



FOREWORD

When *Structure in Architecture* first appeared in 1963, it awakened architects to a qualitative, conceptual understanding of structures that was lacking, as engineers had always described structures clouded with mathematics. Here was an important new path that showed how structures work rather than how they are computed. Not only architects but engineers themselves and the general public were able for the first time to learn from this innovative approach. A strength of this book is that it demonstrates that even the most complicated-looking structure can be deconstructed to reveal its elementary roots: beams, columns, frames, trusses, and shells, whose actions can be conceptually understood, clarifying the way in which the whole structure works.

In the 50 years since the first edition of this book was published, a vastly expanded catalog of available structural types has appeared; new materials have been developed, new shapes have been introduced, and, above all, advances in computing technology have allowed architects and engineers

the freedom to conceive designs never before possible. A new edition was therefore inevitable.

Mario Salvadori was my teacher, my mentor, and then my partner in Weidlinger Associates. Together, we wrote four books on structural design, failures, and seismicity. All were descended from the approach Mario conceived in *Structure in Architecture* to explain technical concepts using simplified language, making them accessible to readers of any age. I am honored, and it gives me great pleasure to introduce both new readers and readers of previous editions of *Structure in Architecture* to this new edition. The classic work has now been greatly improved to bring the original into the twenty-first century with updated graphics and structural examples, as well as a revised text to reflect recent advances in structural typology. This new edition will undoubtedly stand for the next decades as the go-to reference to understanding how structures work.

Matthys Levy



PREFACE

It has been 30 years since Mario Salvadori updated the last edition of *Structure in Architecture*. On its initial publication in 1963, it was one of the first and only books of its kind to introduce the principles of structures to architectural students in a largely nonmathematical manner. The variety of textbooks of this genre has grown and changed dramatically since that time, and contemporary publishing practices have dramatically evolved as well. Now long out of print and superseded by many newer books presenting rich graphic content, *Structure in Architecture* has not only been surpassed in popularity by other texts, but the presentation may also seem dated or unappealing to contemporary students. Nevertheless, it remains an outstanding work of one of the most influential individuals in the area of architectural structures education. Rather than relegate it to the bin of history, a new edition to perpetuate its legacy was called for. This edition thus presents a substantial revision of the graphic presentation, while retaining the clarity of, and expanding on, the original text.

ON MARIO SALVADORI

To better understand the history, place, and authority of this text, it is helpful to understand briefly something about Mario Salvadori. Throughout his career, he wrote voluminously and taught extensively on the topic of architectural structures, as well as engaging in a number of conference discussions about the nature of the dialog between architects and engineers. Holding Italian doctorate degrees in mathematics and civil engineering, for nearly 50 years he taught in both schools of civil engineering and architecture at Columbia University in New York, rising to be one of the most distinguished faculty members of that era.

Fourteen years into his teaching career, while continuing his academic appointment, he joined the practice of the brilliant Hungarian engineer Paul Weidlinger. There, too, Dr. Salvadori distinguished himself by becoming a partner in 1963 and later chairman of Weidlinger Associates, thus impacting the design of many important structures, conducting numerous forensic structural investigations, as well as shaping the careers of generations of young engineering practitioners. For his lifetime of contributions, he was widely honored by engineering, architecture, and academic societies alike.

Of all the achievements of an illustrious career, however, Mario Salvadori was most proud of his work teaching science and math to inner-city children in the New York City region, using buildings and bridge structures as a spring-board. The last three decades of his life were increasingly

dedicated to this personal educational mission. The legacy of this work lives on today in the form of the Salvadori Center (salvadori.org), a nonprofit educational center that he established in 1987—an organization dedicated to the mission of educating children in what is now referred to as STEM, for Science, Technology, Engineering, and Math. Clearly decades ahead of his time, Mario was active with the Center until the very end of his life, passing away in 1997 at the age of 90.

ABOUT STRUCTURE IN ARCHITECTURE

Along with the works produced in his dual careers of academia and practice, Mario Salvadori wrote also for the lay audience. His most popular books such as *Why Buildings Stand Up* and *Why Buildings Fall Down* (coauthored with Matthys Levy) have been in print continuously since their first publication in 1980 and 1992, respectively. These can be seen as later-career books very much influenced by his work with children, written in a manner accessible to anyone with no formal training beyond basic schooling.

The first edition of *Structure in Architecture*, in contrast, came much earlier (1963), yet Dr. Salvadori had at this point been teaching at Columbia for nearly twenty-five years and this was already his fourth published book. Two subsequent editions in 1975 and 1986, plus ten foreign-language translations, attest to the interest and worldwide popularity of the book. Unlike the later popular texts, however, *Structure in Architecture* went deeply into principles that are important for architects to understand, though never with much mathematics.

The issue of just how technical an engineering education an architectural student requires has been a matter of debate for decades. A polarity exists even within the community of educators who teach and research in architectural structures: On the one hand, there are those who firmly believe that calculations are the basis for the study while, on the other hand, there are also those who feel quite the opposite. With his unique talents, Mario Salvadori was able to successfully bridge these two disparate worlds and recognize the commonality between the two. He was able to translate arcane principles of mathematics and science into simple language that—quite literally—even young children could understand. Dr. Salvadori believed that the conceptual approach was a vital starting point for (or at least concurrent study with) a more technical study. He was thus able to engage many architecture students who would otherwise have had no interest in the more technical aspects of architectural design.

THE INTENT OF THE FOURTH EDITION

Deborah Oakley was approached by Pearson Education to undertake the project as a new coauthor, joining with Robert Heller to revisit the manuscript for an update of this classic book. As noted previously, the objective was to appeal to a new audience, while retaining all of the strong points of the earlier editions. The organizational structure of the new edition has been largely retained from the previous. Rather than making any drastic changes to the text and examples of the third edition, we consider the book to be a mid-to-late career watermark of one of the most celebrated architectural technology educators, and thus important to conserve the spirit of the previous editions. Editing of the text was a shared effort between Deborah Oakley and Robert Heller, while the acquisition of photos and creation of the majority of illustrations and 3D models were by Deborah Oakley.

The approach was to strike a balance between what should be retained and/or expanded, and what should be updated or removed. With respect to the written text, it remains largely that of Mario Salvadori, with additions and alterations ranging from minimal to significant, depending on the chapter. Regarding example projects, where possible we retained those that are iconic and clearly illustrate fundamental principles, while replacing with contemporary projects some that had been superseded. Visually, the greatest difference will be seen in the graphics and computer renderings by the new author, and in the color photographs. Many illustrations have been provided with extensive supplemental captioning. Original 2D illustrations have been greatly expanded and are full color for best clarity. Some readers who know the earlier editions may miss the simple line drawings conceived by Robert Heller and executed by Felix Cooper. Unfortunately, the originals for these are lost to the sands of time. More than a few of them, however, live on in updated reproductions.

Among the more noticeable changes are that the text has been made gender neutral in language, following current practices and reality. Errors or omissions that we identified have been corrected, and contemporary topics have been added in various chapters. This edition therefore renews a classic volume with a new look and feel and more recent examples. In so doing, we intend for it to reclaim a place in the canon of modern architectural structures texts, and to reintroduce Mario Salvadori to a contemporary audience, a new generation of students, and even educators.

There are numerous books on architectural structures that feature extensive use of calculations, but far fewer that explain complex principles to new students using a largely nonmathematical, conceptual approach. With the updated graphic presentation, this book can be studied at the image and caption level first, and then more deeply in the text itself. This is a text that any intelligent individual with an understanding of elementary trigonometry and algebra should be able to pick up and learn from on his or her own. It remains an excellent preparatory or companion book for a numerically based study.

Looking to the future, we envision not only updates to examples but also branching into new media and learning resources of the digital age. But whatever may come to pass with future editions, one thing remains constant: The reason that a more than 50-year-old book such as this can still remain relevant in the twenty-first century is that the fundamental principles of structure have not changed. In fact (at the risk of oversimplification), it can be said that they have most elementally not changed since the time of Newton. Thus, Dr. Salvadori's voice remains vibrantly alive in this work, as it has in perpetuity with his several other works oriented toward the lay audience. We hope that the spirit of Mario Salvadori approves of the new edition, and that new generations are introduced to his work.

*Deborah Oakley,
Las Vegas, Nevada*

*Robert Heller,
Burlington, North Carolina
June 2015*

NEW FOURTH EDITION HIGHLIGHTS

- Entirely new graphics package:
 - Previous line illustrations updated with over 150 full color photographs, nearly 500 new full color rendered illustrations by Deborah Oakley, and extensive new image captioning
 - Many completely new illustrations added throughout the book to best demonstrate fundamental concepts
 - Designed to be accessible and attractive to the current generation of architectural students in a media-saturated world:
 - Big ideas can be grasped by studying the images and captions.
 - An in-depth understanding comes by studying the text with the images and experimenting with end-of-chapter exercises.
- Broken into three overall sections for better comprehension of organizational structure:
 - Part I: Fundamental Concepts (Chapters 1–5)
 - Part II: Structural Forms (Chapters 6–9)
 - Part III: Beyond the Basics (Chapters 10–15)
- New example structures illustrated throughout text
- Expanded content with enhanced text discussion and related graphics on critical topics such as beam behavior, moment of inertia, redundancy, and so on
- New at the end of each chapter:
 - Summary key ideas of chapter
 - Thought questions and simple exercises for further reflection
 - List of recommended key references of similar subject matter

FEATURES RETAINED FROM PREVIOUS EDITIONS

- Intuitive, nonmathematical approach
- Geared as an introductory text for beginning architectural students, students of technical schools, and interested laypeople
- Most of the historical examples, since they represent milestone accomplishments
- Most of the original text by Mario Salvadori

About metric units in the text It has been more than 40 years since the U.S. congress passed the Metric Conversion Act of 1975, and yet the country continues to use U.S. Customary (a version of British Imperial) units. When first written, this text was all in U.S. Customary units, and illustrations were created using whole numbers. This presents a quandary to the current edition. With an international audience, we cannot ignore the fact that as of 2015 all but two other countries (Liberia and Myanmar) have adopted SI units (*Système International d'Unités*, the international standard), and yet the text is directed primarily at a U.S. audience. SI units therefore accompany the U.S. units parenthetically and have been rounded to the nearest whole number equivalent (or no more than one decimal place). It is not an optimal solution, but it is also one that Mario Salvadori himself used in some of his other popular works. We continue to hope that

a future edition may be wholly in SI units and thus dispense with this temporary workaround.

ACKNOWLEDGMENTS

Deborah Oakley would like to thank Pearson Education for the opportunity of undertaking this project and also the many individuals who have contributed photographs throughout the text (credit is provided with image captions). Thanks are extended to my colleague Vincent Hui at Ryerson University and his students for some of the initial 3D models in Chapter 6, as well as to my graduate assistants at the University of Nevada, Las Vegas School of Architecture; in particular Vincent del Greco, who also worked on some early Chapter 6 models, and Adam Bradshaw, for conducting photo research and assisting with the final image preparation. Special thanks are extended to Terri Meyer Boake of the University of Waterloo for the many photographs, as well as mentorship and friendship over the years. I would also like to thank my father, Donald Oakley—a writer by trade—for final proofreading. And the most important thanks of all go to the many students who have taught me how to teach structures to architecture students.

Robert Heller wishes to extend his appreciation to Deborah J. Oakley for her diligence, drive, and ingenuity in making this work, a tribute to the memory of his late friend Dr. Mario G. Salvadori, possible. Coauthoring the first edition of *Structure in Architecture* gave him the impetus to teach structural mechanics for 50 years.

AUTHOR BIOGRAPHIES

Deborah J. Oakley, AIA, PE

Deborah Oakley has been teaching structures to architecture students for nearly 20 years. She is an associate professor at the School of Architecture at the University of Nevada, Las Vegas, where she also teaches design studio classes. Uniquely qualified as both a Registered Architect and Professional Engineer, she came to academia with education and experience in fields of both civil (structural) engineering and architecture. She is a passionate crusader for the integration of architecture and structure, including associated educational endeavors in the field. She is a founding member, past president, and board member of the Building Technology Educators' Society (BTESonline.org), the only North American academic organization of architectural educators focused on construction and structural technology education and research. Prior appointments have been as an assistant professor at the University of Maryland School of Architecture, Planning and Preservation and at Philadelphia University School of Architecture and Design. Her current work

involves conducting Discipline-Based Education Research in the area of architectural structures pedagogy.

Robert A. Heller, PhD, PE

Robert Heller received his education at Columbia University. After earning a PhD in engineering mechanics, he joined the Faculty of Columbia's Department of Civil Engineering. There he was Mario Salvadori's colleague and eventually became his coauthor. After leaving Columbia, Heller was appointed Professor of Engineering Science and Mechanics at Virginia Tech. In that capacity, he developed new courses on probabilistic structural mechanics and reliability and service life of structures and courses for architects.

His series of educational videos entitled "Mechanics of Structures and Materials" has been widely used in Schools of Architecture and Engineering. Heller's research work on the Service Life of Solid Rocket Propellants and on Aircraft Fatigue for the Department of Defense has been published in numerous scientific journals.

STRUCTURAL FORMS

Part II of this text illustrates the application of basic principles introduced in Part I. Beginning with the most elementary structural types and moving through complex forms, the reader is introduced to the wide diversity of possible structural types, including tension and compression structures (Chapter 6), bending structures (Chapter 7), frames and

arches (Chapter 8), and a more refined look at the nuances of structural behavior (Chapter 9). The fundamental concepts behind those structures, plus illustrative examples, form the basis for this presentation. Since some of the later material of Part III builds on the present material, it is recommended that Chapters 6 through 9 be studied before the later chapters.



The Millau Viaduct in southern France. See Figure 6.12.

Photo: Igor Plotnikov/123RF

TENSION AND COMPRESSION STRUCTURES

6.1 CABLES

The most elementary of all structural elements, and thus the most easily understood, is the simple tension cable. Cables have been used for thousands of years, beginning with the form of simple ropes made of natural plant fibers and animal hairs, to the present day where the properties of advanced materials have made the long-span bridges of the modern world possible. The high tensile strength of steel, in particular, combined with the efficiency of simple tension, makes a steel cable the ideal structural element to span large distances.

Cables are flexible because of their small lateral dimensions in relation to their length. This flexibility indicates that in a cable there is a limited resistance to bending. As introduced in Chapter 5 (and further discussed in Chapter 7), bending is a complex structural action that involves simultaneous tensile and compressive stresses within a member cross section. In the case of cables, uneven stresses due to bending are prevented by flexibility. The tensile load in a cable is thus evenly divided among the cable's strands, permitting each strand to be loaded to the same safe, allowable stress. This behavior makes cables the singularly most efficient structural form possible. *All* of the material of a cable can be effectively used to carry loads, and there is no

possibility of buckling. Bridges with single spans longer than a full mile are now common due to the combined strength of steel and efficiency of pure tension (Figure 6.1).

As introduced in Chapter 3, it is very easy to visualize the load-carrying action of a simple cable carrying a weight when suspended along its length. This type of behavior is very familiar to almost everyone and clearly produces pure tension in the cable. Loads acting perpendicular to a cable spanning a distance will always produce pure tension; however, the magnitude of the tensile force can vary throughout the cable length, depending on the placement of the loads.

In order to understand the mechanism of how an initially horizontal cable supports vertical loads, consider a cable suspended between two fixed points located at the same level and carrying a single load at midspan (Figure 6.2). Under the action of the load, the cable assumes a symmetrical, triangular shape, and half the load is carried to each support by simple tension along the two halves of the cable.

The characteristic triangular shape acquired by the cable is referred to as the *sag*: the vertical distance between the supports and the lowest point in the cable. Without sag the cable could not carry the load. We see from the vector free body diagram (FBD) of Figure 6.3 that without this sag



Figure 6.1 The Akashi Kaikyo Bridge

With a main span of 6532 ft (1991m) the Akashi Kaikyo bridge currently (2015) has the longest central span of any bridge in the world, demonstrating the efficiency of using high strength steel cables in tension.

Photo: Toshitaka Morita/Getty Images

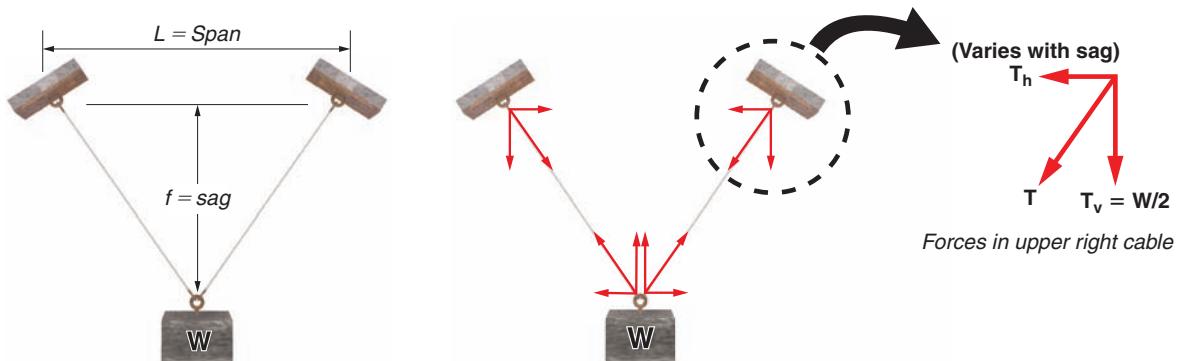


Figure 6.2 Symmetrical load on cable (above left)

A single load, W , placed at the midspan of a suspended cable will naturally deform the cable into a triangular shape. The vertical distance of the cable measured from the highest to lowest points along its length is referred to as its *sag*.

Figure 6.3 Internal Cable Force Actions (above right)

This illustration demonstrates the internal forces on the cable of Figure 6.2 as a free body diagram with the upper right joint isolated for clarity.

The tension force on a cable structure can be resolved into horizontal and vertical components. The combination of the two force components, T_v & T_h , have the same net effect on the structure as the actual force, T , but facilitate a clearer understanding of the horizontal and vertical equilibrium of the forces. Note that in both horizontal and vertical directions, every force vector is balanced by an equal and opposite vector to maintain static equilibrium—were this not the case, the structure would be in motion.

For a symmetrically loaded cable, it is evident by inspection that $\frac{1}{2}$ of the total vertical load W is carried by each support. The vertical components of the forces must therefore each carry $\frac{1}{2}$ of the load W . The inclination of the cables generates a horizontal inward pull, T_h , on the supports, each of which must be equal and opposite in direction to maintain horizontal equilibrium. The magnitude of T_h , however, depends entirely on the sag distance f , as illustrated in Figures 6.4a and 6.4b.

the cable tension forces would need to be horizontal, but purely horizontal forces cannot balance a vertical load — this would not fulfill the requirement for linear equilibrium in the vertical direction. The inclined pull of the sagging cable on each support may be split into the equivalent of two components: a downward force equal to half the load and a horizontal inward pull. Due to the horizontal action of this inward pull, if the supports were not fixed against horizontal displacements, they would move inward under its action, and the two halves of the cable would become vertical.

A simple experiment can bear this out. If the reader holds a thread in each hand and attaches a weight at the middle, one may sense physically that the string develops no horizontal pull when the fingers are touching, while an increasing pull is developed as the hands are moved apart, thus decreasing the string sag. The pull may be shown to be inversely proportional to the sag: Reducing the sag by half in fact doubles the pull (see Figure 6.4). For vertical equilibrium to be maintained, the vertical pull on the hands is always equal to one half of the load and is independent of

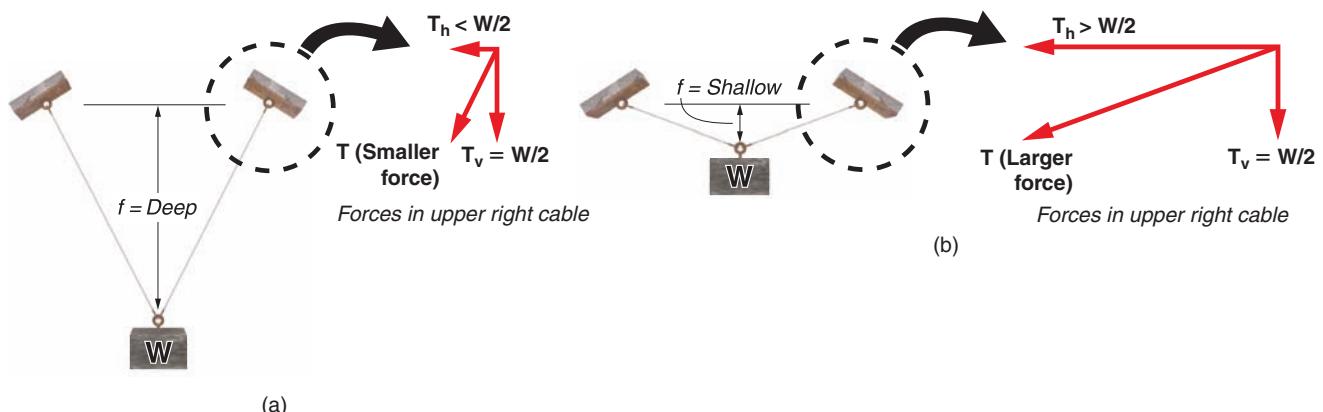


Figure 6.4 Variation of Cable Thrust with Sag

The graphic representation of force vectors is drawn in proportion to the force magnitude and direction, so the free body diagram therefore is a visual representation of the force intensity that can be understood at a glance. The vertical components of the inclined cable forces are always equal to one half of the load (when the load is placed at midspan); however, the magnitude of the horizontal force can be seen to decrease as the cable sag is increased (6.4a), and conversely will increase as the sag is decreased (6.4b). There is thus an inverse relationship between the amount of sag and the magnitude of force in the cable.

the sag. Hence, as the sag decreases, the tension the cable exerts on the hands increases because of the increase in the horizontal, not vertical pull. If the thread used is weak enough, there comes a point when it snaps, indicating that, as the sag diminishes, the tension eventually becomes larger

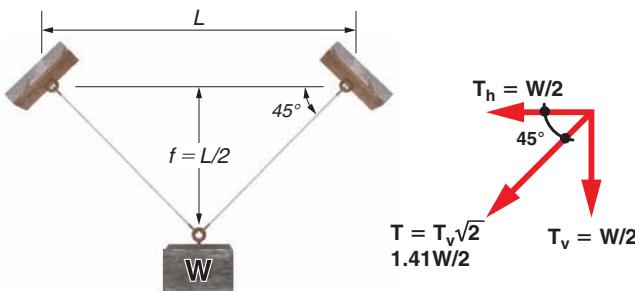


Figure 6.5 Optimal Sag

For a load placed at midspan, the optimal sag is one-half of the span distance, L . This results in a cable inclination of 45 degrees, and so both the horizontal and vertical components of the cable force will be equal to half of the applied load. Although the force magnitude will be higher than a cable with greater sag, the length of the cable will be longer, thereby requiring more total material. A sag distance of one half the span represents an optimal balance between the amount of force in the cable and the total amount of material required in the cable.

than the tensile strength of the thread. In actuality, if we look at the graphic vector equilibrium of the FBD (Figure 6.4b), it is seen that the horizontal component becomes infinitely long as the angle decreases to zero, indicating that it is technically impossible for a *completely horizontal* tension element with no sag to carry a vertical force.

The cable problem just considered raises an interesting question of economy. A larger sag increases the cable length, but reduces the tensile force in the cable and, hence, allows a reduction of its cross section; a smaller sag reduces the cable length, but requires a larger cross section because of the higher tension developed in the cable. Hence, the total *volume* of the cable material, the product of its cross section and its length, is large for both very small and very large sags and must be minimum for some intermediate value of the sag. The optimal or “most economical sag” for a given horizontal distance between the supports turns out to be one-half the span, and corresponds to a symmetrical, 45-degree-triangle cable configuration with a horizontal pull equal to half of the load (Figure 6.5).

If the *load is shifted* from its midspan position, because of its flexibility the *cable changes shape*, and adapts itself to carrying the load in tension by means of straight sides of *different inclinations* (Figures 6.6a). The two supports develop different vertical reactions, but equal horizontal pulls since

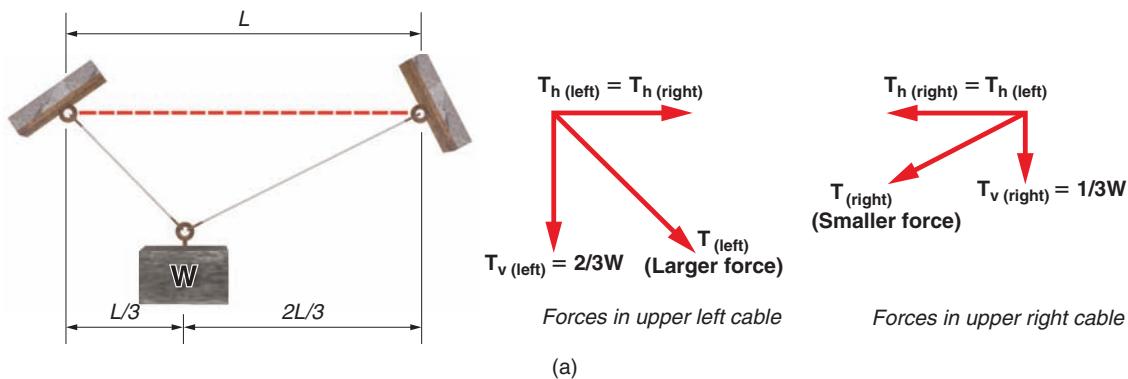


Figure 6.6a

For a single, asymmetrically placed load, free body diagrams for the upper left and right cable ends clearly illustrate that the force magnitude in the cable is not equal on either side of the load, the left side being greater than the right. For a load positioned at $1/3$ the distance from the left support, the vertical reaction components will be $2/3$ of the total load on the left side and $1/3$ the total load on the right side. Since no other horizontal forces are present, however, the horizontal components on either side will be equal and opposite one another, the actual magnitude varying with the amount of cable sag.

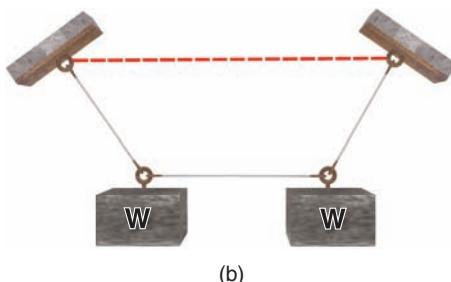


Figure 6.6b

Two symmetrically placed loads on a cable will reshape the cable into a three-sided polygon.

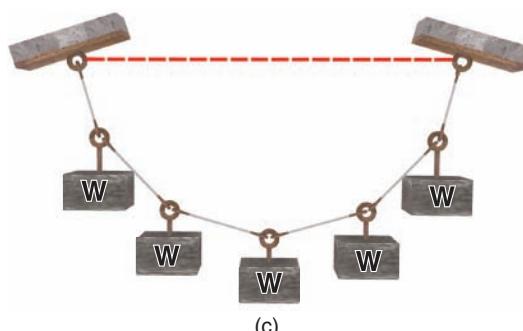


Figure 6.6c

Additional loads will continue to reshape the cable into a closer approximation of a curve as the straight sides become smaller and smaller.

the cable forces must always be in equilibrium in the horizontal direction. The value of the horizontal pull differs from the value for a centered load, but still varies inversely as the sag. The reader may sense this by shifting the load along the hand-supported thread. Because the vertical components on each side of the cable are different, the *resultant total tension* forces on each side of the load are also no longer equal to one another. This fact may at first be counterintuitive, yet can be clearly demonstrated by a graphic FBD at the upper left and right joints (Figure 6.6 a).

If the single load now is replaced by two equal loads placed on the cable in symmetrical locations, the cable again adapts itself and carries the loads by acquiring a new configuration, this time with three straight sides, the middle of which is horizontal (Figure 6.6b). As the number of loads is increased, with each new loading the cable again acquires a new shape in response to new equilibrium configurations. Each of the new shapes will have straight sides between the loads and changes in direction at the points of application of the loads. This process can continue, and each time the cable will readjust with a new form for each additional load.

It is important to note that for each configuration of loading, there is one and only one shape that the cable will take. This characteristic shape acquired by a cable under concentrated loads is called a *funicular polygon* (Figure 6.6c). The name is derived from the Latin word *funis* for rope, and the Greek words *poly* for many and *gonia* for angle. The funicular form is the natural shape required to carry loads in pure tension or (as will be shown) pure compression and therefore represents the optimum structural form that can be achieved by a unidirectional spanning structure. It is for this reason that the longest-spanning bridges are supported by cables.

As the number of loads on the cable continues to increase, the funicular or *string polygon*, acquires an increasing number of smaller sides and approaches a smooth curve. If one could apply an infinite number of infinitesimally small loads to the cable, the polygon would become a *funicular curve*. For example, the funicular polygon for a large set of equal loads evenly spaced horizontally approaches a well-known geometrical curve, the *parabola* (Figure 6.7 a). The optimal sag for a parabolic cable equals three-tenths of the cable span.

If the equal loads are distributed evenly *along the curved length* of the cable, rather than horizontally, the funicular curve differs from a parabola, although it has the same general configuration: It is a *catenary*, the natural shape acquired by a cable of constant cross section or a heavy chain (*catena* in Latin) under its own weight, which is uniformly distributed along its length (Figure 6.7 b). The optimal sag for the catenary is about one-third of the span; for such sag ratio, the catenary and the parabola are very similar curves (Figure 6.7 c).

A cable carrying a combined load of its own self-weight plus a load uniformly distributed horizontally acquires a shape that is intermediate between a catenary and a parabola. This is the shape of the cables in the central span of suspension bridges, which carry their weight and that of the stiffening trusses on which the roadway is laid (Figure 6.8).

A cable would span the *largest* possible distance if it could just carry its weight, but break under the smallest additional load (which is to say that under its own dead load it is stressed to its limit). Assuming an optimal sag-span ratio of one-third to minimize the weight of the cable, it is found that such a steel cable with a strength of 200,000 pounds per square inch (1.38 GPa) could span a distance of 17 miles (27.4 km)! This maximum distance is independent of the cable diameter, since both the weight of the cable and the tension in it are proportional to the area of the cross section. Obviously, actual cable spans are built to carry loads, which are usually much heavier than the cables themselves; hence, cable spans are much shorter than the limit span of 17 miles. The longest North American suspension bridge to date (2015), the Verrazano Narrows Bridge at the entrance of New York harbor, spans 4260 feet (1,298m) between the towers, a length over two-and-a-half times that spanned by the Brooklyn Bridge (which opened in 1883).

The Verrazano Narrows Bridge reigned as the longest in the world for 17 years from 1964 until surpassed in 1981 by the Humber Bridge in England, with a span of 4626 feet (1,410m) between towers. The Akashi-Kaykio Bridge in Japan (fig 6.1), completed in 1998 with a span between towers of 6,532 feet (1,991m) presently has the longest main span in the world. Such spans are rapidly approaching limiting values, beyond which it is not practically conceivable to go with the types of steel available today. Only an improvement in

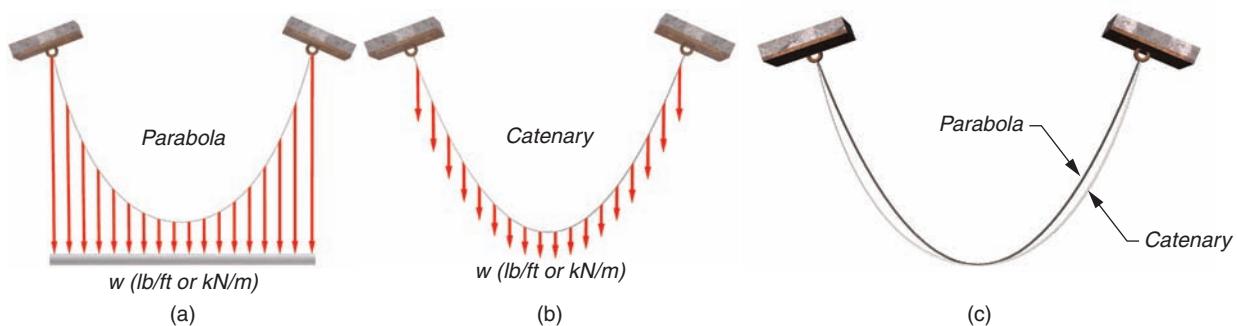


Figure 6.7 Funicular Curves

The variation between a catenary curve and a parabola is illustrated in these series of diagrams with gravity-induced loads. A parabola (6.7a) is the natural result of an equal, uniform load suspended along the length of the cable. A catenary (6.7b) is the result of the cable self-weight, which follows the natural curve of the cable. The two forms are closely similar; however, the catenary has a slightly greater outward bulge as can be seen in the superimposition of 6.7c.



Figure 6.8 The Golden Gate Bridge

One of the most iconic bridges in the world, the Golden Gate Bridge is a classic suspension bridge. Smaller suspender cables are hung from the main suspension cables, which are anchored by massive blocks at either end. The suspender cables support a deep stiffening truss, which carries the weight of the roadway. Without the stiffening truss, the roadway would continually flex with shifting weight of the moving vehicles.

Photo: Martin Molcan/123rf



Figure 6.9 Proposal for a bridge across the Strait of Gibraltar by Prof. T.Y Lin

With a main span of 16,400 ft (5000 m), the bridge would be 2.5 times longer than that of the Akashi Kaikyo bridge of Figure 6.1. This incredible span would be made possible by a hybrid structural system of cable-stayed structures at the masts that in turn support suspension cables, in turn supporting a deck of high strength but light weight glass fiber. At the present time (2015), the bridge remains an unrealized proposal. The obstacles to be overcome, particularly with supporting piers plunging nearly 3300 feet (1 KM) in water, are enormous.

Photo courtesy of Deborah Oakley

cable strength will make substantially larger spans possible with a single suspension cable, although hybrid designs that combine suspension cables with cable-stayed structures can further extend the range, such as the proposed span at the Strait of Gibraltar (Figure 6.9) by Dr. T.Y Lin.

Given the inherent efficiency and economy of steel cables, one may wonder why they are not used more frequently in smaller structures. The limitations in the application of cables stem directly from their adaptability to changing loads: Cables are unstable, and (as introduced in Chapter 4) stability is one of the basic requirements of structural systems. The trusses hanging from the cables of a suspension bridge have the purpose not only of supporting the roadway but also of stiffening the cables against motions due to changing or moving loads.

Stiffening trusses are usually rigid in the direction of the bridge axis, but less so in a transverse direction: Large displacements of suspension bridges caused by lateral winds can be substantial. Moreover, the long roadway and the shallow trusses constitute a thin ribbon, so flexible in the vertical direction that it may develop a tendency to twist and oscillate vertically under steady winds (see Section 2.6). Modern suspension bridges are made safe against such dangers by the introduction of stiffening guy wires (like those used in the Brooklyn Bridge in New York, designed in 1867) and by an increase in the bending and twisting rigidity of their roadway cross section.

In so-called *stayed bridges* of the “harp” or “fan” type (Figures 6.10 and 6.11), the guy wires—or *stays*—have the double role of supporting the deck and of stabilizing it.



Figure 6.10 The Senator William V. Roth Jr. Bridge

Unlike a suspension bridge that uses a main cable from which suspender cables are hung to support the road deck, a cable-stayed bridge supports the deck directly from inclined stay cables that attach to the towers. The cable arrangement of this bridge over the Chesapeake and Delaware Canal is known as a *harp shape* because the parallel arrangement of cables resembles the strings of a harp instrument. In the background can be seen the older arch bridge which the newer one replaced with a much wider road deck, capable of carrying more traffic, as well as longer span that eliminated piers in the waterway.

Photo courtesy of Scott Gore



Figure 6.11 The Clark Bridge

Crossing the Mississippi river near Alton Illinois, the Clark bridge represents another form of the cable-stayed type with the cables arranged in a radial pattern known as a *fan*.

Photo courtesy of Ted Engler

Their elegance and economy has made them popular for middle-range spans. Following the extensive destruction of European bridges during World War II, rapid reconstruction of the highway infrastructure was critically urgent. Cable-stayed bridge design progressed rapidly in the years following the war since they were both economical and capable of being constructed more rapidly in comparison with similar spans using suspension designs.

A cable is not a self-supporting structure unless ways and means are found to absorb its tension, which in large spans may reach values of the order of thousands of tons. In suspension-bridge design, this result is achieved by channelling the tension of the main-span over the towers to the side spans, and by anchoring the cables in the ground. The heavy anchoring blocks of reinforced concrete are usually poured into rock, and resist tension both by the action of the block's substantial dead weight and by the reaction of the adjoining rock (Figure 6.13). Under these circumstances the optimal sag to minimize the cost of the entire structure is approximately 1/12 of the span, since a 3/10 sag-span



Figure 6.12 The Millau Viaduct

An example of one of the more common forms of the cable stayed bridge, a semi-fan, the cables are intermediate between the parallel lines of the harp shape and the more radial arrangement of the fan. Located in southern France, the Millau Viaduct is not only one of the longest multispan bridges in the world, it is also (at the time of this writing, or 2015) the tallest, the highest supporting pier exceeding the height of the Eiffel Tower.

Photo: Igor Plotnikov/123RF

Figure 6.13 Suspension bridge anchorage

This diagram illustrates the heavy concrete anchorage for the suspension cables of New York's Verazzano Narrows Bridge, which opened in 1964. The main suspension cables actually comprise numerous bundles of smaller cables, each of which in turn are made of multiple single wires. The cables are splayed within the anchorage to permit each wire bundle to have a connection within the anchorage structure. The enormous mass of the concrete anchorage counterbalances the tension from the main suspension cable.

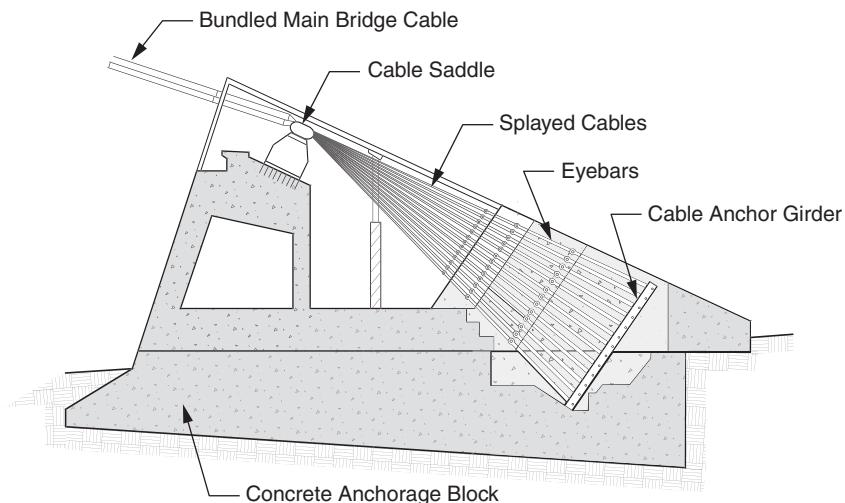
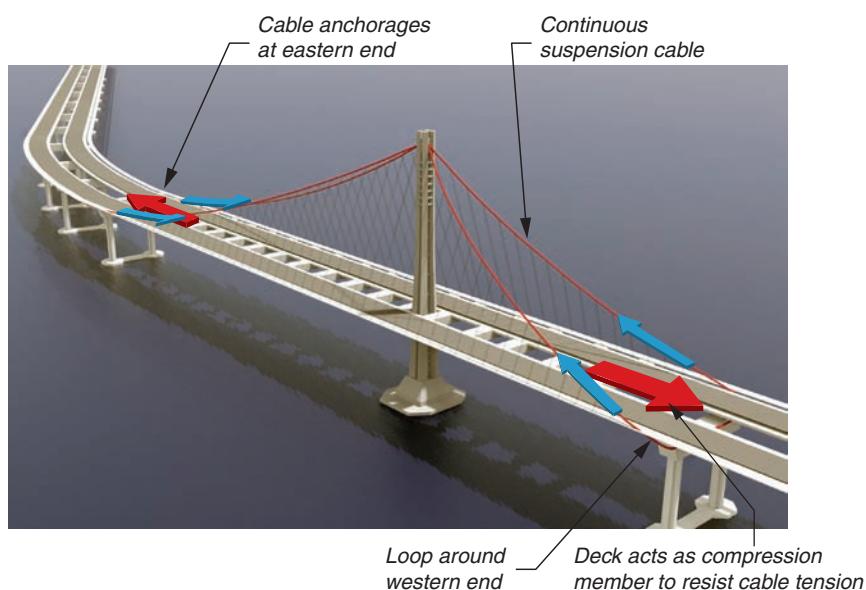


Figure 6.14 The New San Francisco-Oakland Bay Bridge East Span

Following the Loma Prieta earthquake of 1989, the San Francisco-Oakland Bay bridge (one of the world's busiest) suffered damage on its eastern span, which was constructed of rigid truss structures.

Considered likely to catastrophically fail in the next major earthquake, a replacement span was called for. The final design employs the same self-anchoring principle of the Burgo Paper Mill (Figure 6.16) but on a massively larger scale. The bridge is the largest in the world to employ a self-anchored suspension cable, and is further unique in that the cable is one continuous piece. Starting at one anchorage at the east end, it passes over the tower, then loops around the western end of the span and returns back to the tower and then down to the anchorage. The two end anchorages are completely contained within the eastern end bridge structure, with the road deck acting as a massive compression structure.



ratio leads to very tall, expensive towers. Compression in the towers, bending in the deck (often comprised of trusses), and shear in the anchorages are essential to the stability and strength of the tensile cables of suspension bridges. In *self-anchored* bridges the cables are anchored to the ends of the stiffening trusses or beams, thus compressing them, while the ends of the trusses are anchored to the piers to develop downward reactions (see Figure 6.14).

Cable bridges are essentially unidirectional spanning structures, which is appropriate for bridges. But this does not mean that the use of cables is constrained only to one direction. On the contrary, complex structures involving cables at multiple angles that cover a surface as well and other tensile structures are frequently used in building structures, and are considered in the next section.

6.2 CABLE ROOFS

The exceptional efficiency of steel cables suggests their use in the construction of large roofs such as sports stadia and transit terminals. This relatively recent twentieth century

development has brought about a number of new solutions in which tensile cables are the basic element in what may otherwise be a complex structural system. As noted above, the relative flexibility of cables is a primary consideration. There are numerous design approaches, each with different aesthetic qualities and fit with the architectural requirements, but each design solution is essentially aimed at stabilization of the cable system.

The most simple tensile roof design consists of a series of cables hanging from the tops of columns or buttresses, as though taking a number of suspension bridges and placing them side-by-side. Unlike the massive anchorages of a suspension bridge, however, the columns must be capable of significant bending resistance if the cable terminates at the column, due to the cable's large horizontal force component. An alternative design solution that prevents this column bending is to pass the suspension cable over the tops of compressive struts (i.e., columns) and anchor them to the ground, instead of terminating the cable at the column. In either design strategy, straight beams or plates then connect the parallel suspension cables, thus creating a polygonal or

Figure 6.15 The David Lawrence Convention Center in Pittsburgh, PA

This roof structure exemplifies the use of a suspension cable in a building structure. The cables are supported by anchorages similar to a suspension bridge at the low side of the building, and by stayed columns at the high side. The suspension cables carry the weight of the roof structure in a similar manner to a suspension bridge.

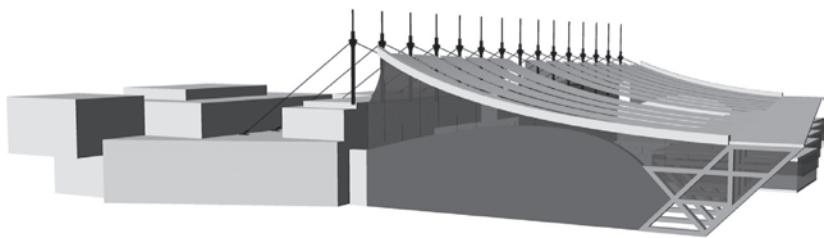


Figure 6.16 The BurgoPaper Mill in Mantua Italy

The requirements for a column-free interior space of this manufacturing plant necessitated the creation of an external structural support system. The ingenious solution by famed Italian engineer Pier Luigi Nervi employs the same structure as a suspension bridge, with two towers carrying main cables (which are actually solid rectangular bars that support suspender cables, which in turn support a trussed roof). The primary difference between this roof structure and a suspension bridge is the lack of a heavy anchorage at the ends. The horizontal force components are instead resolved by compression into the trussed roof deck, making it a self-anchoring structure.



Figure 6.17 Dulles Airport Terminal, Chantilly, Virginia

A masterpiece of modern architecture designed by famed Finnish-American architect Eero Saarinen, the roof slab is directly supported on parallel cables anchored to the exterior angled columns. The massive weight of the columns, plus their outward tilt, acts to counterbalance the cable tension forces.

Photo courtesy of Deborah Oakley



inverted barrel roof surface (Figure 6.15). The simplicity and low cost of this suspension-bridge scheme would make it popular, but for the fact that the straight elements connecting the cables are usually light and tend to oscillate or “flutter” under the action of wind. To avoid flutter, the roofing material must be relatively heavy, or the cables must be stabilized by guy wires or stiffening trusses.

The suspension-bridge principle was directly adopted in a structure designed in 1961 by Nervi and Cover for an Italian paper manufacturing plant (Figure 6.16). This structural scheme was an ideal fit with the architectural program because of the linear nature of the paper-making process. Unlike most suspension bridge designs, this is a self-anchoring structure (similar to the much later bridge of Figure 6.14), which balances the cable tension with internal compression in the roof structure rather than directing the tension to large anchorages in the ground. The reinforced concrete towers of each roof section (100 feet (30.5 m) wide and 830 feet (253 m) long) are

inclined posts supported by shorter compression struts that provide overall lateral stability to the building. The horizontal roof consists of reinforced concrete beams and slabs prefabricated on the ground and is suspended from the cables by means of wire hangers. The dead weight of this relatively heavy roof acts as a stiffening truss. It provides the necessary stabilizing force for the suspension cables, plus resists their tensile anchorage force through in-plane compression. This brilliantly simple structure permitted the economic roofing of a 10,000 square feet (930 m^2) area without a single intermediate support or interior column. The peripheral walls are independent of the roof structure, and wind pressure against these exterior walls is resisted by vertical columns. Although vertical, these act more like beams than columns, since most of their structural action is in bending.

Regarded as a twentieth century architectural masterpiece, Eero Saarinen’s 1962 Dulles Airport Terminal near Washington, D.C. (Figure 6.17), is similar in structural

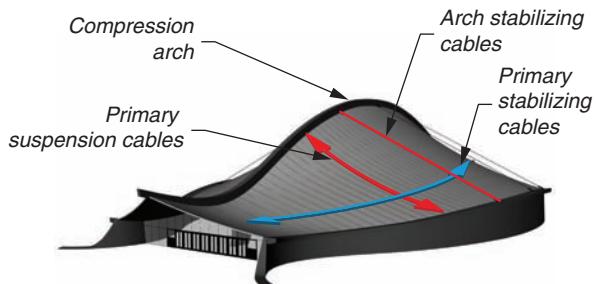


Figure 6.18 The David S. Ingalls Hockey Rink at Yale University

Designed by architect Eero Saarinen and engineered by Fred Severud (who in engineering circles was nearly as famous as Saarinen in architecture), the central concrete rib supports suspension cables that are anchored by a curved perimeter concrete wall. Since the roof is lightweight wood, in order to stabilize the cables from uplift, *upward arcing* stabilizing cables run perpendicular to and above the suspension cables along the length of the structure. For aesthetic reasons, the central concrete rib was made very thin; however, this created problems of instability for the rib. Also visible are thus six straight cables that connect the rib to the perimeter. This was a minor consolation to architecture that deviated slightly from a more pure structural aesthetic, where the rib would be designed such that these cables would not be required.

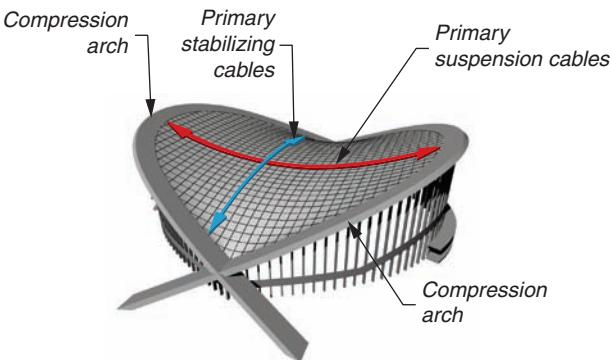


Figure 6.19 The J.S. Dorton Arena in Raleigh, North Carolina (Originally the North Carolina State Fair Livestock Judging Pavilion)

The arena uses the principle of a doubly curved structure with upward arcing suspension cables and downward arcing stabilizing cables (see Chapter 11). Engineered by Fred Severud (designer of the Ingalls Rink (Figure 6.18)), the two intersecting concrete compression rings function in a manner analogous to the principle of a director's chair. Tension in the cables prevents the rings from falling down, while this very tendency to collapse generates the tension in the roof structure, which acts in a manner similar to the seat of the analogous chair. The structure was designated an Historic Civil Engineering Landmark by the American Society of Civil Engineers in 2002.

principle to Nervi's paper mill, but consists of multiple parallel cables. The roof structure is a heavy concrete slab supported directly by the suspension cables; however, it does not resolve the tensile force of the cables. Here instead, the massive concrete pylons supporting the roof are angled outward, their dead weight and tendency to outwardly overturn counterbalances the horizontal pull of the roof cables. Designed at the start for expansion, the terminal was more than doubled in length in the late 1990s by adding additional columns, cables, and roof structure matching the original design.

A related yet different principle was used by Saarinen in the Yale University Ingalls skating rink in 1958 (Figure 6.18). In this design, the cables are suspended perpendicularly from each side of a central concrete arch, which has an inverted curvature at the ends. The cables hang with a natural downward sag, and the outer ends are anchored to the rink's heavy peripheral walls that are curved outward in plan. The roofing material is wood: Unlike Nervi's paper mill structure or the Dulles Airport Terminal, its relatively lightweight does not stabilize the cables entirely. The stabilizing is therefore accomplished by *upward curving* tension cables that pull downward against the primary suspension cables. The central concrete spine was too slender to be laterally stabilized by the roof structure alone, and so several additional straight cables tie it directly to the perimeter walls—a slight concession to the architectural desire of making the spine as slender as possible.

The 1952 solution by Mathew Nowicki for the roof of the Raleigh, North Carolina, arena illustrates an early implementation of the concept of interlocking counter-curved cables. The building profile is dominated by two large inclined, intersecting concrete arches. In a manner similar to the Dulles Airport Terminal pylons, these massive

parabolic arches simultaneously support a series of main suspension cables and provide for cable tensioning by their deadweight (Figure 6.19). Stabilization of the main downward-sagging cables is obtained by upward-curving cables at right angles to, and on top of, the primary cables—this then creates a mesh for support of the roof structure. The roofing consists of lightweight corrugated metal plates permanently anchored to the cable mesh. The concrete arches are themselves stabilized by vertical columns. By means of compression along their curvature, the arches resist the inward pull of the main cables. The surface thus defined by the cables resembles a saddle and is more stable under wind loads than a barrel-shaped roof. Notwithstanding the shape of the roof, in order to avoid flutter of the lightweight corrugated plates, it was still necessary to stabilize the roof panels by guy wires connecting a number of internal mesh points to the outer vertical columns. The interior of the structure is completely column free, and the essentially free-floating roof allows for abundant daylight through the perimeter walls.

In designing the roof for the 1956 Cilindro Municipal stadium in Montevideo, Uruguay, Leonel Viera invented an inexpensive and stable system that was well suited to cover large circular areas (Figure 6.20). In this roof, a series of radial cables connects a lower, central tension ring of steel to an outer compression ring of concrete. The outer ring resists all the tensile force of the cables through circumferential compression, and is supported by a cylindrical exterior concrete wall. With all tensile forces resolved within the roof structure itself, the exterior walls were required to only carry vertical loads, and thus were relatively thin. The roof decking consisted of a large number of prefabricated, wedge-shaped concrete slabs, which were supported on the radial cables by the hooked ends of their own reinforcing bars.

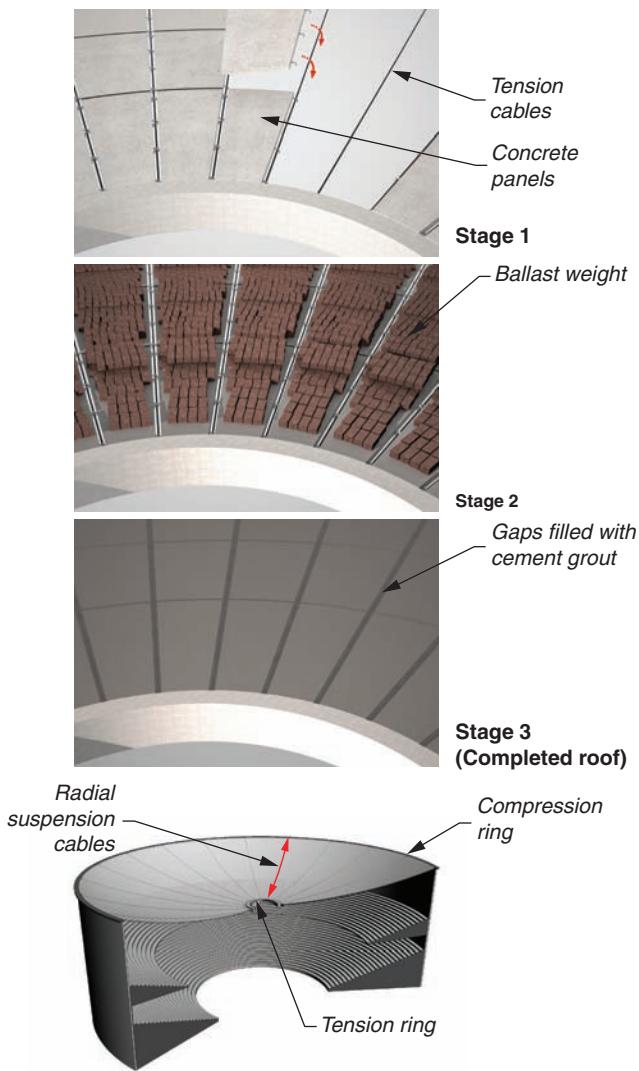


Figure 6.20 The Cilindro Municipal, Montevideo, Uruguay, by Leonel Viera
In order to provide permanent rigidity in the essentially simple cable-supported roof structure, Viera's construction process innovation was to hang wedge-shaped tiles on cables with gaps in between. The tiles were then covered with additional ballast weight, which caused the cables to stretch. Cement grout was filled within the gaps and the ballast was removed after curing. The lessening weight caused the cables to shrink, but with this movement prevented by the now cemented roof, a permanent compressive prestress in the roof surface was created. The roof structure functioned for 54 years until a fire inside the stadium caused its collapse in 2010. The remaining structure was subsequently demolished.

Figure 6.21 The Oakland-Alameda County Coliseum Arena (Presently the Oracle Arena)

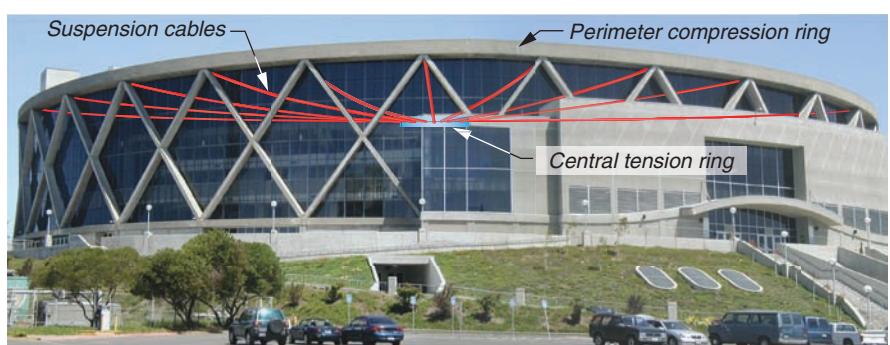
Designed by Skidmore, Owings and Merrill, the arena employed radially-arranged suspension cables similar to the Cilindro Municipal of Figure 6.20, the perimeter functions as a compression ring, which is supported on a diagonal gridwork of perimeter columns that provide lateral and torsional stability. Constructed in 1966, the structure has gone through substantial renovations to increase its capacity, which unfortunately detract from the clarity of its structural concept.

Photo courtesy of Deborah Oakley

The genius of this roof structure was due as much to its construction technique as to its structural concept. Here, to reduce cable instability, during construction the slabs were loaded with a ballast of bricks or sandbags after placement, which temporarily over-tensioned the cables. The resulting stretch of the cables created gaps between the wedge-shaped slabs. These radial and circumferential gaps were subsequently filled with cement mortar. Once the mortar had set, the entire roof became a monolithic concrete "dish." When the temporary ballast was taken off the dish, the cables tended to shorten, but were prevented from doing so by the monolithic concrete roof in which they were embedded (see also Section 12.7). The inverted roof was thus pre-stressed by the cables, and showed little tendency to flutter. Similar roofs, like that of Madison Square Garden in New York City and the Oakland-Alameda County Coliseum Arena (Figure 6.21), have been successfully and economically built in the United States and elsewhere on this principle (though with different construction technique), which Viera also applied to suspension bridge design.

The dish shape of downward sagging cable-supported roofs presents an architectural challenge of how to address the natural tendency for such shapes to collect rainwater. In the case of the roof of the Dulles Airport Terminal, three large sculptural elements dominate the interior roof surface of the terminal, which conceal vertical drainpipes. In the case of arenas, such centrally located drainpipes would be completely counter to the need for having an open clear span in the first place. The drainage of Viera-type roofs is obtained by the somewhat inelegant solution of pumping the rainwater to drain pipes located on the outer rim of the roof. In the Madison Square Garden and Oakland arenas, structures with very low-slope roofs housing offices and mechanical rooms were constructed atop the downward curving main roofs. Rainwater on these slightly sloped roofs drains naturally by gravity to the perimeter of the structures, thus avoiding the need for mechanical pumping.

Unlike the stadium or terminal roofs described above, in the design of airplane hangars it is essential to provide large front doors that slide open smoothly. These sliding doors cannot be supported by columns and are usually hung from a top beam, longer than the hangar opening. The structural problem to be solved for this type of building consists in covering a rectangular area having columns on



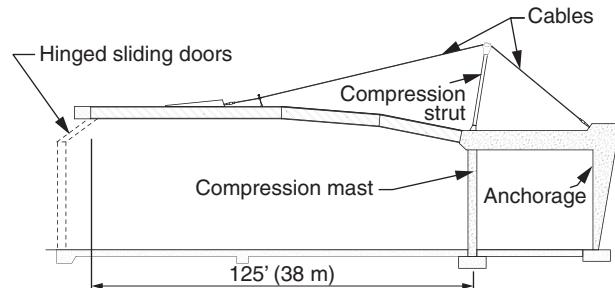
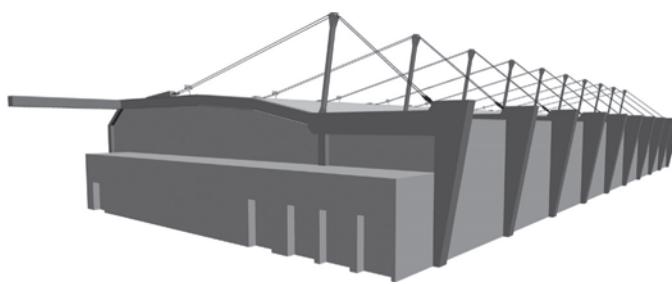


Figure 6.22 The TWA Maintenance Hangar at Philadelphia International Airport

One of the key requirements of an aircraft hangar is a large column-free space. Using the cable-stayed principle, this structure achieved a tremendous span with minimal materials use owing to the efficiency of tension cables. The rear of the structure consists of heavy concrete L-shaped moment frames (see chapter 8), which form a counterbalancing anchorage off which the front of the structure cantilevers 125 feet (37.8 m).

not more than three of its sides. A solution, realized by Ammann and Whitney in 1955 for the TWA Maintenance Hangar at the Philadelphia Airport, used a scheme in which a cantilevered span is equivalent to one half of a stayed bridge (Figure 6.22). The space between “tower” and “anchorage” was used for offices or shops, while the cable-supported cantilevered roof consisted of “folded-plate” reinforced concrete construction (see Section 10.8). The limited weight and high resistance to bending and compression of folded plates, together with the tensile strength of cables, make such structures capable of economically cantilevering as much as 125 feet (38 m).

Figure 6.23 The Pan Am Worldport Terminal at JFK Airport

Applying a similar principle to the cantilevered roof structure of the hangar of Figure 6.22, the roof of this building was constructed as a radial cantilever from a central ring. Considered revolutionary when it opened in 1960, the terminal’s capacity was soon exceeded and subsequent additions detracted from the purity of its structural concept. The most recent owner, Delta Airlines, moved out of the terminal into a new facility, and, despite opposition by preservationists, the structure was demolished in 2013.

A related solution was adopted by Tippets-Abbett-McCarthy and Stratton in roofing the 1960 Pan-American Worldport terminal at John F. Kennedy International Airport in New York. If one could imagine taking the cross section of the Philadelphia hangar, and rotating that section about a central point, this essentially describes the Pan-American terminal concept, though the form was elliptical versus circular in plan. Considered revolutionary in its day, the roof consisted of reinforced concrete plates supported by radial beams, an outer elliptical ring and an inner elliptical ring (Figure 6.23). The beams are cantilevered from the outer ring, and supported by cable stays running over compression struts at the outer ring,

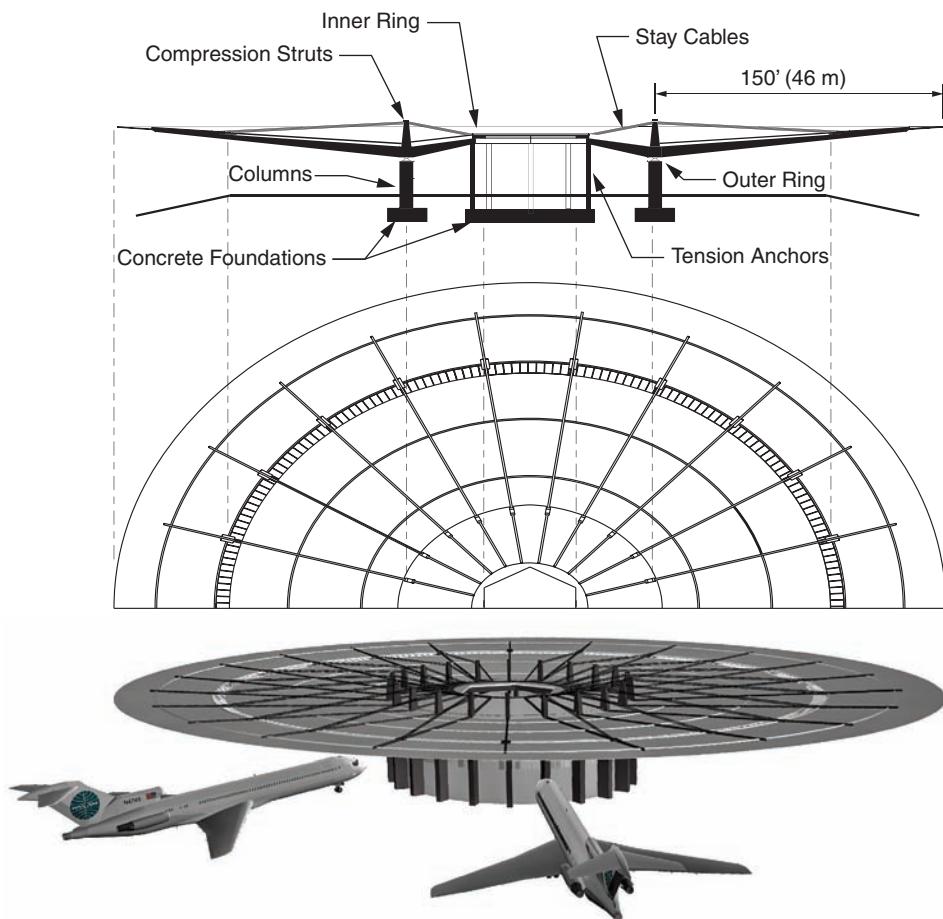




Figure 6.24 Tensegrity Sculpture by Kenneth Snelson at the Hirshhorn Museum, Washington, D.C.

Unlike traditional systems, tensegrity structures have compression members that do not contact one another. Though initially popularized by famed designer Buckminster Fuller, it was his student, Kenneth Snelson who originated the concept in 1948. In his more than 50-year-long career, Snelson's works appear in communities and galleries around the globe.

Photo courtesy of James Dymond



Figure 6.25 The Kurilpa Bridge in Brisbane, Australia

This pedestrian bridge with a main span of 394 ft (120m) is the world's longest bridge to use the principle of tensegrity as its primary structural system. The design is by the famous engineering firm Arup.

Photo courtesy of Terri Meyer Boake

and anchored at the inner ring. The outer ring is supported by compression columns; the inner ring is anchored to tension struts attached to heavy concrete blocks in the ground. The 150-feet-long cantilevers sheltered the planes during the embarkation and debarkation of the passengers.

In 1948, the sculptor Kenneth Snelson exhibited his first *Tensegrity* sculpture, consisting of a space truss with tensile members of prestressed steel cable and compressive members of steel pipe. In the principle of tensegrity, compression members separate tensile members connected at both ends, but no compression member is connected directly to any other compression member. In the following years, his sculptures assumed the dimensions of large structures (e.g., Figure 6.24). The Tensegrity principle has been successfully applied to large tensile roofs since 1955, but the structural theory of Tensegrity structures was only given in 1972 by G. Minke. More recent examples of the application of tensegrity to utilitarian structures include the 2009 Kurilpa pedestrian bridge in Melbourne Australia, designed by Ove Arup & Partners (Figure 6.25).

A noteworthy example of a tensile structure, built by means of radial tensile elements connecting inner and outer rings, is the bicycle wheel. The two sets of spokes are tensed between the tensile circular hub and the compressed circular rim, forming a structure with high "locked-in" stresses, which is stable against both in-plane and transverse loads. Since the circle is the funicular curve for a compression arch acted upon by radial forces (see Section 6.4), the entire (unloaded) wheel is a funicular prestressed structure. A groundbreaking project applying this principle is the roof of the auditorium in Utica, New York, designed by Lev Zetlin in 1955. It is based on the bicycle-wheel principle (Figure 6.26), but a wheel turned on its side. Two series of cables (with different cross sections because of different force magnitudes) connect the outer compression ring to the upper and lower rims of a central hub, consisting of two separate tension rings connected by a truss system. The cables are kept separate and posttensioned by compression struts of adjustable length. Each pair of cables can be correctly tensed by turning the turnbuckles of the struts, and the roof, covered by a series of prefabricated metal plates, is practically free of flutter because the high tension in the cables makes them more rigid than if they were freely hanging. The reader may note the similarity to the Viera-designed stadium roof; however, in the Utica design the upward-bowed stabilizing cables are stressed against the lower suspension cables, providing the stabilization that the Viera roof achieves by deadweight. This design also eliminates the issue of roof drainage because of the upward bow of the roof, providing for natural drainage to the outer rim.

David Geiger has designed tensegrity *domes* spanning up to 800 feet (244 m), the first of which for St. Petersburg, Florida, covers a circular stadium with a seating capacity of 43,000 people and a diameter of 680 feet (207 m). Its structure consists of radial trusses with diagonals and chords of steel cables, prestressed against verticals of steel piping, which span between an inner tensile ring of steel and an

Figure 6.26 The Utica Memorial Auditorium

Using the circular suspension cable concept similar to the roofs of figures 6.20 and 6.21, engineer Lev Zetlin added *upward* stabilizing cables separated from the suspension cables by compression struts. Similar to spokes on a bicycle wheel, both the top and bottom surfaces thus comprise tensile cables. An advantage of this system is that the upper surface has a natural outward bow that sheds rainwater to the perimeter. The structure was the first of its kind when it opened in 1960, and was designated an Historic Civil Engineering Landmark by the American Society of Civil Engineers in 2011.

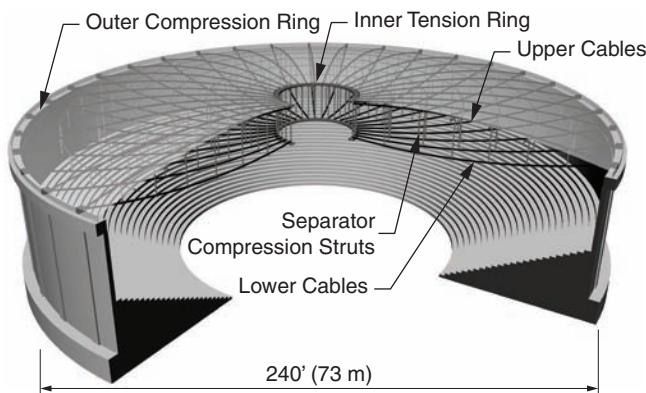
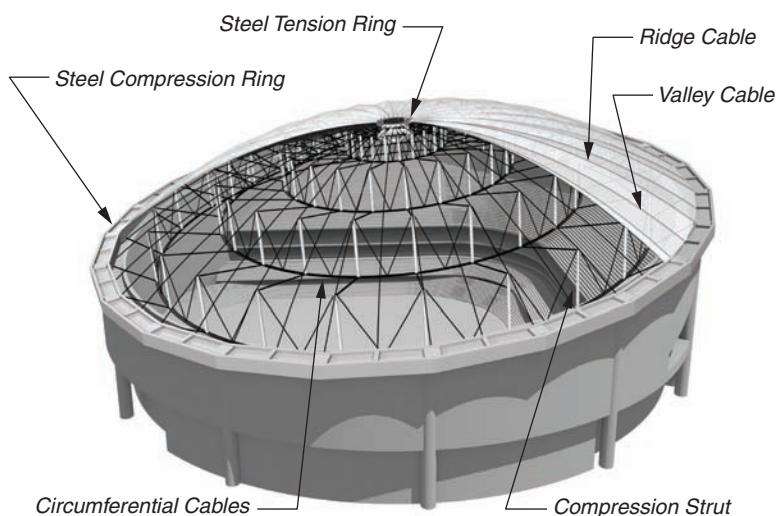


Figure 6.27 Tropicana Field, St. Petersburg, Florida (Originally the Florida Suncoast Dome)

The roof structure of this indoor baseball stadium was designed by engineer David Geiger and employed a variant of the tensegrity principle known as a “cable dome” with some similarities to the Utica Auditorium of Figure 6.26. In this structure, concentric tension rings increase in elevation toward the center, and each carry compression masts that support tension cables along concentric radial ridges. Diagonal cables connecting to each ring stabilize the masts, and these attachment points create circumferential radial valleys. The roof is clad in translucent fabric. A larger version of the dome structure was created for the 1988 Olympic Games in Seoul, South Korea.



outer compressive ring of reinforced concrete (Figure 6.27). The vertical pipes, sheathing the continuous cables, are supported by the tensed diagonals, and kept vertical by concentric steel rings connected to their foot and inclined stays connected to their top of concentric steel rings. Radial-tensed cables, running between the compression and tension rings along the vertical pipes’ bottoms, constitute the lower chords of the trusses. Similar radial cables (the “ridge cables”) running along their tops constitute the upper chords of the trusses. The prestress in the radial ridge cables increases the tension in the lower chords due to the roof loads, and is high enough to entirely cancel the compression in the upper chords due to these loads. A third set of pre-stressed radial cables (the “valley cables”) runs from the compression to the tension ring along the “valleys” formed by the intersections of the inclined stays at the concentric steel rings. All the components of the structure can be bought “off the shelf.” The undulating roof surface is a membrane of silicone fiberglass fabric wrapped over and attached to the ridge and valley cables. Since the tension ring is at a higher level than the compression ring, these roofs are shallow tensile domes similar in principle to “bicycle-wheel” roofs. The 1992 Georgia Dome by Weidlinger’s Matthys Levy uses a similar principle, and at a span of just

under 800 feet (244 m) it is presently (2015) the largest cable-supported domed stadium in the world. The 2012 La Plata dome (Figure 6.28) is the latest iteration of the Levy-type “Tenstar Dome.”

Pneumatic roofs present one of the most interesting applications of cables to the reinforcing and stiffening of membranes. They consist of air-supported or air-inflated plastic fabrics stretched over a network of cables and can span hundreds of feet. Geiger and Levy-style tensegrity domes can also be considered as membrane roofs supported by trusses rather than air pressure: Elimination of the fan system and revolving doors (needed to maintain air pressure) reduces the cost of these roofs in comparison with that of pure pneumatic roofs. Chapter 11 covers these membrane structural types in detail.

The tensile solutions mentioned above are just a few of the most recently adopted to roof large areas. Whereas the largest span covered by a compressive roof to date (2015) is the 715 feet (218 m) C.N.I.T. double concrete shell in Paris (see Section 12.7), tensile roofs can easily span much larger distances. In view of the exceptional potentialities of cable roofs, it is to be expected that their use will increase with the increasing dimensions of future areas to be covered.

Figure 6.28 La Plata Dome

The La Plata Dome in Argentina is an extension of the Geiger principle by engineer Matthys Levy of Weidlinger Associates. Though similar in principle to the Geiger dome, the *Tenstar Dome* uses triangulated regions between cables that enable it to be formed around irregular nonround arena shapes.

Photo courtesy of Federico García Zúñiga



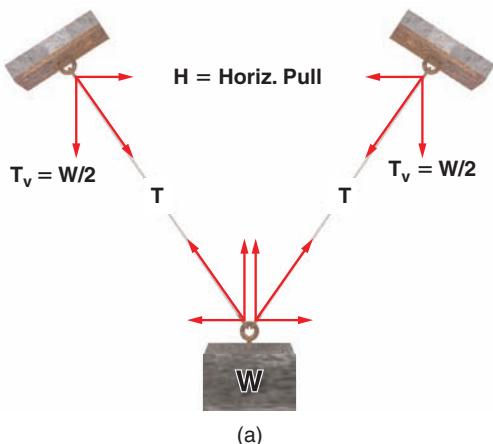
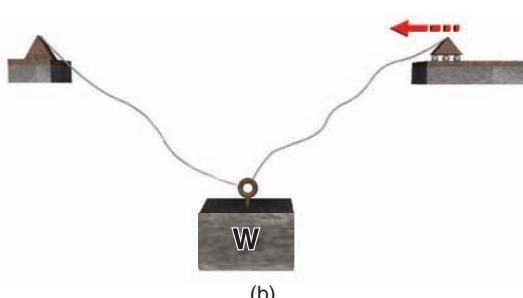
6.3 TRUSSES

At the beginning of this chapter, a flexible cable supporting a load at midspan was found to be a pure tensile structure (figs. 6.3 and 6.29a). Structural stability of this basic cable system requires that the ends be fixed to supports that prevent movement of the cables. If one support, for example, were on a roller, the tensile pull on the cable would cause an immediate collapse by horizontal movement of the roller (Figure 6.29b). If instead a wooden strut

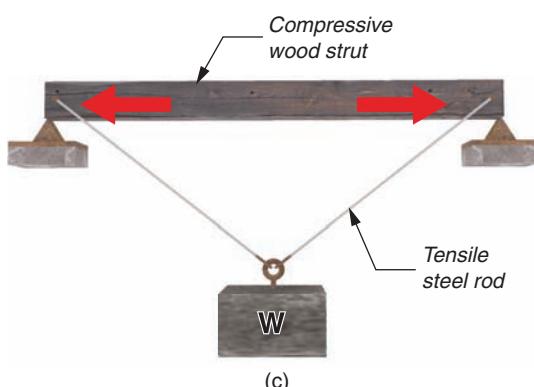
is placed between the two supports, this horizontal movement will be prevented, and the tensile force will be balanced by compression within the strut (fig 6.29c). This is the simplest form of the structural type known as a *truss*. The triangular shape described by the cables and compression strut is referred to as a *panel*—larger trusses described below are multipanel trusses. The outer structural elements of the panels are referred to as *chords* of a truss. In these initial examples, the chords are horizontal, but sloping chords are common as well.

Consider now the structure that is created by *inverting* the original cable structure and strengthening its inclined sides to make them capable of resisting compression. The “negative sag,” or *rise* changes the nature of the stresses, and the inverted cable becomes a pure compressive structure (Figure 6.30).

The load at the top of the truss is channeled by the compressed struts to the supports, which are acted upon by downward forces equal to one-half the load and by *outward horizontal thrusts*. By inverting the structure, therefore, all of the forces are exactly equal in magnitude, but opposite in direction, to the original tensile truss. The horizontal thrust of the inverted truss can be absorbed either by compression in buttresses of a material such as stone, masonry, or concrete,

**Figure 6.29a Hanging Cable****Figure 6.29b Weight on cable with roller support**

If the rigid anchorage of the hanging cable is replaced on one side by a roller connection, a collapse mechanism results due to the tension of the cable. It is an inherently unstable structure.

**Figure 6.29c Tensile truss with compressive strut**

The horizontal pull in the hanging cable is resisted by compression developed in the strut, instead of transferring this force to the support. This is the most simple form of a truss, consisting of a single panel.

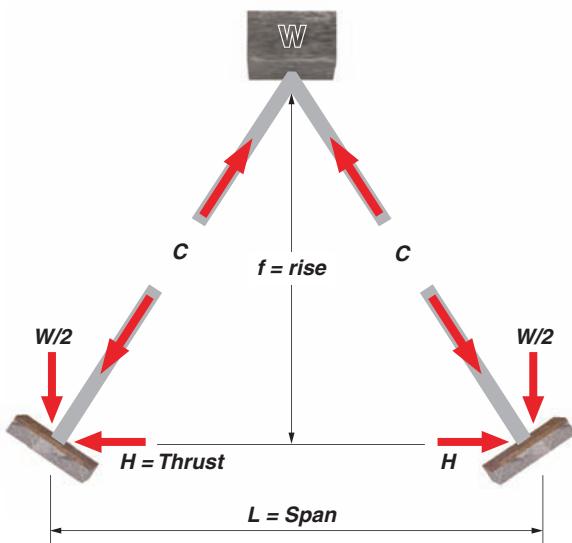


Figure 6.30 Compressive Arch

Inverting the hanging cable of figure 6.28a results in a mirror image of the forces, where previously tensile members become compressive. The inward pull from the cable likewise now becomes an outward thrust against the support. If the rise of the two structures is the same, the forces will be exactly equal in magnitude, but opposite in direction, for the same applied load.

or by tension in an element such as a wood or a steel *tie-rod* (see Figure 3.15). Such elementary trusses, constructed of wood compression members with iron tie-rods, were built in the Middle Ages to support the roofs of churches, and there is reason to believe that the Greek temples were covered by wooden structures of similar design. The introduction of iron and later steel allowed the use of very slender tensile members. As truss spans became larger, it was found practical to hang the tie-rod from the top of the truss to eliminate the large sag of this relatively flexible element (see Figure 3.15).

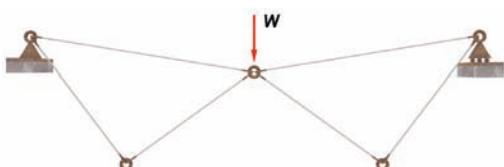


Figure 6.31a Two Disconnected Truss Panels

Two truss panels connected at a central joint, but lacking a bottom bar member will create a collapse mechanism and cannot support a load.

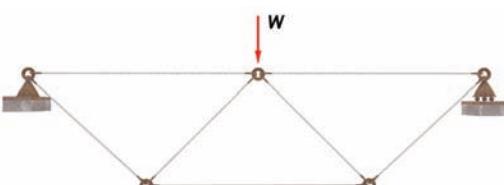


Figure 6.31b Three Panel Truss

The same truss above with the addition of a bottom member creates a complete and stable truss system. The bottom member becomes a tensile preventing the outward movement of the two lower joints.

Trusses capable of spanning large distances by means of members that experience *only* tension and compression forces (with no shear or bending behavior like beams—see Chapter 7) are obtained by combining multiple elementary single-panel triangular trusses. For example, if two of the most basic triangular trusses are joined at an upper *joint* (Figure 6.31a), they cannot support a load unless a tensile bar prevents the vertices at the bottom from moving apart. The addition of a tie rod at this location thus creates a larger truss, now in the form of a three-panel truss, capable of spanning a greater distance (Figure 6.31b). By adding more single-panel trusses and connecting them with tension ties, ever larger trusses can be constructed.

The conceptual development of a more complex multi-panel truss can be understood through the sequence of Figures 6.32a–6.32c. Starting in Figure 6.32a with a single-panel truss supporting one concentrated load at the center, the one panel truss is supported at the two upper end joints. Note that the center vertical member is drawn as a dotted line, indicating that it is not carrying any force *under this loading*. This member is connected into the horizontal top chord of the single panel, and since these chord members are completely horizontal they are incapable of resisting a vertical force—only another vertical or sloping member connected to this joint would be capable of this. Such elements that carry no load are referred to as *zero*

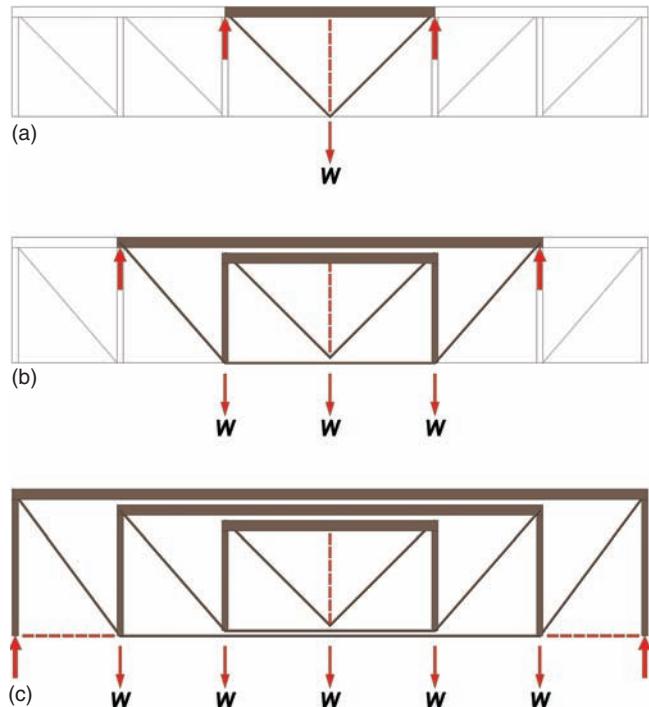


Figure 6.32 Conceptual Development of a Multipanel Truss

By adding successive cables and struts to support smaller truss units, increasingly longer span trusses are created. The additional elements provided to support the lower-ordered elements reflect the magnitude of forces at the varying truss locations, with the highest forces in the outer chords at the center of the span, and the highest forces in the diagonal cables in the outer panels.

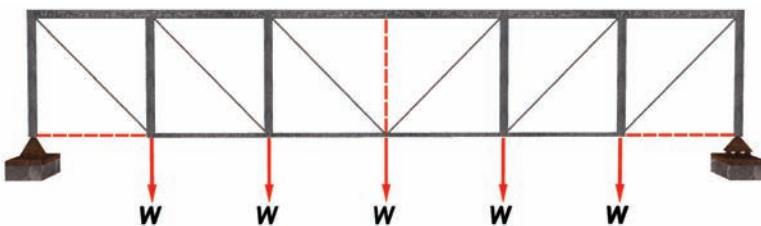


Figure 6.33 Truss with Tension Diagonals

Developed in 1844 by father and son designers Caleb and Thomas Pratt, the diagonal members of the truss are in tension while the vertical members are in compression. This arrangement is well suited for iron and steel structures to take advantage of their high tensile capacity, and all-steel Pratt trusses became a standard design by the early 20th century. The dotted lines indicate theoretical zero-stress members when the bottom chord is loaded equally at each panel point. In practice, only the center vertical member can safely be eliminated, because the two horizontal members are required for overall stability of the truss.

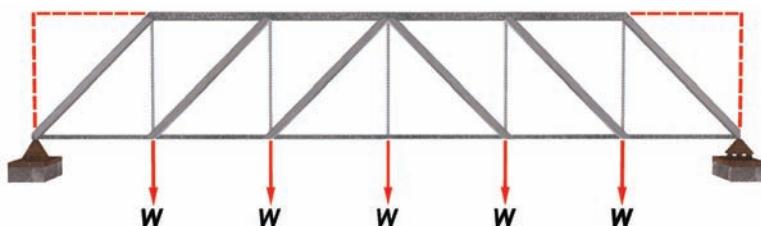


Figure 6.34 Truss with Compression Diagonals

Inverting the direction of the diagonals of the Pratt truss in Figure 6.33 will also cause the internal forces to invert. Providing the same equal load at each panel point as the Pratt truss, the diagonal members switch from tension to compression members, and the shorter vertical members switch from compression to tension. Created by the designer William Howe in 1840, the construction typically combined heavy wood diagonal members with light iron vertical members, which simplified construction compared to the all-wooden trusses of the era. The dotted lines represent theoretical zero-force members. If all loads are applied at the lower panel points, the horizontal and vertical end members may be eliminated from the structure altogether since they carry no force. This is the form of many railway and highway bridges of the late 19th and early 20th centuries.

force members. This vertical member would be necessary, however, to support a load placed at the upper joint, making the formerly zero-force member a compression member.

If the smaller truss of Figure 6.32a is itself supported by a larger cable and strut structure (Figure 6.32b), then a longer-span truss of six panels is created. Note that the “doubling-up” of the compression member of the top chord is reflective of the increase in force in this member. If the six-panel truss is in turn supported yet by another cable and strut structure (Figure 6.32c), then a still longer truss consisting of 12 panels is created. Again, the additional horizontal top strut and bottom cable elements in the larger structure are reflective of the increase in force in the members toward the center of the span. A complete *Pratt* truss is created in this conceptual process as illustrated in Figure 6.33.

The bars of trusses are considered *hinged* at their connection or panel points. Because they are hinged, they are free to rotate at their ends and do not develop bending if properly loaded. If, as is desirable, the loads on the truss are applied only at the panel points, and the dead load of the truss members is negligible, all the truss members are only tensed or compressed. When loads are applied *between* the panel points and the dead load is not negligible, the truss bars develop some bending also (see Section 7.4). Therefore, for maximum efficiency, the heaviest loads should be located only at panel points. Numerous structural failures have occurred through loading that

created bending forces on members that were designed for only tension or compression.

In Figure 6.33, we can see that merely reversing the inclination of the interior diagonal members causes these bars to work in compression, and the vertical members in tension, much as the single panel compressive arch of Figure 6.30 is a mirror of a hanging cable. The reader may wish to diagram the conceptual assembly of this truss type in the same manner as the diagrams of Figure 6.32a-c to follow its load-channeling mechanism. In this truss—*under this specific loading*—the end verticals and last upper chord bars are unnecessary and are thus theoretical zero-force members. Similarly, the end verticals and the last lower chord bars would have been unstressed (and thus redundant) if the truss of Figure 6.33 had been supported at the upper left and right joints. The scheme of Figure 6.34 is commonly used in highway bridges, and that of Figure 6.33 in railroad bridges, where the truss is often below the roadway. Additional insight on truss behavior may be gained by analogy with beam behavior, as shown in Section 7.2.

Upper chord members, as well as interior verticals and diagonals, may buckle under compression unless properly designed. One of the first studies on the buckling of trussed bridge structures was prompted by the failure in buckling of a Russian railroad bridge at the end of the nineteenth century. Since, moreover, moving loads may produce *either* tension *or* compression in the *same* member, depending on the

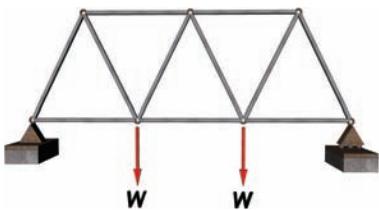


Figure 6.35 A Warren Truss

Named for its inventor, James Warren, who patented it in 1848. Well suited for prefabricated construction, there are no vertical members and all diagonals are of the same length. The diagonals must be designed for the maximum compression force, however, since a heavy moving load may cause a tension member to become compressive, or vice-versa.

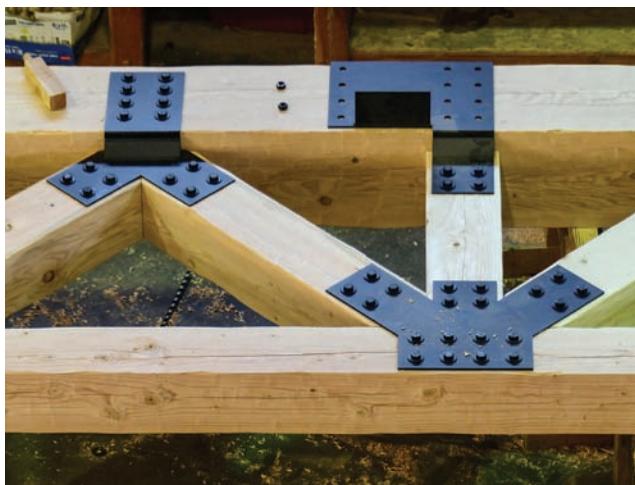


Figure 6.37 Truss gusset plate

A common type of connector in a truss is known as a *gusset plate*. A gusset plate is a means of physically connecting members while transferring large forces between them. They may be used in a decorative manner, such as this heavy timber truss shown being fabricated, or may be hidden within the member thickness in so-called *knife plate connections*. Only the bolts are visible on the outside of the members in the latter case, and sometimes even these are countersunk and the holes plugged for a completely smooth appearance.

Photo courtesy of Deborah Oakley

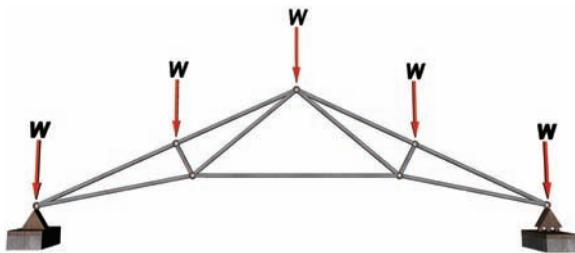


Figure 6.36 A Gable Truss

Commonly used in residential construction, this truss form provides for a vaulted ceiling. The angle between the upper and lower chords at the supports is limited by large forces developing as the angle becomes smaller. At small angles, very high shear forces develop at the connection that must be transferred between each wood member. Typically, bolting and/or a variety of metal connector pieces are used in wood construction to augment the wood itself.

load location, some trusses are built with both tension and compression diagonals, so that loads may be always carried by tension diagonals with purposely slender compression diagonals that are simply considered inactive when buckled.

The combinations of tension and compression bars capable of producing practical trusses are extremely varied. Figures 6.35 and 6.36 illustrate two of the many forms of trusses possible.

The bars of a truss are joined by being bolted or welded to a “gusset plate” at their panel points (Figure 6.37). In either case, the restraint against relative rotation produced by the gusset plates transforms the truss bars from pure tension or compression members into elements developing a minor amount of additional bending and shear stresses. These so-called *secondary stresses* are considered in Section 7.4.

Trusses are used in bridge design to span hundreds of feet between supports. They may be cantilevered from piers and in turn carry other simply supported trusses (Figure 6.38). Bridge trusses with curved top chords behave very much like suspension bridges (Figure 6.39). Parallel trusses are commonly used in bridges and in steel design to cover large halls (Figure 6.40). *Open web joists* are “off the shelf” light steel



Figure 6.38 The Forth Railway Bridge, at the Firth of Forth, Scotland

This bridge, consisting of two main spans of 1,710 feet (520 m) each, was inaugurated in 1890. Designed by engineers Sir Benjamin Baker and Sir John Fowler, it is constructed as three double-cantilever spans, each supported at their centers by enormous stone and wood caissons sunk into the riverbed. The two outermost cantilever arms are separated from the central structure by much shorter and smaller trusses, simply supported by the cantilever arms of the center and outer structures. The span is thus increased without adding even more depth to the already enormous main cantilever trusses, allowing ships to pass freely. It remains the second longest cantilever bridge in the world even after more than 125 years of continuous service.

Photo: Ramonespelt/Fotolia



Figure 6.39 The Macombs Dam Bridge, Spanning the Harlem River in New York

Opened in 1895, the Macombs bridge is a double cantilever supported from a central pivot point, referred to as a *swing bridge*, since the entire bridge can pivot about the central support to allow ships to pass on either side. The curving shape of the top chord reflects the nature of the increasing forces toward the central support, and in fact bears resemblance to a cable suspension bridge design.

Photo courtesy of Davie Fried

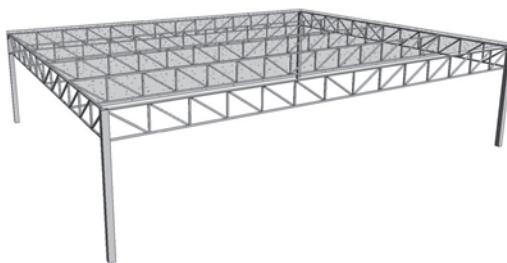


Figure 6.40 A Parallel Chord Trussed Roof

Rows of parallel chord trusses are a common and practical method of creating roofs or floors over long spans such as auditoriums, concert halls, stadiums, and so on. Smaller spaces may utilize preengineered/prefabricated members selected from a catalog, based on span and load requirements. Larger spaces (and thus longer clear spans) commonly feature custom fabricated trusses designed for a single specific project.

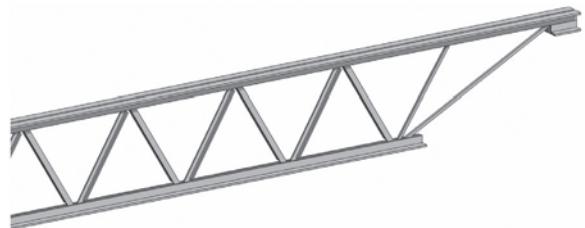


Figure 6.41 An Open-Web Steel Joist

Basically a premanufactured truss, the open-web steel joist (OWSJ) is a mainstay of efficient modern construction. Fabricated in a range of standard depths, lengths, and capacities, designers can select the required member type from a catalog to suit the span and load capacity requirements of a specific design.

trusses used to span small distances, either as roof or as floor structures (Figure 6.41). Vertical trusses are used in high-rise steel buildings to stiffen their frames against wind and earthquake forces (see Section 8.3).

Although not as popular today as they were in the 1800s, at the beginning of the structural steel era, trusses are still to this day one of the most essential components of large structures.

6.4 FUNICULAR ARCHES

Returning once more to the pure funicular forms introduced at the start of this chapter to consider the inverse of the tensile form: the funicular arch. The parabolic shape assumed by a tensed cable carrying loads uniformly distributed horizontally may be inverted to give the ideal shape for an arch developing only compression under this type of load (Figure 6.42). The arch is an essentially

compressive structure. It was developed in the shape of a half-circle by the Romans (the greatest road builders of antiquity) to span large distances. An aqueduct supported by a series of semicircular arches survives today in Segovia, Spain (Figure 6.43). Arches are also used in a variety of shapes to span smaller distances. The arch is one of the basic structural elements of all types of architecture.

The ideal shape of an arch capable of supporting a given set of loads by means of simple compression may always be found as the overturned shape of the funicular polygon for the corresponding tension structure: It is by this method that the Spanish architect Antonio Gaudi determined the form of the arches in the Church of the Sacred Family in Barcelona and many of his other structures (see Figure 14.15).

The funicular polygon for a set of equal and equally spaced loads *converging toward* or *diverging from* a common point is a regular polygon, centered about this point (Figure 6.44a). At the limit, when the loads become infinite



Figure 6.42 The Roosevelt Lake Bridge

Located northeast of Phoenix, Arizona, the graceful arch of the bridge represents a nearly perfect funicular compression form to carry the roadway suspended below it.

Photo courtesy of Deborah Oakley



Figure 6.43 Roman Aqueduct

The Roman Aqueduct in Segovia, Spain, is still standing after two thousand years, owing to the efficiency and strength of carrying loads compressively through stone arches.

Photo: Mrallen/Fotolia

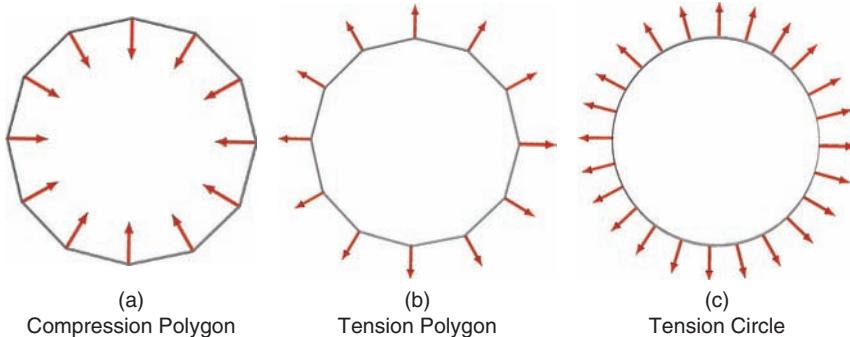


Figure 6.44 Funicular polygons for equal radial load

The ideal form for a radial load, whether directed inward in compression (6.44a) or outward in tension (6.44b), begins to approach a circle as the number of loads increases (6.44c). Such forms are the basis for tension and compression rings employed in structures such as those illustrated in Figures 6.20, 6.21, and 6.27. Perimeter rings will be in compression for hanging cable structures to resist their inward pull, while the center rings will be in tension for such structures. In rigid domelike structures, the forces will be reversed, with the outer ring acting in tension and the inner ring in compression.

in number and infinitesimally small, the funicular polygon becomes the funicular curve for a *radial inward pressure* or *outward suction*, and is a circle (Figure 6.44c). Since arches can be funicular for only one specific set of loads, the circle cannot be the funicular curve for a vertical load uniformly distributed either along the horizontal or along the circular arch. Hence, the Roman arch develops some bending and, although a compression structure, is not *uniformly compressed* across its depth.

The shape of a masonry arch is usually chosen to be the funicular of the dead load. But whenever an arch is used in a bridge, a variety of moving loads must be assumed to travel over the arch, and a state of stress other than simple compression is bound to develop: The arch also develops some bending stresses. A cable can carry any set of loads in tension by changing shape; a rigid arch cannot change shape and, hence, cannot be funicular for all the loads it is supposed to carry. The stability of the arch implies lack of adaptability. The relative importance of bending stresses in arches is considered in Section 8.4.

The channeling of vertical loads along a curve by means of compression is today such an elementary concept that it is hard to realize how slow its evolution has been. Practically unknown to the Greeks, it produced the daring and lovely lines of the Gothic cathedrals as well as those of modern bridges (see Section 8.4). The ultimate consequences of the use of curved structural elements are even more recent and interesting: They are considered in Chapters 11 and 12.

KEY IDEAS DEVELOPED IN THIS CHAPTER

- Cables are flexible structures that support loads in pure tension.
- Because of their flexibility, cables change their shape under moving loads.
- A cable hung from two supports and loaded by a concentrated force in the middle will form an inverted triangular shape; the sides of which will be straight lines.

- The inclined reactions at the support will match the cable angle, and can be described by two components: one vertical and one horizontal. The vertical components balance the vertical load by carrying a portion of the load on each end, while the horizontal components prevent the cable from collapsing inward.
- The horizontal components are always equal and opposite to each other, and the magnitude is inversely proportional to the sag of the cable. The smaller the sag of the cable, the greater will be the horizontal force components at the supports.
- When additional loads are applied, the cable readjusts with straight lines between loads and supports. The vertical reactions add up to the total load; the horizontal components will increase but remain equal and opposite to each other.
- Under an evenly distributed vertical load, the cable forms a smooth parabolic shape.
- Suspension bridge cables are parabolic.
- The cable ends of suspension bridges are typically embedded into heavy buttresses (*anchorages*) in order to supply the necessary horizontal reaction. Because of the inherent instability of cables, stiffening trusses are used to stabilize suspension bridge cables.
- Cables supporting roofs are laid parallel to each other or are arranged radially. In either case, the cable ends are anchored or are held by a compression ring.
- When a cable that supports a load at midspan is turned upside down, it becomes a compressive structure. Its sloping sides are in pure compression, and horizontal buttress reactions prevent the ends from moving.
- If a third horizontal, tension member is added to replace the horizontal support reactions, a basic three-bar truss panel is created.
- Several panels connected to each other may form larger and more complicated trusses. In ideal trusses, the members are in either pure tension or in pure compression.
- Cables loaded at several points when turned upside down become arches, with their members in compression.
- Stone and concrete arches that can support compression have been built since Roman times as bridges, aqueducts, and cathedrals.
- The longest-spanning arch bridges of today are made of structural steel elements
- Circular arches such as bicycle wheels and roofs of similar shape are in circumferential compression and are loaded by radial tension members or even membranes.

QUESTIONS AND EXERCISES

1. Using a piece of string approximately 12" (30 cm) long, hold the string between the thumb and forefinger of each hand while suspending a small weight of about one pound (4.5 N) from the string (a sturdy coffee mug will work for this). Observe the tension felt in the string through the fingers. Notice how the force decreases as the hands are brought together and the string gets deeper, and how the force increases as the hands move apart. Is it possible to make the string completely flat with enough tension? Why or why not?
2. Tie the weight (e.g., a coffee mug) at a point not in the middle at the string (it needs to be tied to prevent sliding on the string). Lift the string again with two hands and feel the different forces on your hands. Which one is greater? Why?
3. Take a flexible ruler, bend it into a shallow arch and place the ends between two heavy books. Press down on top of the arch. Why do the books move?
4. Observe spanning systems in buildings and bridges. This is ideally done in person, but many structural images can now be found on the Internet. Which structures use suspension cables, which use stay cables, which are trusses, and which use arches? Is one type more common than the others? How does it appear that the spanning distance or usage of the structure impacts the choice of the structural system?

FURTHER READING

Allen, Edward and Zalewski, Waclaw. *Form and Forces: Designing Efficient, Expressive Structures*. John Wiley & Sons, Inc. 2009. (Chapters 1 and 2)

Sandaker, Bjorn N., Eggen, Arne P., and Cruvellier, Mark R. *The Structural Basis of Architecture*, 2nd Edition. Routledge. 2011. (Chapter 10)

Schodek, Daniel and Bechthold, Martin. *Structures*, 6th Edition. Pearson Prentice Hall. 2008. (Chapter 5)