

# CHAPTER 6: CONCLUSION

The following Chapter 6 summarizes the most important issues raised in this study and points out related areas for future research that may be of value for the engineering community.

## 6.1 SUMMARY

After introductory remarks on the background, intent, and organization of this study, the fascinating history of bridge construction is unraveled in this study. This section is supposed to help putting the profession into to context of its long continuous history and show the remarkable achievements that were made from the times of the very first bridges to the current days.

Already the earliest recorded times used the same variety of general structural principles to cross obstacles that are still used in modern bridge building. In particular bridges with stone arches dominated throughout the Old World and several of them have survived to the present day. The initially only semicircular stone arch developed into more elaborate shapes of pointed arches and arches with a greater span-to-rise ratio during medieval times. This development reached its height in Renaissance times when the visible elements of bridges, i.e. substructures and superstructures became much more slender and daring. More arch types such as poly-centered and elliptical arches were used. Improvements were made in putting the bridges on more solid foundations that were built with cofferdams and caissons. Hence bridge builders gained much more flexibility in where and how to erect their structures. Even more possibilities in bridge building were added through the introduction of iron as a completely new material during the Industrial Revolution. The high tensile and compressive strength of iron made completely new shapes for structural members and bridge superstructures, e.g. trusses possible. Growing industrialization also brought along a new source of power in form of the steam engine, which also required bridges to withstand the heavy dynamic loads of the first locomotives. Further development of iron and steel contributed to the rise of yet another type of bridges that have

remained amongst the largest structures ever built – suspension bridges, several of them in the New World. New methods of superstructure erection were invented. Yet the quick growth of major bridges also saw some failures, as engineers were still learning how the large structural systems reacted to environmental influences such as wind load. Suspension bridges incorporated stiffening trusses or made use of aerodynamic box girders in an attempt to withstand the forces of nature. Steel structures were built that would not have been possible with conventional iron. In the meantime advancement had also taken place in bridge construction. Pressurized caissons were employed to overcome adverse soils and build very deep and solid foundations.

The twentieth century finally saw two major innovations in bridge design and construction. Reinforced concrete gave the bridge engineers a most versatile construction material at hand that could be cast into literally any shape, only limited by laws of nature and the imagination of the designer. Incorporating prestressing steel into the concrete superstructures and making use of precast or cast-in-place segmental construction contributed much to the overall economy of concrete bridge spans in comparison with steel structures. With growing span lengths the weight of concrete superstructures increases very much and steel girders become more economical. Secondly, the new type of cable-stayed bridges appeared in the second half of the twentieth century and quickly established itself as a very economical and aesthetically satisfying member of the bridge family.

It is certain that technological advancement will continue to influence the ways in which bridges are designed and constructed. Several points are pointed out as to how bridge structures might develop in coming decades. New structural concepts in connection with improved or newly engineered materials offer a wide range of possibilities for future bridges.

Bridge engineering is based on concepts that are introduced in Chapter 3. When designing a bridge it needs to be established what functions it needs to fulfill. The four main functions – structural safety, serviceability, economy and ecology, and aesthetics – are introduced and their interrelationships are explained. Furthermore it is important to realize that the concept of ‘failure’ also relates to the four main functions, i.e. a bridge project may be considered an unsuccessful undertaking if e.g. the bridge is structurally sound but shows excessive deflections that decrease the riding comfort. Bridge designers need to keep this concept in mind when beginning work on

a new project. The design process is usually subdivided into several steps, beginning with conceptual design. Compiling the requirements for the new bridge and any important characteristics of its planned site forms the base for any design. The further design process will comprise many drafts and revisions until a feasible design has been produced. Constructability issues need to be included from a very early stage on to ensure that the bridge can be built in a safe and economical manner. In the beginning the dimensions of structural members will be chosen mostly based on the designer's experience, in later stages engineering software is then employed to compare alternatives and optimize member dimensions. Finally, complete analytical calculations for all important construction stages and detailed shop drawings will be produced.

As mentioned above, aesthetics is considered one of the four main functions of bridges. Several so-called aesthetic values of bridge structures are identified. These are character and function, proportions and harmony, complexity and order, color and texture, and environmental scale. It is the composition of all of these values together that makes a bridge become accepted by the general public as an appealing structure. With respect to the bridge site itself, several influencing factors are identified. Soil conditions, topography, the river crossing, protection of the environment, and the local climate are the main environmental influences. Furthermore, technical factors such as bridge type and erection method, labor-related factors, and the particular needs of the owner need to be considered by the designer.

All aforementioned factors should have been considered in designing the bridge before structural analysis is begun. Analysis of the structural system generally makes use of a variety of simplifying assumptions. The four main elements of a structure – its geometry and boundary conditions, structural details such as bearings and expansion joints, material properties, and actions affecting the structure, i.e. loads or restraints on deformations are modeled mathematically. An adequate factor of safety will have to be incorporated to account for any uncertainties on the load and resistance sides of structural equations. Designing with redundancy against structural failure increases the overall safety of the bridge. Both Ultimate Limit States and Serviceability Limit States need to be examined during structural analysis. Any numerical results produced by engineering software need to be checked for consistency and accuracy of results to

capture errors or omissions that might have been incurred during the modeling process. Finally, the results need to be interpreted by the structural engineer to apply them to the real structure.

Issues pertaining to cast-in-place segmental cantilever construction are dealt with in the second part of Chapter 3. Characteristics of segmental construction, especially for longitudinally segmented bridge superstructures are pointed out. Cantilevering the bridge superstructure subsequently with cast-in-place segments requires consideration of different segment ages and time-dependent material properties. Major points in time for structural analysis are the end of construction and the state of 'infinity'. Furthermore, the stepwise changes in the overall structural system until continuity is achieved need to be considered. Interaction between these issues makes cast-in-place cantilevering a challenging task. Usually newly added segments are stressed to their predecessors when they have reached only a specific portion of the 28-day compressive strength of the concrete. Young concrete that is loaded is susceptible to increased time-dependent effects that depend on ambient conditions, i.e. concrete shrinkage and creep that can cause losses of prestressing forces in the post-tensioning tendons. Further losses are incurred immediately at the time of stressing e.g. through elastic shortening of the segment and in the long run through relaxation of the steel tendons themselves. After continuity is achieved in the structural system redistribution of bending moments takes place, effectively shifting moments from the supports more towards midspan. Thus internal forces change and influence the further development of time-dependent effects. Furthermore, movements or rotations of the bridge substructure can impose additional forces, which would not have been the case in the statically determinate cantilever system before continuity was achieved. Structural analysis needs to thoroughly incorporate the outlined effects and their interactions in modeling of the structural system and its construction stages. Cambering the superstructure by the anticipated overall deflections will ensure proper long-term alignment of the bridge.

Cast-in-place cantilever construction is technically feasible for span length up to more than 250 m. Form travelers are employed at the tip of the cantilever to place the concrete. These travelers remain in place until the concrete has cured sufficiently to achieve minimum strength for post-tensioning. Another factor determining the minimum casting cycle time is the speed with which the form travelers can be adjusted to possibly changing segment geometry, reinforcement can be

installed, and concrete can be placed. The aforementioned time-dependent effects in the concrete segments occur to an increased extent in cast-in-place segments in comparison with prefabricated segments.

A very common type of concrete bridge superstructures (and also in steel bridges) is the box girder. Box girders consist of a top slab, usually with cantilevering flanges, webs, and a bottom slab. They have several distinct advantages when used in medium-span to long-span bridges. They are extremely versatile and can be adjusted to a great number of different superstructure alignments as required by the topography of the bridge site. Width can easily be adjusted by varying the width of the cantilevering flanges of the top slab without affecting the main box girder itself. Their simple beam-type structural system incorporates all structural load-carrying elements below the bridge deck and is aesthetically pleasing through its clear, smooth lines. The box girder can also have variable depth to better withstand the bending moments in long spans and increase navigation clearance beneath the bridge. For wider bridges an increased number of boxes and webs may be used in the bridge superstructure. In any case, box girders with their closed cross-section have a high torsional stiffness that allows relatively long prestressed spans. Box girders facilitate prestressing operations and maintenance works because elements such as tendon anchorages are accessible from within the bridge superstructure.

Chapter 4 provides an overview of different modern erection methods for concrete segmental bridges. Modern concrete segmental bridges are prestressed structures in which the post-tensioning tendons provide enough built-in moment resistance to withstand dead loads and live loads on the long and slender spans. In most cases post-tensioning is employed, i.e. the prestressing tendons are stressed with hydraulic jacks after the concrete has been placed and cured. Usually the tendons are located in steel ducts within the concrete and are anchored in special anchorages.

Cantilevering can be carried out in two different fashions. In case the cantilever system consists of two arms on both sides of a pier support it is called Balanced Cantilever Construction as the cantilever arms balance each other with their respective weight in a scales-like fashion. The second type of cantilevering is the Progressive Placement Method, in which only one cantilever arm is growing from its pier or abutment. Usually the superstructure is then supported by

overhead stay cables that are attached to a temporary tower or by temporary towers under the superstructure. Cantilevering has the important advantage of being an erection method with which the valley that is crossed is widely left unobstructed by the construction process. Thus it is possible to bridge even very inaccessible mountain gorges with this method. The repetitive nature of segmental construction, either with cast-in-place or as precast segments can be used very advantageously in cantilevering. Once cantilevering is finished the closure segments are placed between the cantilever arms to form a continuous superstructure.

Special construction equipment is employed in cast-in-place cantilevering. So-called form travelers made of steel framework are attached to the cantilever tip where they carry the formwork in which new segments are cast. After a newly cast segment has gained strength it is stressed to the already existing part of the superstructure and the form traveler is advanced and adjusted for the next segment. Maximum segment length achieved with form travelers is about 5.00 m.

A different type of construction equipment is launching girders, which are used to place precast segments. Launching girders are distinguished by their length and configuration. These parameters also determine how the placement and advancement sequence for a particular launching girder can be carried out.

Incremental Launching was developed in the early 1960s. It is characterized by stationary construction of all superstructure segments in a so-called casting bed. Upon curing the segments are stressed together like a chain and are launched over the valley in small increments with hydraulic jacks. Segment lengths are significantly longer than in cantilevering. In order to reduce the cantilever moments a lightweight launching nose is oftentimes attached to the tip of the cantilever. This steel launching nose reaches the next support before the concrete girder does and thus provides early propped support for the concrete superstructure. Certain limitations exist in alignment of bridges as the stationary casting bed only allows small changes in curvature of the bridge superstructure.

Falsework was traditionally used to construct bridges, e.g. stone arches of all kinds, and is still a feasible means of construction. Falsework can be either stationary or traveling, depending on the

site conditions and the materials and labor available. A main advantage of falsework is that it allows construction even of geometrically very complex bridge alignments as in e.g. highway interchanges. A special kind of falsework is temporary towers, which are often used to provide additional support to a bridge under construction.

Span-By-Span Erection is an erection method in which prefabricated segments are assembled and stressed together before this set is lifted into position. Steel trusses are used to support the segments prior to completion of the spans.

After having dealt with a variety of erection methods the last part of Chapter 4 deals with construction loads and stresses. Construction loads, understood in a general way as actions as defined before, often influence structural systems only temporarily. However, they can have considerable effects due to the following reasons. Construction loads can create higher stresses in the structure than any loads anticipated for the bridge under service conditions could cause. They are directly related to the chosen erection method and the sequence in which erection is carried out. In addition to that, construction loads affect the structure in its weak stages prior to completion – the structural system has not reached continuity and thus additional redundancy due to being statically indeterminate. Furthermore, materials such as concrete may have reached only a minimum level of compressive strength that is less than the specified 28-day compressive strength.

Considering especially Balanced Cantilever Construction, a variety of construction loads needs to be considered, such as weight of erection equipment, e.g. form travelers with newly cast segments, imbalance from differences in erection of new segments at the tips of both cantilever arms, materials being stored on the superstructure, wind, and thermal gradients. Additional stresses can be induced in the structure through e.g. temporary supports and jacking forces from alignment corrections. As outlined before, consideration of all construction stages with their respective geometry and boundary conditions, structural details, time-dependent material properties, and construction loads is a key factor to adequately analyze the structure and design against failures. Examples of bridge failures due to improper consideration of construction loads illustrate the importance of this matter.

Codes and regulations from professional organizations that are applicable to bridge construction are reviewed for their dealing with construction loads. Provisions pertaining to construction loads are described for ease of accessibility.

Chapter 5 comprises the case study part of this study, dealing with the Wilson Creek Bridge in the Commonwealth of Virginia. Background information on the location and objective of this project is provided. The Wilson Creek Bridge, also called 'Smart Bridge' belongs to the so-called Smart Road research project of the Commonwealth of Virginia Department of Transportation (VDOT) and other organizations. The bridge is a 605.00-m long, five-span cast-in-place concrete segmental bridge built with Balanced Cantilever Construction. The superstructure of the bridge consists of a single box girder with cantilevering flanges, inclined webs, and variable depth that will accommodate two lanes of traffic on the 12.00-m wide deck. Issues pertaining to design and construction of this bridge are discussed. The bridge piers are hollow concrete members with a vertical taper that are cast continuously to the bridge superstructure. One of the abutments is founded on piles because of the load-carrying capacity of the fill on which it rests. Major elements in the bridge superstructure are the four pier tables, each including a pair of diaphragms to facilitate flow of forces from the superstructure into the piers. Due to their large volume of concrete the piers are composed of several single placements.

Interestingly, the whole cantilevering arrangement about the pier tables is asymmetric by the length of half a superstructure segment. This was chosen to reduce overall segment imbalance due to the alternating sequence of segment casting to only the weight of half a segment at any given time.

Two important value engineering change proposals were brought forward by the contractor and approved by the owner. First, the originally planned segment length of mostly 4.50 m was changed to generally 5.00 m to facilitate a more economical casting operation. Secondly, the order in which piers were to be erected was changed to Pier 2 - Pier 3 - Pier 4 - Pier 1. This was done to begin with the highest pier first on the solid bedrock at that location and construct Pier 1 at the sloping edge of the valley, which is more difficult to access at a later stage. In the structural calculations this change required consideration of the changes ages of the cantilever arms and their respective camber data. The consulting engineers of the contractor incorporated both



changes in their detailed structural analysis and in the shop drawings. The consulting engineers also produced the so-called Geometry Control Manual as a casting and surveying reference guide for the engineering personnel on site.

The pier tables are the starting points for cantilevering operations. A set of two form travelers is used to cast the superstructure segments. The specific casting cycle for the Wilson Creek Bridge, including use of the form travelers is explained in detail. A discussion of constructability issues concludes the chapter.

## **6.2 CONTRIBUTIONS**

This study initially arose from several reports on failures of bridge superstructures during the process of erection. Further investigation showed that several other authors have shown concern with respect to a certain gap that exists between current education for young Civil Engineers at the universities and the challenges of bridge engineering practice. Trying to bring more knowledge and experience from the engineering fieldwork into the classrooms is supposed to better prepare future engineers for their tasks.

Summarizing, the goal of this study was to provide a comprehensible discussion of the concepts used by bridge engineers to anticipate and overcome problems in planning and execution of bridge superstructure erection. This discussion led to the important topic of construction loads. It is shown how external and internal factors in their combination are considered by bridge engineers to come up with safe and economical means of building impressive bridge structures. Clear schemes were developed based on the reviewed literature and were presented to explain interrelationships of structures and the way in which they are built, i.e. construction loads and what how they are linked to construction procedures. Provision of a case study enhanced the concepts outlined in previous parts of this study and gave insight into how these concepts are applied in real engineering practice. This can ultimately lead to yet safer and economical construction of bridges to serve the public.

### **6.3 RECOMMENDATIONS**

This study has mainly dealt with the Balanced Cantilever Construction as an example of a major method for erection of bridge superstructures. Future research could include other erection methods, such as e.g. Incremental Launching and analyze these with respect to constructability issues. Providing a collection of several different construction methods, each illustrated with real-life examples would be a valuable source of information in teaching future bridge engineers. It would then also be possible to better compare advantages and disadvantages of the various methods and thus generate a more broad view of bridge engineering.

A number of notions regarding the future development of bridge construction have been pointed out in this study. Linking currently existing construction procedures with these new structural concepts would contribute to the body of knowledge in that current methods are assessed and possibly adjusted to future challenges in bridge engineering.