRESTRESSED SYSTEMS

Two notable examples of planar prestressed systems are Peter Rice's cable mullions for the Grandes Serres at La Villette, designed in 1981 (Rice 1994) and David Geiger's radial cable trusses that form his Tropicana Dome. Both planar designs have no out-of-plane bracing but yet are stable with respect to out-of-plane motion. Such out-of-plane stability is not always guaranteed and must be verified by analysis. For example, Fig. 5 shows a simple planar three-element prestressed system that may be stable, neutral or unstable with respect to out-of-plane motion depending on the length of the compressive element.

Peter Rice's planar cable mullions are stable because the compressive struts are designed to have a horizontal axis of rotation in the plane of the glass. The out-of-plane stiffness is of "second order," proportional to the prestress axial forces. Such reliance on second-order behaviour for stability and stiffness is a relatively recent design paradigm, not always understood and accepted by structural

engineers. Another simple example of out-of-plane stability is provided by single Howe and Pratt truss panels, as shown in Fig. 6.
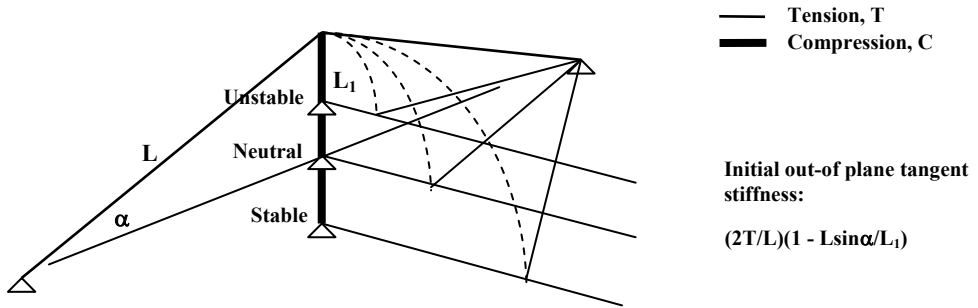
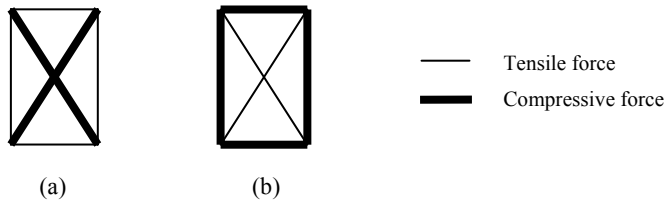Figure 5. Stability of equilibrium of a planar truss

Figure 6. Howe truss panel (a) is stable out-of-plane; Pratt truss panel (b) is unstable out-of-plane

The Howe truss panel is stable with respect to out-of-plane motion whereas the Pratt truss panel is unstable.

STATIC STRENGTH AND RELIABILITY OF PRESTRESSED SYSTEMS

A question naturally arises in the context of prestressed systems. Can a self-equilibrated state of prestress decrease the static strength and reliability of a system? For materials and elements that are ductile, it is well-known (Drucker 1952) that a self-equilibrated initial state of stress does not affect the load that causes a kinematic mechanism limit state. However, if the materials and elements are brittle, a state of self-stress can indeed reduce the static strength and reliability of a system. For prestressed trusses, the static strengths and reliabilities of analogous hypostatic and hyperstatic forms differ. Moreover, the static strength and reliability of trusses depend strongly on whether tension-only and/or compression-only elements are used. These are important design issues for structural engineers.

TOPOLOGIES OF TENSEGRITIES

"Tensegrity" is a neologism coined by R. Buckminster Fuller to describe prestressed trusses, generally three-dimensional, in which compressive elements are connected only to cable (tension-only) elements. The topology; i.e., the geometry and connectivity, of such systems has intrigued mathematicians (Connelly 1998; http://mathlab.cit.cornell.edu/visualization/tenseg/tenseg.html) and artists such as Kenneth Snelson (http://www.kennethsnelson.net). Geiger's Tropicana Dome, Levy's Georgia Dome and Arup's Phoenix Central Library reading room roof are, in fact, tensegrities. In most cases, tensegrity systems are hypostatic; that is, their linear stiffness matrix is singular. As explained by Calladine (1978), the geometry of prestressed hypostatic forms corresponds to extrema of the lengths of certain elements. For example, the geometry of Kenneth Snelson's "VX" sculpture (see Snelson website) is understood by fixing the lengths of the compressive elements, fixing the lengths of the tensile elements that form the two polygonal rings and rotating one polygon as a rigid body relative to the other. At the relative rotation that gives minima for the lengths of the longitudinal tensile elements, the system allows a state of self-stress which in turn imparts second-order stiffness. Understanding the geometry of Snelson's "Easy Landing" sculpture (see Snelson website) is however, much more difficult. Conceptualization of new tensegric topologies, for example as proposed by Arup for a bridge within the National Building Museum in Washington DC (see Architectural Record 06 04 p. 282), remains a challenge for structural engineers.

OBSERVATIONS

Prestressing has been used throughout history, in conjunction with most construction materials. Prestressing may be used to achieve functionality, improve structural performance, simplify connections and to preclude reversals of stress. It is often useful for structural intervention, to stabilize and strengthen systems.

In the context of space trusses, the conceptualization of new tensegric topologies remains challenging. The choice between hypostatic and hyperstatic prestressed forms and reliance on geometrically non-linear behaviour are producing innovative designs. Conceptualization of practical erection and prestressing procedures that give desired prestress states is essential and often difficult. Verifying the static stability, stiffness, strength and reliability of prestressed systems can require advanced engineering modelling and analyses. And in particular, the dynamic behaviour of geometrically non-linear systems is poorly understood.

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