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28
Towers

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28.1 Introduction

Towers are the most visible structural elements of long-span bridges. They project above the superstructure and are seen from all directions by viewers and by users. Towers give bridges their character and a unifying theme. They project a mnemonic image that people remember as a lasting impression of the bridge itself. As examples of the powerful imagery of towers, contrast the elegant art deco towers of the Golden Gate Bridge (Figure 28.1) with the utilitarian but timeless architecture of the towers of the San Francisco–Oakland Bay Bridge (Figure 28.2). Or contrast the massive, rugged stone towers of the Brooklyn Bridge (Figure 28.3) with the awkward confusing steel towers of the Williamsburg Bridge in New York City (Figure 28.4).

Towers can be defined as vertical steel or concrete structures projecting above the deck, supporting cables and carrying the forces to which the bridge is subjected to the ground. By this definition, towers are used only for suspension bridges or for cable-stayed bridges, or hybrid suspension–cable-stayed structures. The word *pylon* is sometimes used for the towers of cable–stayed bridges. Both *pylon* and *tower* have about the same meaning — a tall and narrow structure supporting itself and the roadway. In this chapter, the word *tower* will be used for both suspension and for cabled-stayed bridges, to avoid any confusion in terms.

Both suspension and cable-stayed bridges are supported by abutments or piers at the point where these structures transition to the approach roadway or the approach structure. Abutments are discussed in Chapter 30. Piers and columns that support the superstructure for other forms of bridge structures such as girders, trusses, or arches, usually do not project above the deck. Piers and columns are discussed in Chapter 27.

The famous bridges noted above were opened in 1937, 1936, 1883, and 1903, respectively, and, if well maintained, could continue to serve for another 100 years. Bridge engineers will not design structures like these today because of changing technologies. These bridges are excellent examples of enduring structures and can serve to remind bridge engineers that well-designed and maintained structures do

FIGURE 28.1 Golden Gate Bridge, San Francisco. (Courtesy of Charles Seim.)

last for 150 years or longer. Robust designs, durable materials, provisions for access for inspection and maintenance, and a well-executed maintenance program will help ensure a long life. The appearance of the bridge, good or bad, is locked in for the life of the facility and towers are the most important visual feature leading to the viewer's impression of an aesthetic structure.

28.2 Functions

The main structural function of the towers of cable-stayed and suspension bridges is carrying the weight of the bridge, traffic loads, and the forces of nature to the foundations. The towers must perform these function in a reliable, serviceable, aesthetic, and economical manner for the life of the bridge, as towers, unlike other bridge components, cannot be replaced. Without reliability, towers may become unsafe and the life of the entire bridge could be shortened. Without serviceability being designed into the structure, which means that it is designed for access and ease of maintenance, the bridge will not provide continuing long service to the user. The public demands that long-span bridges be attractive, aesthetic statements with long lives, so as not to be wasteful of public funds.

28.3 Aesthetics

While the main function of the towers is structural, an important secondary function is visual. The towers reveal the character or motif of the bridge. The bridges used as examples in the introduction are good illustrations of the image of the structure as revealed by the towers. Indeed, perhaps they are famous because of their towers. Most people visualize the character of the Brooklyn Bridge by the gothic, arched, masonry towers alone. The San Francisco–Oakland Bay Bridge and the Golden Gate Bridge give completely different impressions to the viewer as conveyed by the towers. Seim [7] measured the ratios of the visible components of the towers of the latter two bridges and found important, but subtle, diminution of these ratios with height above the tower base. It is the subtle changes in these ratios within the height of the towers that produce the much-admired proportions of these world-renowned bridges. The proportions of the towers for any new long-span bridge

FIGURE 28.2 San Francisco–Oakland Bay Bridge. (Courtesy of Charles Seim.)

should be carefully shaped and designed to give the entire bridge a strong — even robust — graceful, and soaring visual image. The aesthetics of bridges are discussed in greater detail in Chapters 2 and 3 of this volume.

The aesthetics of the array of cables many times are of secondary importance to the aesthetics of the towers. However, the array or form of the cables must be considered in the overall aesthetic and structural evaluation of the bridge. Main cables of suspension bridges always drape in a parabolic curve that most people instinctively enjoy. The large diameter of the cables makes them stand out as an important contribution to the overall visual impression as the supporting element of the roadway.

The cables of cable-stayed bridges are usually of small diameter and do not stand out visually as strongly as do the cables of suspension bridges. However, the array of the stays, such as harp, fan, radiating star, or others, should be considered in context with the tower form. The separated, parallel cables of the harp form, for example, will not be as obtrusive to the towers as will other arrangements. However, the harp cable form may not be appropriate for very long spans or for certain tower shapes. The cables and the towers should be considered together as a visual system.

Billington [2] presents an overview of the importance of the role of aesthetics in the history of the development of modern bridge design. Leonhardt [5] presents many examples of completed bridges showing various tower shapes and cable arrangements for both suspension and cable-stayed bridges.

FIGURE 28.3 Brooklyn Bridge, New York. (Courtesy of Charles Seim.)

28.4 Conceptual Design

Perhaps the most important step in the design of a new bridge is the design concept for the structure that ultimately will be developed into a final design and then constructed. The cost, appearance, and reliability and serviceability of the facility will all be determined, for good or for ill, by the conceptual design of the structure. The cost can be increased, sometimes significantly, by a concept that is very difficult to erect. Once constructed, the structure will always be there for users to admire — or to criticize. The user ultimately pays for the cost of the facility and also usually pays for the cost of maintaining the structure. Gimsing [4] treats the concept design issues of both cable-stayed and suspension bridges very extensively and presents examples to help guide designers.

A proper bridge design that considers the four functions of reliability, serviceability, appearance, and cost together with an erectable scheme that requires low maintenance, is the ideal that the design concept should meet.

A recent trend is to employ an architect as part of the design team. Architects may view a structure in a manner different from engineers, and their roles in the project are not the same. The role of the engineer is to be involved in all four functions and, most importantly, to take responsibility for the structural adequacy of the bridge. The role of the architect generally only involves the function of aesthetics. Their roles overlap in achieving aesthetics, which may also affect the economy of the structure. Since both engineers and architects have as a common objective an elegant and economical bridge, there should be cooperation and respect between them.

Occasional differences do occur when the architect's aesthetic desires conflict with the engineer's structural calculations. Towers, as the most visible component of the bridge, seem to be a target for this type of conflict. Each professional must understand that these differences in viewpoints will occur and must be resolved for a successful and fruitful union between the two disciplines.

While economy is usually important, on occasions, cost is not an objective because the owner or the public desires a "symbolic" structure. The architect's fancy then controls and the engineer can only provide the functions of safety and serviceability.

FIGURE 28.4 Williamsburg Bridge, New York. (Courtesy of Charles Seim.)

28.4.1 Materials

Until the 1970s steel was the predominant material used for the towers of both cable-stayed and suspension bridges. The towers were often rectangular in elevation with a cross-sectional shape of rectangular, cruciform, tee, or a similar shape easily fabricated in steel. Examples of suspension bridge steel tower design are the plain, rectangular steel towers for the two Delaware Memorial Bridges; the first constructed in 1951 and the parallel one in 1968 (Figure 28.5). 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 28.6).

The cross sections of steel towers are usually designed as a series of adjoining cells formed by shop-welding steel plates together in units from 6 to 12 m long. 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 concentrated load from the saddles. The steel cellular towers for a cable-stayed bridge with cables framing in the towers must be designed for the local forces from the numerous anchorages of the cables.

Since the 1970s, reinforced concrete has been used in many forms with rectangular and other compact cross sections. Concrete towers are usually designed as hollow shafts to save weight and to reduce the amount of concrete and reinforcing bars required. As with steel towers, concrete towers must

FIGURE 28.5 Delaware Memorial Bridges. (Courtesy of D. Sailors.)

FIGURE 28.6 Luling Bridge, New Orleans, Louisiana. (Courtesy of Charles Seim.)

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 a potential for savings in foundation costs. Steel towers will generally be more flexible and 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.

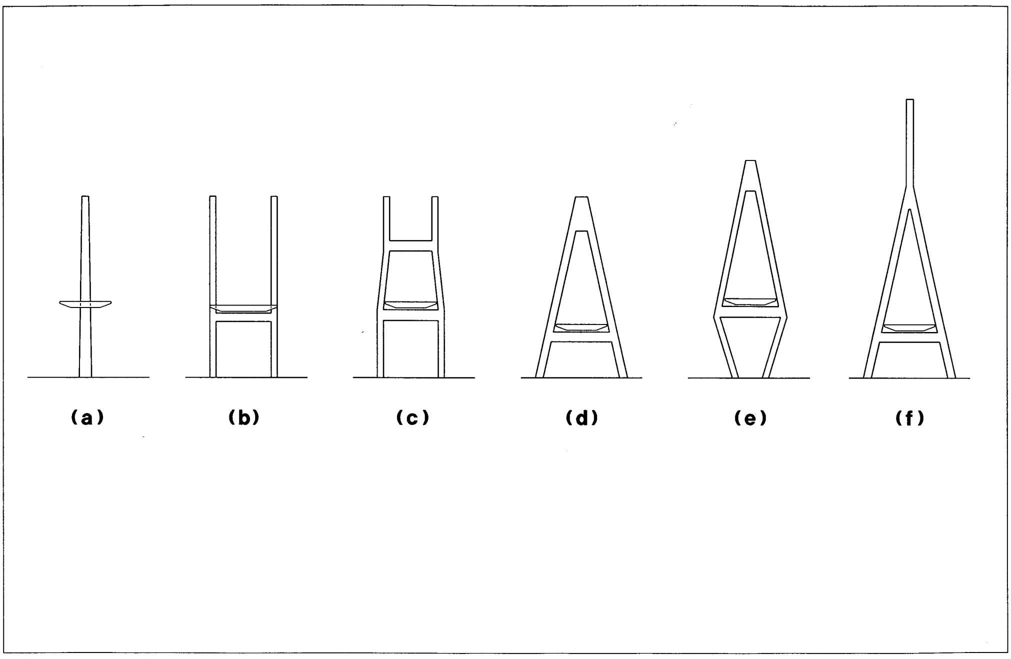

FIGURE 28.7 Generic forms for towers of cable-stayed bridges. (a) Single tower, I; (b) double vertical shafts, H; (c) double cranked shafts; (d) inclined shafts, A; (e) inclined shafts, diamond; (f) inverted Y.

The cost of steel or concrete towers can vary with a number of factors so that market conditions, contractor's experience, equipment availability, and the design details and site-specific influences will most likely determine whether steel or concrete is the most economical material. For pedestrian bridges, timber towers may be economical and aesthetically pleasing.

During the conceptual design phase of the bridge, approximate construction costs of both 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 a present-worth evaluation.

28.4.2 Forms and Shapes

Towers of cable-stayed bridges can have a wide variety of shapes and forms. Stay cables can also be arranged in a variety of forms. See Chapter 19. For conceptual design, the height of cable-stayed towers above the deck can be assumed to be about 20% of the main span length. To this value must be added the structural depth of the girder and the clearance to the foundation for determining the approximate total tower height. The final height of the towers will be determined during the final design phase.

The simplest tower form is a single shaft, usually vertical (Figure 28.7a). Occasionally, the single tower is inclined longitudinally. Stay cables can be arranged in a single plane to align with the tower or be splayed outward to connect with longitudinal edge beams. This form is usually employed for bridges with two-way traffic, to avoid splitting a one-way traffic flow. For roadways on curves, the single tower may be offset to the outside of the convex curve of the roadway and inclined transversely to support the curving deck more effectively.

Two vertical shafts straddling the roadway with or without cross struts above the roadway form a simple tower and are used with two planes of cables (Figure 28.7b) The stay cables would incline inward to connect to the girder, introducing a tension component across the deck support system; however, the girders are usually extended outward between the towers to align the cables vertically

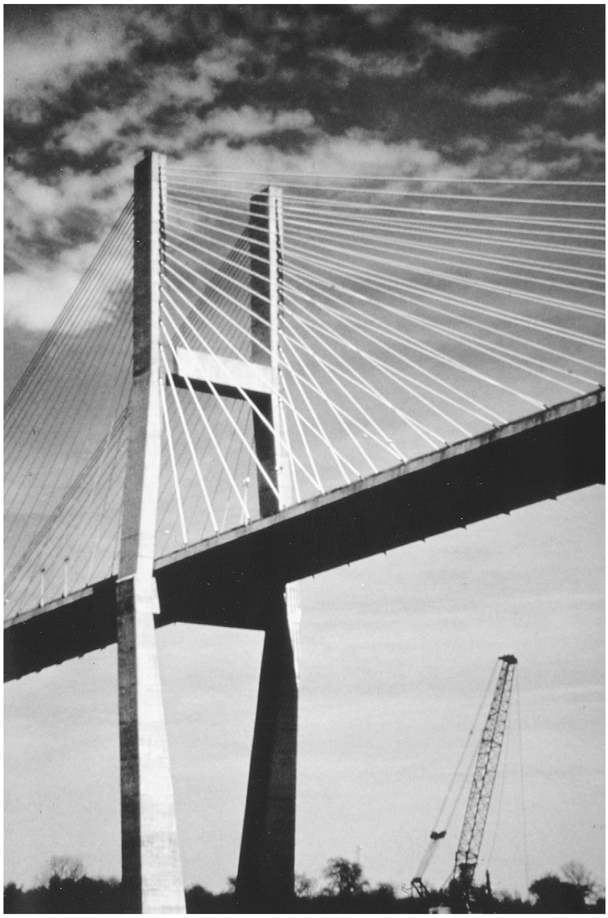

FIGURE 28.8 Talmadge Bridge, Georgia. (Courtesy of T. Y. Lin International.)

with the tower shafts. The tower shafts can also be "cranked" or offset above the roadway (Figure 28.7c). This allows the cables to be aligned in a vertical plane and to be attached to the girder, which can pass continuously through the towers as used for the Talmadge Bridge, Georgia (Figure 28.8). A horizontal strut is used between the tower shafts, 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 the Luling Bridge towers (Figure 28.6), or inclined to bring the shafts tops together to form a full A-frame (Figure 28.7d). The two planes of stay cables are inclined outward, producing a more desirable compression component across the deck support system.

The form of the towers of cable-stayed bridge below the roadway is also import for both aesthetics and costs. The shafts of the towers for a modified A-frame can be carried down to the foundations at the same slope as above the roadway, particularly for sites with low clearance. 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. The aesthetic proportions also may be affected adversely. Projecting the A-frame shafts downward vertically can give an awkward appearance. Sometimes the lower shafts are inclined inward under the roadway producing a modified diamond (Figure 28.7e), similar to the towers of the Glebe Island Bridge, Sidney, Australia (Figure 28.9). For very high roadways, the inward inclination can form a full diamond or a double diamond as in the Baytown Bridge, Texas (Figure 28.10). For very long spans requiring tall towers, the A-frame can be extended with a single vertical shaft forming an inverted Y shape (Figure 28.7f) as in the Yang Pu Bridge, China

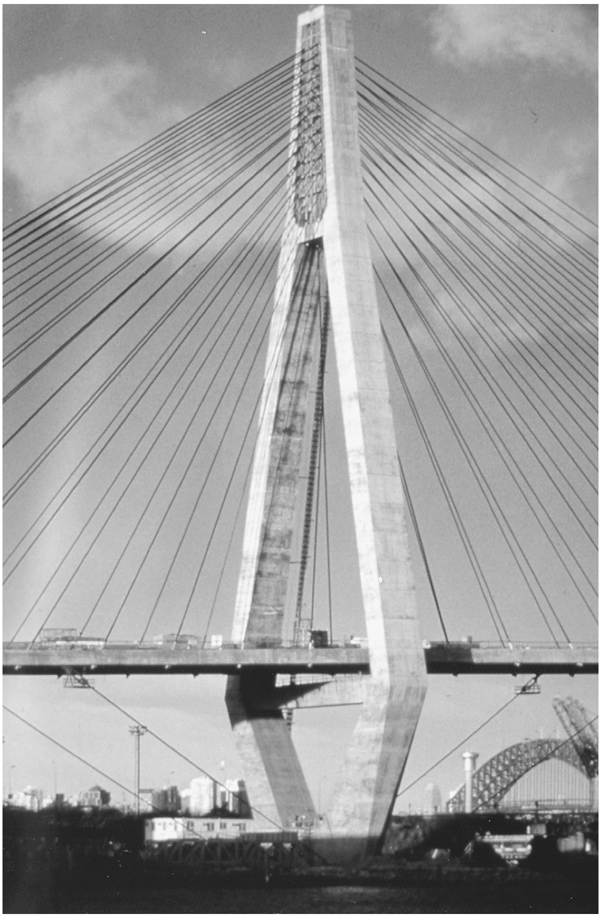

FIGURE 28.9 Glebe Island Bridge, Sidney, Australia. (Courtesy of T. Y. Lin International.)

(Figure 28.11). This form is very effective for very long spans where additional tower height is required and the inclined legs add stiffness and frame action for wind resistance.

The number of shafts or columns within the towers of cable-stayed bridges can vary from one to four. Three-shaft towers generally are not used for cable-stayed bridges except for very wide decks. Four-shaft towers can be used best to support two separate structures instead of a single wide deck. The towers could share a common foundation or each have its own foundation depending on the cost.

Suspension bridges can have from one to four cables depending on structural or architectural needs. Only a few single-cable suspension bridges have been designed with an A or inverted Y form of towers. Usually towers of suspension bridges follow a more traditional design using two vertical shafts and two planes of cables, as illustrated by the steel towers for the Delaware Memorial Bridges (see Figure 28.5). However, concrete towers have recently proved to be economical for some bridges. The very long span (1410 m) Humber Bridge, England, 1983, used uniformly spaced, multi-strut concrete towers (Figure 28.12). The crossing of the Great Belt seaway in Denmark (Figure 28.13), opening in 1999, has concrete towers 254 m high with two struts, one near the midheight and one at the top.

For conceptual designs, the height of suspension bridge 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 about 1:10. To this value must be added the structural depth of the deck and the clearance to the foundations to obtain the approximate total tower height. The shafts are usually connected together with several

FIGURE 28.10 Baytown Bridge, Texas. (Courtesy of T. Y. Lin International.)

FIGURE 28.11 Yang Pu Bridge, China. (Courtesy of T. Y. Lin International.)

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 is usually required for suspension bridges as 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 cross struts to form a tower-frame action.

28.4.3 Erection

During the concept design phase, many different tower forms may be considered, and preliminary designs and cost estimates completed. Each alternative considered should have at least one method

FIGURE 28.12 Humber Bridge, England. (Courtesy of Charles Seim.)

of erection developed during the concept design phase to ensure that the scheme under consideration is feasible to construct. The cost of unusual tower designs can be difficult to estimate and can add significant cost to the project.

28.5 Final Design

The AASHTO Standard Specifications for Highway Bridges [1] apply to bridges 150 m or less in span. For important bridges and for long-span cable-supported bridge projects, special design criteria may have to be developed by the designer. The special design criteria may have to be also developed in cooperation with the owners of the facility to include their operations and maintenance requirements and their bridge-performance expectations after large natural events such as earthquakes. See Chapter 18 for suspension bridge design and Chapter 19 for cable-stayed bridge design. Troitsky [8], Podolny and Salzi [6], and Walther [9] present detailed design theory for cable-stayed bridges.

Design methodology for the towers should follow the same practice as 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 analyses, the towers can be modeled as a substructure unit with forces and deformations imposed as boundary conditions.

Detailed structural analyses form the basis for the final design of the tower and its components and connections. Both cabled-stayed and suspension bridges are highly indeterminate and require careful analysis in at least a geometric nonlinear program.

28.5.1 Design Loads

The towers are subject to many different loading cases. The towers, as well as the entire structure, must be analyzed, designed, and checked for the controlling loading cases. Chapter 6 presents a detailed discussion of bridge loading.

The weight of the superstructure, including the self-weight of the towers, is obtained in the design process utilizing the unit weights of the materials used in the superstructure and distributed to the tower in accordance with a structural analysis of the completed structure or by the erection equipment during the construction phases.

FIGURE 28.13 Great Belt Bridge, Denmark. (Courtesy of Ben C. Gerwick, Inc.)

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 are loads moving across the bridge and the forces imparted to the towers must be obtained from a structural analysis that considers the moving loading. These are all gravity effects that act downward on the structure, but will induce both vertical and horizontal forces on the towers.

A current trend for spanning wide widths of waterways is to design multispan bridges linked together to form a long, continuous structure. With ordinary tower designs, the multispan cable-stayed girders will deflect excessively under live loads as the towers will not be sufficiently stiffened by the cable stays anchored within the flexible adjacent spans. For multispan suspension bridges with ordinary tower designs, the same excessive live-load deflection can also occur. Towers for multispan cable-supported bridges must be designed to be sufficiently rigid to control live-load deflections.

Towers are also subject to temperature-induced displacements, both from the superstructure and cable framing into the towers, and from the temperature-induced movement of the tower itself. Towers can expand and contract differentially along the tower height from the sun shining on them from morning until sunset. These temperature effects can cause deflection and torsional twisting along the height of the tower.

Wind blowing on the towers as a bluff shape induces forces and displacements in the tower. Forces will be induced into the cables by the pressure of wind on the superstructure, as well as by the wind forces on the cables themselves. These additional forces will be carried to the towers.

For long-span bridges and for locations with known high wind speeds, wind should be treated as a dynamic loading. This usually requires a wind tunnel test on a sectional model of the superstructure in a wind tunnel and, for important bridges, an aeroelastic model in a large wind tunnel. See Chapter 57. Under certain wind flows, the wind can also excite the tower itself, particularly if the tower is designed with light steel components. In the rare instances in which wind-induced excitation of the tower does occur, appropriate changes in the cross section of the tower can be made or a faring can be added to change the dynamic characteristics of the tower.

Forces and deformations of long-span structures from earthquakes are discussed in Chapter 40. The seismic excitation should be treated as dynamic inertia loadings inducing response within the structure by exciting the vibrational modes of the towers. Induced seismic forces and displacement can control the design of towers 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 34.

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

28.5.2 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 and smaller, but important, transverse and longitudinal forces from temperature, wind, earthquake, or from the unbalanced cable forces between main and 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 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 with heavy cables. For long spans, the saddles can be displaced temporarily on rollers. As the stiffening deck elements are being erected into position and the cable begins to take loads, the towers or saddles are gradually brought into final vertical alignment. After the erection of the stiffening deck elements are 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 stiffening truss carrying the roadway. These forces depend on the structural framing of the connection of the deck and tower. Traditional suspension bridge designs usually terminate the stiffening truss or box girder at the towers, which produces transverse, and longitudinal, forces on the tower at this point. Contemporary suspension bridge designs usually provide for passing a box girder continuously through the tower opening which may produce transverse forces but not longitudinal forces. For this arrangement, the longitudinal forces must be carried by the girder to the abutments.

The most critical area of the tower design is the tower-to-foundation connection. Both shear forces and moments are maximum at this point. Anchor bolts are generally used at the base of steel towers. The bolts must be proportioned to transfer the loads from the tower to the bolts. The bolts must be deeply embedded in the concrete footing block to transfer their loads to the footing reinforcement. Providing good drainage for the rainwater running down the tower shafts will increase the life of the steel paint system at the tower base and provide some protection to the anchor bolts.

Concrete towers must be joined to the foundations with full shear and moment connections. Lapped reinforcing bars splices are usually avoided as the lapping tends to congest the connections, the strength of the bars cannot 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.

Careful coordination between the foundation designers and tower designers is required to achieve a stable, 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 can pass completely through the tower cross section and then anchor on the far side of the tower. This method of anchoring produces compression in the tower cross section at these 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 designs to provide reliable, long-life support for the cables.

Just as for suspension bridges, the erection of cable-stayed bridges must be analyzed and the sequence shown on the construction plans. The girders, as they are erected outward from the towers, are very vulnerable. The critical erection sequence is just before closing 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 without benefit of girder continuity to distribute the loads.

28.6 Construction

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 then erected by cranes and bolted together with high-strength bolts. The contractor should use a method of tensioning the high-strength bolts to give constant results and achieve the required tension. Occasionally, field welding is used, but this presents difficulties in holding the component rigidly in position while the weld is completed. Field welding can be difficult to control in poor weather conditions to achieve ductile welds, particularly for vertical and overhead welds. 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 are removed and reused, or jumped to the next level. Concrete placing heights are usually restricted to about 6 to 12 m to limit form pressure from the freshly placed concrete. Reinforcing bar cages are usually preassembled on the ground or on a work barge, and lifted into position by crane. This requires the main load-carrying reinforcing bars to be spliced with each lift. Lapped splices are the easiest to make, but 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 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 not vertical but are angled longitudinally toward or away from the main span. This can be done if such a design can be justified structurally and aesthetically, and the extra cost can be covered within the project budget. The difficulties of the design of longitudinally inclined towers must be carefully considered as well as the more expensive and slower erection, which will create additional costs.

Many towers of cable-stayed bridges have legs sloped toward each 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. 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 28.9.

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 extreme 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 28.9. 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.

The erection sequence for a suspension bridge may require that the towers be pulled by cables from the vertical toward the sides spans or that the cable saddles be placed on rollers and displaced toward the side spans on temporary supports. The tower restraints are gradually released or the rollers pushed toward their final position as the erection of the deck element nears completion. This operation is usually required to induce the design forces into the cables in the side spans. The cable saddles then are permanently anchored to the towers.

Because the tower erection must be done in stages, each stage must be checked for stability and for stresses and deflections. The specifications should require the tower erection to 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. This evaluation should be thorough enough to determine if the proposed tower erection staging will meet the intent of the original design, or if it needs to be modified to bring the completed tower into compliance.

28.7 Summary

Towers provide the visible means of support of the roadway on which goods and people travel. Being the most visible elements in a bridge, they give the bridge, for good or for ill, its character, its motif, and its identifying aesthetic impression. Towers usually form structural portals through which people pass as they travel from one point to another. Of themselves, towers form an aesthetic structural statement.

Towers are the most critical structural element in the bridge as their function is to carry the forces imposed on the bridge to the ground. 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 aesthetic manner for the entire life of the bridge. Towers must also be practicable to erect without extraordinary expense.

Practicable tower shapes for cable-stayed bridges are many and varied. Towers can have one or several legs or shafts arrayed from vertical to inclined and forming A- or inverted Y-shaped frames. Suspension bridge towers are usually vertical, with two shafts connected with one or several struts.

The conceptual design is the most important phase in the design of a long-span bridge. 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 aesthetic, economics, and constructibility of the bridge. A conceptual erection scheme should be developed during this phase to ensure that the bridge can be economically constructed.

The final design phase sets the specific shape, dimensions, and materials for the bridge. A practical erection method should be developed during this phase and shown on the construction drawings. If an unusual tower design is used, the tower erection should also be shown. The specifications should allow the contractor to employ an alternative method of erection, provided that the method is designed by an engineer and submitted to the design engineer for review. It is essential that the design engineer follow the project into the construction stages. The designer must understand each erection step that is submitted by the contractor in accordance with the specifications, to ensure the construction complies with the design documents. Only by this means are owners assured that the serviceability and reliability that they are paying for are actually achieved in construction.

The successful design of a cable-stayed or a suspension bridge involves many factors and decisions that must be made during the planning, design, and construction phases of the project. Towers play an important role in that successful execution. The final judgment of a successful project is made by the people who use the facility and pay for its construction, maintenance, and long-life service to society.

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