Bridge Engineering Handbook
Substructure Design
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Towers

Publication details
Wai-Fah Chen, Lian Duan
Published online on: 24 Jan 2014

How to cite: Wai-Fah Chen, Lian Duan. 24 Jan 2014, Towers from: Bridge Engineering Handbook, Substructure Design CRC Press
Accessed on: 14 Oct 2020

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3.1 Introduction

Towers are the most visible structural elements of long-span bridges, because they project above the superstructure and can be seen from all directions by both viewers and bridge users. Towers give to a bridge a characteristic identity, a unifying theme, a motif from which people can identify that particular bridge. Towers project a mnemonic bridge image that people can recall as their lasting impression of that bridge itself, making towers an important part of the overall esthetics.

As examples of the powerful imagery of towers, contrast the elegant art deco towers of the 1937 Golden Gate Bridge (Figure 3.1) with the utilitarian, but timeless, architecture of the towers of the 1936 San Francisco–Oakland Bay Bridge (Figure 3.2).

Then compare these robust towers to those of the 1964 delicate towers of the Firth of Forth Suspension Bridge (Figure 3.3); ponder the disproportions between the massive, rugged stone towers of the 1883 Brooklyn Bridge (Figure 3.4) with the awkward and confusing steel towers of the 1903 Williamsburg Bridge in New York (Figure 3.5).

Alternatively, one may contrast those older, Iconic Bridges, with the new and distinctive San Francisco–Oakland Bay Bridge East Span with its single-tower suspension bridge (Figure 3.19d, later in the chapter) and with the quasi-diamond-shaped towers of the 2000 Yeongjong Grand Bridge, Incheon, South Korea (Figure 3.6). Both of these are self-anchored suspension bridges and have no heavy and bulky concrete anchorages visible at each end.

Then compare the concrete quasi-diamond-shaped towers of the 1995 Glebe Island Bridge (Figure 3.7) to the concrete full-diamond-shaped towers of the 2005 Cooper River Bridge (Figure 3.8); the heights of the roadways dictated the differences between these tower shapes and not the whims of the designers!

One can easily see that there is great diversity in bridge tower designs; the only requirement that these towers have in common is that they must resist the loads and forces of nature and be in equilibrium according to the three equations of statics. Towers surely do impact the appearance of bridges, for good or for bad.
FIGURE 3.1  Golden Gate Bridge, San Francisco. (Courtesy of Charles Seim.)

FIGURE 3.2  San Francisco–Oakland Bay Bridge. (Courtesy of Charles Seim.)
FIGURE 3.3  Firth of Forth Suspension Bridge. (Courtesy of Charles Seim.)

FIGURE 3.4  Brooklyn Bridge, New York. (Courtesy of Charles Seim.)
FIGURE 3.5  Williamsburg Bridge, New York. (Courtesy of Charles Seim.)

FIGURE 3.6  Yeongjong Grand Bridge, Incheon, South Korea.
FIGURE 3.7  Glebe Island Bridge, Sydney, Australia. (Courtesy of T. Y. Lin International.)

FIGURE 3.8  Cooper River Bridge, Charleston, South Carolina, under construction. (Courtesy of Charles Seim.)
The famous bridges noted above are all older than three-quarters of a century. If they are well maintained, all these bridges could continue to serve for another 100 years.

The service lives of the new self-anchored suspension span of the San Francisco–Oakland Bay Bridge and the Yeongjong Grand Bridge could be 150 years. These bridges are excellent examples of enduring structures; they serve as a reminder to bridge engineers that well-designed and well-maintained structures can last for 100–150 years, or perhaps longer. Robust designs, durable materials, provisions for inspection and maintenance access, and a well-executed maintenance program will help to ensure long service lives.

Both suspension and cable-stayed bridges are supported by abutments or piers at the point at which these structures transition to an approach roadway or to an approach structure. Abutments are discussed in Chapter 6. Piers and columns that support the superstructure for other types of bridge structures, such as girders, trusses, or arches, usually do not project above the deck. Piers and columns are discussed in Chapter 2.

### 3.2 Functions

“Towers” are usually defined as the vertical steel or concrete structures that project above the bridge deck to support both themselves and the bridge cables and function to carry the loads and the forces to which the bridge is subjected to the ground.

Thus, by this definition, towers are used only for suspension bridges, cable-stayed bridges, or hybrid suspension-cable-stayed structures. The word “pylon” is sometimes used to designate the single-shaft tower of a cable-stayed bridge. In this chapter, the word “tower” is used for structures that are self-supporting; “pylons” is not used, to avoid confusion.

Recently a new term “spar” has been introduced to describe vertical or near-vertical members that are not self-supporting and must depend on cables for its support; however, the spar does function as a tower carrying some bridge loads and forces to the ground. In this chapter, the word “spar” is used to describe a member that cannot support itself but functions as a tower.

Towers must perform its functions economically, be esthetically pleasing and constructible. Towers must also be reliable and serviceable for the entire life of the bridge, as unlike other bridge components, towers cannot be replaced without tearing down the bridge.

Structural serviceability is an important component of good bridge design. This requires that the bridge and towers be designed to allow for ease of carrying out both inspection and maintenance functions to provide continuous good service to its users. The public demands that bridges and towers be attractive, esthetic statements having long service lives, so as not to be wasteful of public funds.

### 3.3 Esthetics

Although the main function of the towers is structural, an important secondary function is visual—beyond mere esthetics, the towers reveal the true character, or motif, of a bridge. The bridges used as examples in Section 3.1 are good illustrations of the image of the structure, as revealed by the towers. Indeed, most are famous because of their towers!

Many people visualize the character of the Brooklyn Bridge by its gothic, arched-masonry towers, the Golden Gate Bridge by its tall, tapered, red steel towers, and across the Bay, the San Francisco–Oakland Bay Bridge by its robust-looking cross bracing and shiny aluminum paint. The elegant white, single tower of the new San Francisco–Oakland Bay Bridge East Span self-anchored suspension bridge will perhaps leave an even more distinctive impression after the bridge is opened in 2013.

Seim (1996) measured the aspect ratios of the length, divided by the thickness of the visible components of the towers of both the Golden Gate and the San Francisco–Oakland Bay Bridges. He found important, but subtle, reduction of these ratios with increasing heights above the tower base; the higher the member, the smaller the aspect ratio. It is these subtle changes in the ratios within the heights of the towers that produce the much-admired proportions of these world-renowned bridges. The towers for a
long span bridge should be carefully shaped and proportioned so as to give that entire bridge a strong and sturdy, but graceful, soaring visual image to the eyes of the viewing public.

The two main cable suspension bridges drape in a parabolic curve between towers that many people instinctively enjoy viewing. The large diameter of the cables makes them stand out as the important contributors to the overall visual impression of the supporting elements of the roadway. The towers of these common types of suspension bridges are as wide as the bridge and extend full height, making them the visual supporting elements, and they project the motif of the bridge design. Just a few suspension bridges employ a single cable, in which case the towers are usually tapered.

The cables of most cable-stayed bridges are small in diameter and usually do not visually stand out as do the large cables of a suspension bridge. The cables can be arrayed in a single plane along the centerline of the bridge, a double plane at the sides of the roadway girder, or a single plane on one side of the tower and a double plane on the other side. A single plane array is usually used with a single-shaft tower and a double plane array usually used with a two-shaft tower. See Chapter 10, Bridge Engineering Handbook, Second Edition: Superstructure Design, Cable-Stayed Bridges. However, arrays of the cable stays, such as a fan, radiating fan, or the little-used harp, should be considered in the context of the form of the tower. The parallel cables of a harp array, for example, usually will not be as obtrusive to the bridge towers as are other cable arrangements, such as a radiating fan array that dominates visually over the tower. Thus, the cables and the towers together should be considered as both visual systems and structural systems.

Billington (1983) presents an overview of the importance of the role of esthetics in the history of the development of modern bridge design. Prof. Billington coined the words “Structural Art” to honor bridges that are efficient, economical, and elegant structures. Leonhardt (1984) presents many examples of completed bridges with many tower shapes and cable arrangements for both suspension and for cable-stayed bridges. Esthetics of bridges is discussed in more detail in Chapters 2 and 3 of Bridge Engineering Handbook, Second Edition: Fundamentals.

3.4 Towers and Spectacular Bridges

Although efficiency, economy, and elegance are usually the major elements in bridge design, occasionally, since the 1990s, efficiency and economy have often not been the prime objectives of bridge designers. This trend started as bridge owners, the public, or both, began demanding “spectacular,” “picturesque,” or “distinctive” bridges, because bridge engineers could design and construct them!

Such a trend often calls for configuring the stay cables in unusual arrays that may dominate the towers, thus allowing the stay cables to become the principle esthetic statements of these bridges. This trend also featured curved, inclined, or kinked towers to add “visual impact” to bridges.

These new spectacular bridge types are designed to attract attention, because efficiency is not an objective and cost is not restricted. One could also argue that although they may be spectacular, these bridge types are not elegant. Regardless, such bridges are not considered “Structural art,” as defined by Billington (1983), because they do not conduct the forces of the bridge to its foundation in the most efficient manner, and they are not economical, because they cost more than a conventional bridge. Instead, such bridges may be considered “extravagant structural art,” and a form of art, nonetheless.

This extravaganza started in the early 1990s, when proven structural engineering programs became accessible to most engineers, and high-performance steel and concrete were readily available; thus, it was inevitable that engineers and architects would begin to exploit these relatively new developments by designing and constructing spectacular bridges that featured distinctive towers.

One of the first of these “spectacular” bridges was the Alamillo Bridge (Figure 3.9), constructed for the 1992 Expo in Seville, Spain. It was designed by Santiago Calatrava, who acted as both architect and engineer. The bridge features a 142-m (466-ft) tall, concrete-filled, steel box tower, angled at 68 degrees; painted white, it is a visible landmark from the old town of Seville. The concrete box girder roadway is a 200-m (656-ft) single span and anchors the single plane, harp-arrayed cables.
The very tall tower and the parallel cables create a beautiful, dramatic structure that immediately attracts the attention of people viewing the bridge. However, this structure is not a genuine cable-stayed bridge, because the tower is not anchored to the ground with backstay cables (Petroski 1996). The traffic crossing the bridge deflects the girder and loads the cables, but the cable loads at the tower are not in horizontal equilibrium, and the tower simply tilts a little.

The bridge was very costly. However, the people who view the structure see it as a very attractive bridge and consider it to be well worth the cost. This motif has been successfully used several times since, most notably on Sun Dial Bridge in California, where the single, pointed tower casts a shadow that tells the time of day. More importantly, the Alamillo Bridge cleared the way for engineers and architects to design and construct outstanding bridges, whenever cost is not an important factor to the bridge owners or to the cities desiring a spectacularly designed bridge as a city icon.

The Erasmus Bridge of Rotterdam, the Netherlands (Figure 3.10), opened in 1996, is another example of a spectacular bridge that is admired by all who view it. This bridge, designed by architect Ben van Berkel, features a tapered-steel tower with a “kink” near the midpoint that instantly attracts attention,
because a kink in a tower is highly unusual! Towers are not usually kinked, because they are compression members; a kink in a compression member introduces a large bending moment, which requires the engineer to add extra steel to resist that moment, substantially increasing the tower cost.

The modified, fan-arrayed stay cables in the main span load the upper portion of the tower in compression and bending; they also produce a reaction force at the top of the tower that is resisted by the two backstay cables that are attached at the top of the tower. The vertical component from the backstay cables adds large compression forces in the tower. Thus, the tower carries the bending moments and the compression from the main span stay cables, compression forces from the backstays, and the bending moments from the kink. The sum total of these cable arrangements and the kink added considerable costs to reinforce the tower to resist the huge bending and compression loads. However, this bridge is a great success because Rotterdam now has a city icon, and the people can marvel at the bridge’s unique architecture!

In 2009, the city of Dublin opened the Samuel Beckett Bridge, named after the famous Irish writer, and designed by Calavatra. This bridge is certainly a picturesque structure, having a thin, curved tower described as a forward-leaning, tubular curved spar (Figure 3.11).

The Samuel Beckett Bridge is a short, 120-m long cable-stayed bridge that is balanced as a swing bridge that pivots on a pier located directly under the base of its 48-m high spar. Each of the two backstay cables connects both to the tip of the spar and to the two backstay edge-girders, forming a “V.” The backstay cables and the forward stay cables combine to create a self-anchored structure that allows the structure to swing open to provide ship passage. The curved spar acts as a tilted-up arch as it is loaded transversely with the forward stay cables that support the main span.

This very picturesque bridge is an ingenious assemblage of girders, cables, and a curved spar. Although costly, it is a true bridge, compared to the Alamillo Bridge, and was supposedly designed to mimic an Irish Harp laid on its side.

China has built many distinctive bridges, and the Nanjing Third Yangtze Bridge is a good example of this type (Figure 3.12). This cable-stayed bridge was the longest of this type in China, when it was opened in 2005 with a central span of 628 m and 215 m tall steel towers. The city fathers wanted each of the two towers of the bridge to look similar to the curved Eiffel Tower in Paris, because one of them had visited Paris and was impressed with the beauty of Eiffel’s masterpiece.

The upper portions of the two steel shafts of each tower are straight and braced by three cross-struts; the lower portions of the two shafts do not have cross-struts but are curved to simulate the curvature of
the Eiffel Tower. The curvature produced extremely large bending moment in each of the curved lower portions of the shaft, and that required additional steel to reduce the stress from the large bending moment to an acceptable value. The Eiffel Tower has cross-struts spaced along the tower height to reduce the bending moments in the four corner shafts of that Paris icon.

Each tower shaft was fabricated in segment approximately 10–12 m high; thus each segment in the tower shafts was fabricated to different dimensions and angles. Every segment required geometric control, which required very accurate field surveying to ensure that each segment was accurately placed on the proper curvature. The contractor believed that the dimensions and angles in each segments could not be controlled accurately enough to use welded connections between the segments and therefore used bolted connections. These bolted connections required very thick splice plates and a large number of high-strength bolts to carry both bending and compression forces. All these items added cost to the construction of the towers.

In addition, the caisson concrete cap required a massive amount of prestressing steel to contain the outwardly directed thrust distributed to the caisson cap from each inclined shaft at the base of the tower.

The Eiffel Tower emulation added cost to the bridge and tower construction. However, it is a very successful bridge, because the curved shafts add a dynamic effect to what otherwise could be dull-looking towers. The City Fathers are delighted, and the bridge users admire the curved appearance of the towers.

Another example of a distinctive bridge is the Sanhao Bridge in Shenyang City, China (Figure 3.13), designed by Man-Chung Tang, who also acted as the architect of this bridge. The bridge features two concrete struts springing from a common support and inclined away from each other and each supporting a curved concrete arch spanning across the bridge roadway.

From each inclined tower, cable stays, arrayed in a harp arrangement, support the 100-m roadway on each side of the piers supporting the towers. Horizontal cables, parallel arrayed, tie the twin towers together.
The towers and cables added a small cost to this very distinctive bridge. The bridge is a success, because Shenyang City now has a distinctive icon, and the people who use and view the bridge from city streets are delighted.

Another distinctive bridge by Man-Chung Tang is the Jiayue Bridge, in Chongqing City, China (Figure 3.14), which is a conventional cable-stayed bridge with unconventional towers projecting 33 m above the roadway and with a total height of 126 m. The main span is 250 m, but the attraction of the bridge is not the main span but the portion of the towers that project above the roadway, acting as out-stretching arms holding up the cable stays. The arms leaning outwardly open up the bridge to the horizon for drivers compared to the conventional tower types that lean inward, enclosing the bridge.
The outward-leaning arms added little cost to the bridge, but they do create a distinctive bridge for all to enjoy, which is the principle feature of a successful bridge.

From these few examples, one can see that these types of bridges can range from the truly spectacular to picturesque, to distinctive bridges; all can be considered art, artistic, or even elegant structures; however, they cannot be considered “Structural Art” according to Prof. Billington’s definition of efficiency, economy, and elegance.

These “bridge” types will continue to be constructed wherever people desire bridge extravaganzas and have the money to back up such desires. Thus, such bridge types as these have entered the repertoire of the bridges that bridge engineers are required to design, construct, and maintain.

Any future discussion of towers for these spectacular bridges is beyond the scope of this chapter.

3.5 Conceptual Design

The most important step in the design of a new bridge is the structural design concept that will ultimately be developed into a final design and then be constructed. The cost, the appearance, the reliability and serviceability of the facility will all be determined, for good or for bad, by the conceptual design of the structure. Towers act as the bridge framework because the superstructure will hang from the towers; thus, towers play a significant role in the conceptual design process. Once it is constructed, the bridge will always be there for users to admire or to criticize. The user ultimately pays for the cost of a structure and also pays for the cost of maintaining that structure.

Gimsing and Georgakis (2012) treat the conceptual design issues of both cable-stayed and suspension bridges very extensively and present examples to help guide bridge designers. Chapter 1 of Bridge Engineering Handbook, Second Edition: Fundamentals presents typical practice and general principles of bridge conceptual design.

A recent trend is to employ an architect to be part of the design team. An architect if employed should start during the conceptual design phase, as the esthetics of the bridge is set during that phase of the work.

Generally the role of the engineer is to develop the structure adequacy and ensure the structural function of the bridge according to the codes of practice. The role of the architect will generally involve only the esthetics function; however, there are no codes of practice for that.

Their two roles do overlap in achieving an esthetic and functional structural design that is within budget. As the common objective of both the engineer and the architect is to build an elegant and economical bridge, cooperation and respect between them is vital to the success of their joint effort.

However, differences may occur when the esthetic desires of the architect and the structural calculations of the engineer conflict. Towers, the most visible components of the bridge, are often the focal point for this type of conflict. Each professional should understand if these differences in viewpoint occur; they must be resolved so that a successful and fruitful union between their two disciplines will produce a strong and beautiful bridge.

3.5.1 Materials

Until the 1970s, steel was the predominant material used for towers for both cable-stayed and suspension bridges. Such towers were often rectangular in elevation, having cross sections shaped as rectangles, cruciforms, tees, or other similar shapes that could be easily fabricated in steel.

Two examples of such suspension-bridge steel-tower designs are the typical, rectangular steel towers of the two Delaware Memorial Bridges: the first bridge was built in 1951, and the parallel bridge was built in 1968 (Figure 3.15).

An example of a cable-stayed bridge that is an exception to the rectangular tower form, is the modified A frame, weathering steel towers of the Luling Bridge near New Orleans, 1983 (Figure 3.16).
The cross section of a steel tower is usually designed as a series of adjoining cells, formed by shop-welding steel plates together in units from 20 to 40 ft (6–12 m) long. The steel cellular towers for a cable-stayed bridge with cables framing into the towers must be designed for the local forces from the numerous anchorages of the cables. The steel towers for a suspension bridge, and for cable-stayed bridges with stays passing over the top of the tower in saddles, must be designed for the local, concentrated load from the saddles.

An excellent example of such a steel tower is the new 525 ft (160 m) tower for the Suspension Span of the San Francisco–Oakland Bay Bridge East Span. This tower is composed of four separated pentagonal, cross-sectional shaped shafts, connected by shear-link beams. The tower shafts are separated about 2 m, allowing light to permeate between the shafts that are tapered toward the top to enhance their appearance. The shear-link beams are both attractive esthetic elements, and the structural steel beams yield in shear and absorb energy when activated by strong earthquakes (Figure 3.17).
For suspension bridges and cable-stayed structures, starting about the 1970s, reinforced concrete began to be extensively used in towers. Concrete towers are usually designed as hollow shafts to save weight and reduce the amount of concrete and reinforcing bars required. As with steel towers, concrete towers must be designed for the concentrated load from the saddles at the top, if used, or for the local forces from the numerous anchorages of the cables framing into the tower shafts.

Towers designed in steel will be lighter than towers designed in concrete, thus giving potential for savings in foundation costs. Steel towers will generally be more flexible, more ductile, and can be erected in less time than concrete towers. Steel towers will require periodic maintenance—painting—although weathering steel can be used for nonmarine environments as for the Luling Bridge, as noted above.

Costs of steel or concrete towers can vary with a number of factors; hence, market conditions, contractor’s experience, equipment availability, design details, and site-specific influences will likely determine whether steel or concrete is the most economic material.

During the conceptual design phase of the bridge, approximate construction costs of all the materials need to be developed and compared. If life-cycle cost is important, then maintenance operations and the frequencies of those operations need to be evaluated and compared, usually by present worth evaluation.

### 3.5.2 Forms and Shapes

#### 3.5.2.1 Cable-Stayed Bridge Towers

Towers of cable-stayed bridges can have a wide variety of shapes and forms (Figure 3.18). For conceptual design, the heights of cable-stayed towers, tower height (TH), above the deck can be assumed to be approximately 20% of the main-span length, span length (SL). Figure 3.18 lists the ratios of typical bridges. To this value must be added the structural depth of the girder and the clearance to the foundation to determine the approximate total tower height. The final height of the towers will be determined during the final design phase. Figure 3.19 lists distinctive towers for cable-stayed and suspension bridges.
Towers

(a) Single Tower, I

(b) Double vertical shafts, H

(c) Double vertical shafts with cross struts above the roadway

(d) Double cranked shafts with cross strut above the roadway

Stonecutters Bridge (Morgenthal et al. 2010), carries dual three-lane highway, crosses Rambler Channel, Hong Kong. Pylon height: 298 m (978 ft), with reinforced concrete from base up to 175 m level and composite top 120 m consisting of inner concrete ring with a stainless steel skin, longest span: 1018 m (3340 ft), clearance below: 73.5 m (241 ft), opened: December 2009, TH/SL: 0.22

Øresund Bridge (Gimsing 2009; Oresund Bridge 2012), carries four lanes of European route E20 and Oresund railway line, crosses Oresund Strait between Copenhagen (Denmark) and Malmö (Sweden). Pylon height: 204 m (669 ft), reinforced concrete, longest span: 490 m (1608 ft), clearance below: 57 m (187 ft), reinforced concrete, opened: May 5, 2011, TH/SL: 0.23

John James Audubon Bridge (Fossier and Duggar 2007), carries four lanes of LA 10, crosses Mississippi River, Louisiana, USA. Pylon height: 152.4 m (500 ft), longest span: 482 m (1583 ft), clearance below: 40 m (130 ft), reinforced concrete, opened: May 5, 2011, TH/SL: 0.23

Talmadge Memorial Bridge (Tang 1995), carries four lanes of US 17 to I-16, crosses Savannah River, Georgia, USA. Pylon height: 127 m (418 ft), longest span 335 m (1100 ft), clearance below: 56 m (185 ft), reinforced concrete, opened: November 1990, TH/SL: 0.2

Bridge to Russky Island (SK-MOST 2011), carries four lanes of roadway, crosses Eastern Bosphorus Strait, Vladivostok (Nazimov peninsula) and Russian Island (Novosiltseva cape). Pylon height: 320.9 m (1052 ft), longest span: 1104 m (3621 ft), clearance: 70 m (230 ft), opened: July 2012 (plans), TH/SL: 0.23

ANZAC Bridge (Moore 1996), carries, freeway, pedestrians and bicycles, crosses Johnston’s Bay, Sydney, Australia. Pylon height: 120 m (390 ft), longest span: 345 m (1132 ft), clearance below: 27 m (88 ft), reinforced concrete, opened: December 2, 1995, TH/SL: 0.27

Yangpu Bridge (Ma and Fan 1993), carries six-lane motorway, crosses Huangpu River, China. Pylon height: 223 m (731 ft), longest span: 602 m (1975 ft), clearance below: 48 m (257 ft) reinforced concrete, opened: October 1993, TH/SL: 0.24

Sundial Bridge (Sundial Bridge 2013), cantilever spar cable-stayed bridge, carries bicycles and pedestrians, crosses Sacramento River, Redding, California, USA, pylon height: 66 m (217 ft), clearance below: 8 m (26 ft), opened: July 4, 2004

FIGURE 3.18 Generic forms and typical examples of towers for cable-stayed bridges.
People driving over a bridge view the towers projecting above the roadway, making this portion of the towers visually the most important feature of the bridge; thus, the towers should be carefully considered by the designers of the bridge.

The simplest tower form is a single shaft, usually vertical (Figure 3.18a). Stay cables from a single tower can be arranged in a single plane to align with a longitudinal center girder or can be splayed outwardly to connect with the longitudinal edge girders. Occasionally, the single shaft may be inclined longitudinally, usually away from the main span; rarely toward the main span. Even more infrequently, on short,
curved spans, a single tower is inclined transversely, which adds a dynamic factor to the esthetics of the bridge. The cables are usually arranged in a star array, radiating from the top of the tower.

Two vertical shafts straddling the roadway, with or without cross struts above the roadway, form a simple tower, which can be used with two planes of cables (Figure 3.18b and 3.18c). The stay cables incline inward to connect to the edge girders or to the edges of a box girder, introducing a tension component across the deck support system. The tower shafts can also be “cranked” or offset above the roadway (Figure 3.18d). This allows the cables to be aligned in a vertical plane and attached to the girder that can pass continuously through the towers. This method was used for the Talmadge Bridge, Georgia (Figure 3.20). A horizontal strut is always used between the tower shafts at the offset to stabilize the towers.

The two shafts of cable-stayed bridges can be inclined inward toward each other to form a modified “A” frame, similar to that of the Luling Bridge towers (Figure 3.16) or the two shafts inclined to bring the shafts tops together to form a full “A” frame (Figure 3.18e). The two planes of stay cables are inclined outward, producing a desirable compression component across the deck support system.

Most of the two shafts of the H-shaped, A-shaped, and the quasi-diamond- and full-diamond-shaped towers for cable-stayed bridges are designed as straight members, for ease of construction. A few of the recently built bridges have curved shafts. The Third Nanjing Yangtze Bridge is an excellent example (Figure 3.19d). As noted in Section 3.5, the form of these towers was copied from the Eiffel Tower in Paris and was the first cable-stayed bridge in China with curved steel towers.

The form of the towers of a cable-stayed bridge below the roadway is also important for reasons of both esthetics and costs. People viewing a bridge from a distance will see the towers as part of a complete structural unit. This total view is important because it displays the motif of the bridge, and it should be carefully considered by the designers of the bridge.

The shafts of the towers for a modified “A” frame bridge can be carried down to their foundations at the same slope as was used above the roadway and particularly on sites with low clearances.

However, at high-clearance locations, if the shafts of the towers for a full “A” frame or for an inverted “Y” frame are carried down to the foundations at the same slope as above the roadway, the foundations may become very wide and costly.
Sometimes the lower shafts are inclined inward under the roadway, producing a modified or “squat” diamond (Figure 3.18f), similar to the towers of the Glebe Island Bridge, Sydney, Australia (Figure 3.7). For very high roadways, the inward inclination can form a full diamond, as in the Cooper River Bridge, Charleston, South Carolina (Figure 3.8), or a double diamond as in the Baytown Bridge, Texas (Figure 3.21). For very long spans requiring tall towers, the “A” frame can be extended by using a single vertical shaft forming an inverted “Y” shape (Figure 3.18g) as in the Yang Pu Bridge (Figure 3.19b) and as in the Shanghai Yangtze River Bridge, China. This form is very effective for very long spans for which additional tower height is required, and the inclined legs add stiffness and frame action for wind resistance.

The numbers of shafts within the towers of cable-stayed bridges can vary from one to four; the Rio-Antirrio Bridge, Greece, has four shafts (Figure 3.19c). Three-shaft towers generally are not used for cable-stayed bridges, except for those with very wide decks. Four-shaft towers are best used to support two separate structures, rather than to support one wide deck. The four shafts of a tower may share a common foundation, or two pairs of shafts may have their own foundations, depending on costs.

3.5.2.2 Suspension Bridge Towers

Suspension bridges are designed to be used on much longer spans than are cable-stayed bridges. Thus, the towers of a suspension bridge must be far more robust than are those of a cable-stayed bridge, to support adequately the large loads and great wind forces a suspension bridge will encounter during its life span.

Usually the towers of suspension bridges follow a traditional design, using two vertical shafts and two planes of cables, as is illustrated by the steel towers for the Delaware Memorial Bridges (Figure 3.15). However, concrete towers have recently proven to be economical for some bridges. The very long span of the 4626 ft (1410 m) Humber Bridge, England, 1983, used uniformly spaced multistruts and concrete towers (Figure 3.22). The crossing of the Great Belt sea way in Denmark (Figure 3.23), opened in 1999, has concrete towers 833 ft (254 m) high with two struts—one near the mid-height and one at the top.

The shafts of suspension bridge towers are usually designed for the full height of the towers, from the foundation to the cable saddles. The tower must accommodate the large aspect ratio for good esthetics. Only a few single-cable suspension bridges have been designed with an “A” or an inverted “Y” form of towers. Typical shapes and forms of suspension bridges are shown in Figure 3.24.

For conceptual designs, the heights of suspension bridges towers, above the deck, depend on the sag-to-span ratio, which can vary from about 1:8 to 1:12. A good preliminary value is approximately 1:10. To this value, one must add the structural depth of the deck and the clearance to the foundations to

![Figure 3.21 Baytown Bridge, Texas. (Courtesy of T. Y. Lin International.)](image_url)
obtain the approximate total tower height. The shafts are usually connected together with several struts, or cross bracing along the height of the tower, or the shafts are connected at the top with a large single strut. Some form of strut between the towers is usually required for suspension bridges because the large cables carry lateral wind and seismic loads to the tops of the tower shafts, which then need to be braced against each other with struts or “X” cross bracing to form a tower-frame action.
3.5.3 Erection

The most crucial stage in the life of a bridge is the erection time of that structure because the risk of adverse happenings is highest during this phase. Adverse happenings can occur from the high cost of opening the bridge to service late, to locked-in unanticipated stresses because of faulty erection procedures, to partial or full collapse. Bridge designers have little control of the first risks; however, unanticipated stresses or partial or full collapse are very troubling because they can be prevented by having a detailed erection scheme. Ordinary towers can usually be erected without much difficulty; however, thin, curved, or inclined towers or towers temporarily supporting or resisting erection forces or loads require a detailed erection plan.

Some bridge designers say that erection is the responsibility of the contractors; however, if something listed above does happen, everyone will become involved, including the designer, and someone will end up paying money.

A better solution is to design a detailed erection scheme that will construct the structure to the proper camber, position, and alignment and with acceptable stresses in all the members. The best person to design this erection scheme is the bridge designer, because the designer knows the structure intimately, works on the design for a year, and develops a bridge model for the design of the bridge; that model can...
Towers also be used to develop all erection stages for the structure. If this is done, the specifications should allow the contractor full freedom to modify that scheme or to develop a separate erection scheme. If the specifications require the contractor to develop the erection scheme, the bridge designer should check and approve the scheme before erection begins.

During the concept-design phase, many different tower forms and cable arrangements may be considered; each should be evaluated for esthetics, constructability, and cost. Each alternative considered should have at least one method of erection developed during the concept-design phase to ensure that the scheme under consideration is constructible. The costs of erecting unusual tower designs such as inclined towers, or curved spars, can be difficult to estimate and may add significant costs to the project.

3.6 Final Design

The AASHTO Standard Specifications for Highway Bridges (AASHTO 2002) and the AASHTO LRFD Bridge Design Specifications (AASHTO 2012) apply to bridges 150 m (500 ft) or less in span. For important bridges, and for long-span cable-supported bridge projects, special design criteria may need to be developed by the owner and/or the designer. The special-design criteria may also need to be developed in cooperation with the owners of the facility, so as to include their operations, maintenance requirements, and bridge performance expectations after large natural events such as earthquakes. See Chapter 9 for suspension bridge design and Chapter 10 for cable-stayed bridge design in Bridge Engineering Handbook, Second Edition: Superstructure Design. Troitsky (1988), Podolny and Scalzi (1986), and Walther et al., (1999) also present detailed design theory for cable-stayed bridges.

Design methodology for the towers should follow the same practices as does the design methodology for the entire bridge. The towers should be part of a global analysis in which the entire structure is treated as a whole. From the global analysis, the towers may be modeled as substructural units with their forces and deformations imposed as boundary conditions.

Detailed structural analyses form the basis for the final designs of the tower, its components, and its connections. Both cable-stayed and suspension bridges are highly indeterminate and both require careful analyses by at least one geometric nonlinear program if erections are to be determined. Prudent design should also include analysis of at least one erection scheme to demonstrate that an experienced contractor may erect the structure.

3.6.1 Design Loads

The towers are subject to many different load cases. The towers, as well as the entire structure, must be analyzed, designed, and checked for the controlling load case. Chapter 6 of Bridge Engineering Handbook, Second Edition: Fundamentals presents a detailed discussion of highway bridge loading.

The weight of the superstructure, including the self-weight of the towers, is obtained in the design process by utilizing the unit weights of the materials used for both the tower and the superstructure. The forces that are distributed to the tower can be calculated by a structural analysis of the completed structure. The forces distributed to the tower may be analyzed for a staged erection of the superstructure, to determine whether the towers will be over-stressed during construction of the superstructure.

Design loads from traffic using the bridge, such as trains, transit, trucks, or pedestrians, are usually prescribed in design codes and specifications or by the owners of the facility. These loads move across the bridge, and the forces imparted to the towers from such moving loads must be obtained from a structural analysis. These are all gravity effects, acting downward on the superstructure, but can induce both vertical and horizontal forces on the towers.

A current trend for spanning wide widths of waterways is to design multispan cable-stayed and suspension bridges, linked together to form a long, continuous structure with the towers evenly spaced for uniform appearance, and having a short span at each end. These multispan bridge roadways will deflect
excessively unless the towers are specially designed for added stiffness. This is because ordinary towers are not sufficiently stiff to resist the pull from cables that are supporting the flexible, multispan roadway.

Several methods have been proposed to stiffen these towers, such as adding four shafts to the towers as was done to the Rio Antirrio Bridge crossing of the Gulf of Corinth, Greece (Figure 3.19). A second method would be to use cables arranged in various ways to stiffen the towers externally; but this is beyond the scope of this chapter.

Towers are also subjected to temperature-induced displacements, from the superstructure and the cables framing into the towers, and the temperature-induced movement of the tower itself. Towers may expand and contract differentially along their tower height because of heat from the sun that shines on them from morning until sunset. Such temperature effects may cause deflection and torsional twisting along the height of the tower.

Wind blowing on the towers as a bluff shape will induce both forces and displacements in the tower. Force will be induced into the cables by the wind pressure on the superstructure and from the wind forces on the cables themselves. These additional forces will be carried to the towers, which must be designed for them.

For long-span bridges and locations with known high-wind speeds, the wind factor should be treated as a dynamic loading. This will usually require a wind-tunnel test on a sectional model of a proposed superstructure in a wind tunnel and for important bridges, a full aeroelastic model test in a large wind tunnel. See Chapter 22 of *Bridge Engineering Handbook, Second Edition: Fundamentals*. Under certain wind flows, the wind may excite the tower itself. In the rare instances where wind-induced excitation of the tower does occur, appropriate changes in the cross section of the tower may be made, or a faring added, to change the dynamic characteristics of the towers. If these methods are not effective in changing the response, installing tuned-mass dampers at various locations within the towers will dampen out excessive vibrations. These types of dampers need periodic maintenance, which requires ladders and elevators for access by maintenance personnel.

Seismic excitations should be treated as dynamic inertia loadings, inducing responses within the structure by exciting the vibrational modes of the towers. Tuned mass dampers can also be installed to dampen seismic excitations. Seismic forces and displacement may control tower design in locations with high seismic activity. For locations with lower seismic activity, the tower design should be checked at least for code-prescribed seismic loadings. The dynamic analysis of bridges is discussed in Chapter 3 of *Bridge Engineering Handbook, Second Edition: Seismic Design*.

A full analysis of the final design will reveal all the forces, displacements, and other design requirements for all loading cases for the final design of the towers.

### 3.6.2 Other Design Considerations

Suspension bridge cables pass over cable saddles that are usually anchored to the top of the tower. A cable produces a large vertical force, as well as smaller, but important, transverse and longitudinal forces from temperature, wind, earthquake, or any unbalanced cable forces between the main and the side spans. These forces are transmitted through the cable-saddle anchorage at each cable location, to the top of the tower. The towers and the permanent saddle anchorages must be designed to resist these cable forces.

The erection of a suspension bridge must be analyzed and the chosen sequence shown on the construction plans. To induce the correct loading into the cables of the side span, the erection sequence usually requires that the saddles be displaced toward the side spans. This is usually accomplished for short spans by displacing the tops of the towers by pulling them with heavy cables. For long spans, the saddles can be displaced temporarily, on rollers. As the stiffening girders or trusses are being erected into position and the cable begins to take loads, the towers or saddles are gradually rolled into final alignment on the tower. After erection of the stiffening girders or trusses is completed, the saddles are permanently fastened into position to take the unbalanced cable loads from the center and the side spans.
At the deck level, other forces may be imposed on the tower, from the box girder or the stiffening truss carrying the roadway. Such forces depend on the structural framing of the connections of the deck and the tower. Traditional suspension bridge designs usually terminate the stiffening truss, or the box girder, at the towers; that produces transverse and longitudinal forces on the tower at this point. More recent suspension bridge designs usually provide for the passing of a box girder continuously through the tower opening; this may produce transverse forces, but not longitudinal forces. For this arrangement, the longitudinal forces must be carried by the stiffing girder or trusses to the abutments.

The most critical area of the tower design is the tower-to-foundation connection. Both shear forces and moments are at a maximum at this point. Anchor bolts are generally used at the base of steel towers. Such bolts must be proportioned to transfer overturning loads from the tower to the bolts. The bolts must be deeply embedded in the concrete footing block in order to transfer their loads to the footing reinforcement.

Providing good drainage for rainwater running down the tower shafts will increase the life of the steel paint system at the tower base and will provide some protection to the anchor bolts.

Concrete towers must be joined to the foundations with full shear and moment connections. Lapped reinforcing bar splices are usually avoided as the lapping tends to congest the connections; the strength of the bars cannot then be developed, and lapped splices cannot be used for high-seismic areas. Using compact mechanical or welded splices will result in less congestion, with easier placement of concrete around the reinforcement, and a more robust tower-to-footing connection. The design of the joint of the tower shafts to the foundation should produce a constructible, efficient, and reliable connection.

The cable arrangements for cable-stayed bridges are many and varied. Some arrangements terminate the cables in the tower, whereas other arrangements pass the cable through the tower on cable saddles. Cables terminating in the tower may pass completely through the tower cross section and then be anchored on the far side of the tower. This method of anchoring produces compression in the tower cross section at the anchorage points. Cables can also be terminated at anchors within the walls of the tower, producing tension in the tower cross section at the anchorage points. These tension forces require special designing to provide reliable, long-life support for the cables.

As for suspension bridges, the erection of cable-stayed bridges must be analyzed, and the sequence be shown on the construction plans. The girders, as they are cantilevered outward from the towers, are very vulnerable. The most critical erection sequence is just before the closing of the two arms of the girders, at the center of the span. High winds can displace the arms and torque the towers, and heavy construction equipment can load the arms that are yet without benefit of the girder continuity to distribute the loads to towers.

3.7 Construction

The towers and superstructure should be constructed according to an erection plan as noted in Section 3.5.3.

Towers constructed of structural steel are usually fabricated in a shop by welding together steel plates and rolled shapes to form cells. Cells must be large enough to allow welders and welding equipment, and if the steel is to be painted, painters and cleaning and painting equipment inside each cell.

The steel tower components are transported to the bridge site and are erected by cranes and are either welded or bolted together with high-strength bolts. For bolting, the contractor should use a method of tensioning the high strength bolts to give consistent results needed to achieve the required tension such as turn-of-the-nut method. Field welding presents difficulties in holding the component rigidly in position while the weld is completed. Field welding may be difficult to control when exposed to windy weather, making ductile welds difficult, particularly the vertical and overhead welds. Field welding should be made within a protective covering that keeps out water and wind. Full-penetration welds require backup bars that must be removed carefully if the weld is subject to fatigue loading.
Towers constructed of reinforced concrete are usually cast in forms that can be removed and reused, or “jumped,” to the next level. Placing height for concrete is usually restricted to approximately 20–40 ft (6–12 m), to limit pressure from the freshly placed concrete. Reinforcing bar cages are usually preassembled on the ground, or on a work barge, and are lifted into position by crane. This requires the reinforcing bars to be spliced with each lift. Lapped splices are the easiest to make, but these are not allowed in seismic areas.

Slip forming is an alternative method that uses forms that are pulled slowly upward, reinforcing bars positioned and the concrete placed in one continuous operation around the clock until the tower is completed. Slip forming can be economical, particularly for constant cross-section towers. Some changes in cross-section geometry can be accommodated. For shorter spans, precast concrete segments can be stacked together and steel tendons tensioned to form the towers.

Tower designers should consider the method of erection that contractors may use in constructing the towers. Often the design can reduce construction costs by incorporating more easily fabricated and assembled steel components or easily assembled reinforcing bar cages and tower shapes that are easily formed. Of course, the tower design cannot be compromised just to lower erection costs.

Some engineers and many architects design towers that are angled longitudinally toward or away from the main span or are curved or kinked. This can be done if such a design can be justified structurally and esthetically, and the extra cost can be covered within the project budget. These types of towers require special erection methods.

Many towers of cable-stayed bridges have legs sloped toward each other to form an “A,” an inverted “Y,” a diamond, or similar shapes. These are not as difficult to construct as the longitudinally inclined tower design. The sloping concrete forms can be supported by vertical temporary supports and cross struts that tie the concrete forms together for each shaft. This arrangement braces the partly cast concrete tower legs against each other for support. Some of the concrete form supports for the double-diamond towers of the Baytown Bridge are visible in Figure 3.19.

As the sloped legs are erected, the inclination may induce bending moments and lateral deflection in the plane of the slope of the legs. Both of these secondary effects must be adjusted by jacking the legs apart by a calculated amount of force or displacement to release the locked-in bending stresses. If the amount of secondary stress is small, then cambering the leg to compensate for the deflection and adding material to lower the induced stress can be used. The jacking procedure adds cost but is an essential step in the tower erection. Neglecting this important construction detail can “lock-in” stresses and deflections that will lower the factor of safety of the tower and, in an extreme case, could cause a failure.

Tower construction usually requires special equipment to erect steel components or concrete forms to the full height of the tower. Suspension bridges and some cable-stayed bridges require cable saddles to be erected on the tower tops. Floating cranes rarely have the capacity to reach to the heights of towers designed for long spans. Tower cranes, connected to the tower as it is erected, can be employed for most tower designs and are a good choice for handling steel forms for the erection of concrete towers. A tower crane used to jump the forms and raise materials can be seen in Figure 3.8. Occasionally, vertical traveling cranes are used to erect steel towers by pulling themselves up the face of the tower following the erection of each new tower component.

Because the tower erection must be done in stages, each stage must be checked for stability and for stresses and deflections. The tower construction specifications should require the tower erection be checked by an engineer, employed by the contractor, for stability and safety at each erection stage. The construction specifications should also require the tower erection stages to be submitted to the design engineer for an evaluation and approval. This evaluation should be full enough to determine whether the proposed tower erection staging will meet the intent of the original design or needs to be modified to bring the completed tower into compliance. Chapters 1 and 4 of Bridge Engineering Handbook, Second Edition: Construction and Maintenance present more detailed construction procedure and techniques for long-span bridges.
3.8 Summary

Towers provide the structural and visible means of support of the bridge superstructure. Towers project above the roadway and are the most visible structural elements in a bridge. Towers usually form visible portals through which people pass as they travel from one point to another. They give the bridge, for good or for bad, its character, its motif, and its identifying esthetic statement and form the enduring impression of the bridge in people’s minds.

Towers are the most critical structural element in the bridge as their function is to carry the weight of the bridge and the forces imposed on the bridge to the foundations. Unlike most other bridge components, they cannot be replaced during the life of the bridge. Towers must fulfill their function in a reliable, serviceable, economical, and esthetic manner for the entire life of the bridge. Towers must also be practicable to erect without extraordinary expense; the exception to this economical requirement is the owners or the public want a spectacular bridge and are willing to pay for the extra cost.

Practicable tower shapes for cable-stayed bridges are many and varied. These towers can have one or several shafts arrayed from vertical to inclined, forming various shapes. Practicable tower shapes for a suspension bridge are usually restricted to two vertical shafts connected with one or several cross struts, although single shafts have been used on a few suspension bridges.

In the early 1990s, a trend began where efficiency and low cost were not always an objective because the owner or the public, or both, desires spectacular, picturesque, or distinctive bridges. This resulted in configuring stay cables and a few suspension bridge cables in unusual arrays that can dominate the towers and act as the principle esthetic statement of the bridge or the opposite of featuring towers that have unusual shapes, kinks, or inclination to add visual impact. This trend will continue into the foreseeable future.

The conceptual design phase is the most important phase in the design of towers for long span bridges. This phase sets, among other items, the span length, type of deck system, and the materials and shape of the towers. It also determines the esthetic, economics, and constructability of the bridge. A conceptual erection scheme should be developed during this phase to ensure the bridge can be economically constructed.

The final design phase sets the specific shape, dimensions, and materials for the bridge. If a usual tower design is used, the tower erection should also be shown. It is preferred that the design engineer follow the project into the construction stages. The design engineer must understand each erection step that is submitted by the contractor to ensure the construction complies with the design documents. The owner assured only by this means that the serviceable and reliability that he is paying for is actually achieved in construction.

The successful design of towers for cable-stayed and suspension bridges involves many factors and decision that must be made during the conceptual and design phases and the construction phase of the project. The final judge of a successful project is always made by the people who use the facility, pay for its construction and maintenance, and view the results of all the effort to provide a long-life bridge to service society (Cerver 1992).

References


