CHAPTER 3: THE DESIGN PROCESS OF SEGMENTAL BRIDGES

After having given an overview of the great history and heritage of bridge building, the next parts shall deal with the factors and characteristics of what engineers do and think when designing a structure. When appropriate, special reference will be given to concrete segmental bridges, whose construction is the topic of Chapter 4.

3.1 DESIGN PHILOSOPHY

Characterizing for the engineering design process is that it is highly subjective and individual. It is not a predetermined path that is laid out in any professional code, the process is rather similar to the process that artists go through when creating a new piece of art. As there are many ways in which the process can be carried out, there will also be many possible outcomes. One specific optimum solution for a project can hardly exist, as every designer will acknowledge. Designing is a complex process consisting of several steps and consideration of a great amount of information is involved. Environmental, technical, and cultural factors give the frame in which the designer performs his work of structural design. In any case, engineering is always seeking for a good compromise between these many factors.

Apart from technical knowledge a lot of creativity, which will be dealt with in Section 3.1.5.1, is necessary for successful design. Many authors have attempted to give guidelines how to achieve a successful design that is both economic and beautiful. In this context Leonhardt (1984, p30) writes very clearly that one “must not assume that the simple application of these rules will in itself lead to beautiful buildings or bridges. The designer must still possess imagination, intuition, and a sense for both form and beauty.”

3.1.1 The Nature of Engineering

Engineering is essential for the human society in that it provides the many tools, systems, and facilities that make modern human life possible. Most importantly, engineering is a social enterprise. By creating the means that are supposed to serve the people of a community and increase their standard of living it is deeply woven into the functioning of society with its manifold interrelationships. Petroski (1997, p80) cites a definition for Civil Engineering that especially tries to grasp the wide scope and ubiquitous nature of this profession:

> *"Civil Engineering is the profession in which a knowledge of the mathematical and physical sciences gained by study, experience, and practice is applied with judgement to develop ways to utilize, economically, the materials and forces of nature for the progressive well-being of humanity in creating, improving and protecting the environment, in providing facilities for community living, industry and transportation and in providing structures for the use of mankind."*

Civil Engineering achievements along with other engineering professions are based on a long history of technological developments that led to today's state-of-the-art. The history of engineering comprises many successes and some tragic failures, from both of which a great deal can be learned. Skillful and thoughtful use of nature's resources and of technical means are and will remain the key elements of engineering. This feature distinguishes engineering from other professions that focus more on understanding the very nature of our world, or create works that stimulate our intellect and senses. Yet engineering "does share traits with both art and science, for engineering is a human endeavor that is both creative and analytical" (Petroski 1992, p80).

An extended model of this relationship is given in Figure 3-1, which is adapted from a paper by Burke (1995). Engineering can be placed between the three areas of science, technology, and arts since it incorporates features from all of them. With science it shares analytical and experimental approaches to investigate and better understand material properties and structural behavior, mostly based on models of the real structure. The knowledge extracted hereof is then used on the technological side in finding a practical way of putting the structure in place by technical means and methods. As Section 3.1.3 lines out, more requirements than just pure functionality need to be fulfilled by the structure while being under construction and during its service life. An important consideration for highly visible structures as e.g. bridges is their appearance. To design a truly satisfactory bridge, the engineer needs aesthetic sensibility as an artist does, too. Creativity is of prime importance to comply with the requirements on structures and make the whole project a successful undertaking.

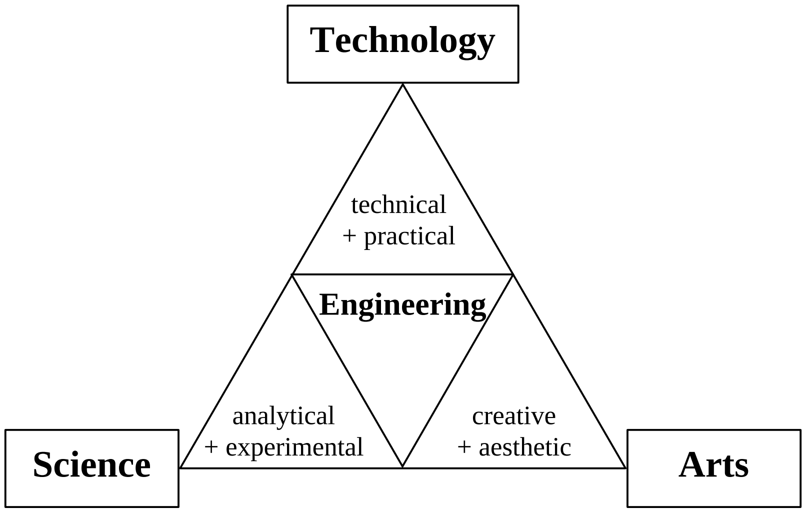

Figure 3-1: Relationship of Engineering with Science, Arts, and Technology (adapted from Burke 1995, p34)

3.1.2 Current Issues in Engineering Education

Traditionally, design philosophy is rarely taught in Civil Engineering education, since much time is taken by conveying codified technical knowledge and its rational application to the students. Professional attention has, however, already been given to the dominance of theory and mathematics in the education as Addis (1990) reports, yet still without much noticeable results. It has been clearly mentioned that the engineering education follows a different path than engineering practice; problems given to students mostly contain a given set of structural information, loads, and clearly stated problems to be solved (Petroski 1996). Much of everyday's work of the engineers, however, deals with determining these data at all, coming up with reasonable assumptions and creating models for the structure to perform analysis of its behavior.

Several other authors also show their concern on the restricted scope of today’s Civil Engineering education in universities. Burke (1995, p34) states that senior professionals “realize that the usual academic education and early professional training of most bridge engineers is restricted almost exclusively to the scientific or analytical aspects of design.” Burke (1995, p35) also expresses hope that “bridge aesthetics study, instruction, research, and eventually (…) the development of bridge aesthetics courses and design manuals” will become part of future education. Study of these issues would certainly include examples from the rich history of structural design and analyze how they are percepted in the eye of the beholder.

Apart from aesthetics in today’s design, authors have even pointed out some more basic concerns. Addis (1990, pp60-63) stresses that practical understanding, i.e. a “feeling” for materials and structural behavior is needed by structural engineers. Yet he also shows concern on the current education of engineers that seems to focus predominantly on calculation efforts in structural analysis. Basic skills, such as visualizing and clearly communicating ideas to peers, owners, and the public by means of sketches, drawings, and descriptions are extremely important for engineers. From this point of view Schlaich (1995, p60) makes the following statement:

> *“Structural engineering is a practical profession and therefore no student should be admitted without practical training, and no university curriculum should fail to include courses in sketching, drawing, and modeling. Students must be taught how to live with computers, but should use them only after getting approximate results by rule-of-thumb calculations. They also should learn how to keep good company with their future architectural colleagues. This is the best investment for quality.”*

3.1.3 Functional Requirements for Structures and Interdependencies

Functionality, safety, economy, and aesthetics are the four main goals of all engineering effort, as O’Connor (1971) expresses. Although technology has advanced considerably during the last century and provided engineers with new challenges in implementation, these four prime issues of engineering have always remained the same.

The author of this thesis added the interrelationships between these four issues and conceptualized them as shown in Figure 3-2. The required safety of the structure under all possible combinations of loads is clearly determined by codes and other regulations. Structural safety is composed of two components. These components are strength of the materials to withstand the loads imposed and overall stability of the structural system.

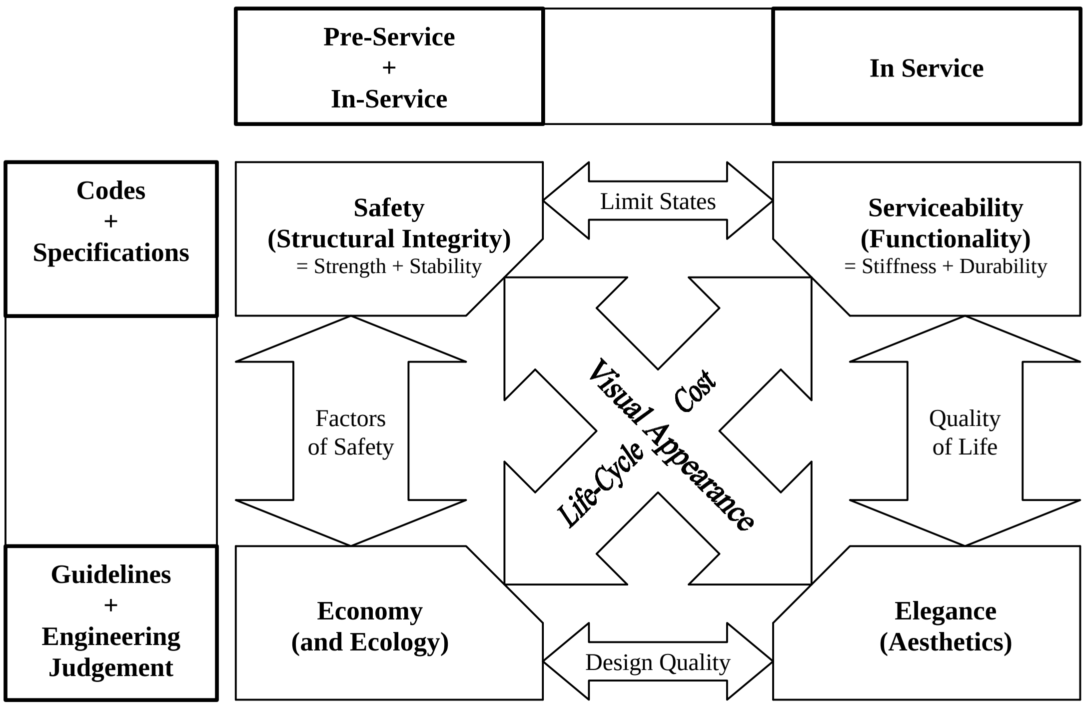

Figure 3-2: Functional Requirements and Interdependencies for Engineering Structures

On the other hand, the structure in service need not only be safe but also has to serve its function in an acceptable manner, as also determined by codes and regulations. Serviceability relates to issues such as durability of the structure against deterioration and to adequate stiffness, e.g. a bridge must not develop excessive yet structurally harmless deflections that would reduce the driving comfort. It must be wide enough for the traffic to safely pass it at an acceptable speed and should not have sudden changes in alignment.

Sufficient structural safety and also serviceability should be clearly expressed in the visual appearance of a structure to be recognized by the public as a successful design. Slight movements under dynamic loads, deflections, or other apparent weaknesses on the other hand may not decrease structural safety under service conditions, but can psychologically lead to disapproval of the structure. As sagging is detrimental to the driving comfort, bridge superstructures are usually built cambered. Codes and regulations provide information as to the so-called *Serviceability Limit State* (SLS) and the *Ultimate Limit State* (ULS). In addition to this, the structure also needs to serve its purpose in an economical way. As part of the overall life-cycle cost it should e.g. be attempted to keep maintenance cost low through careful design and construction.

Much less clearly stated in codes or regulations are the two remaining objectives; meaning both economy and ecology, and aesthetics. In the last decades, growing awareness of responsibility towards the natural environment has become more present in engineering thinking and the new field of environmental engineering is being explored. Environmental laws and technical regulations determine which measures need to be taken when constructing the project and maintaining it. For the owner building the project according to the specifications both on schedule and within budget is the prime interest, in addition to low cost for maintenance during the life-cycle.

The relationship between safety issues and cost is given by factors of safety. Increased structural safety by overdesigning the bridge members will be costly and make the whole structure seem inelegant. Finding the acceptable level of safety at an appropriate cost is the task of the engineer and expresses the quality of the design. The appearance of bridges is the topic of Section 3.3, where some guidelines and opinions on aesthetics are given. Bridges contribute to the society’s quality of living by serving their function in an elegant and delightful way. Overall, an impression of the ‘quality’ of the design may be gained by examining how the structure accounts for both economical and ecological, as well as for aesthetic considerations.

3.1.4 Design against Failure

Since Civil Engineering is a human undertaking, mistakes can and do occur. Liebenberg (1992, p99) gives a list of what he calls gross errors that can directly affect structural safety:

- *"1. A conceptual misunderstanding of one or more aspects of structural function on the part of the designer or analyst.*
- *2. The use of incorrect assumptions as the basis for the design.*
- *3. Gross computational errors.*
- *4. A breakdown in communications (brief, specifications, drawings, instructions).*
- *5. Undetected flaws in materials and serious omissions or errors in the execution of the work (workmanship)."*

Designing a structure deals with the fundamental issue of achieving all requirements that have been set for it. Success in Civil Engineering can be measured as how closely these requirements are met. In other words, engineering success is correctly foreseeing and avoiding failure of structures. Total or partial structural collapse as mentioned above is the most well-known *mode of failure*. Yet failure in a more broad sense as used by Addis (1990) means that any of a set of previously stated objectives has not been met accordingly. Types of failures thus include, with respect to the aforementioned four primary goals of engineering, structural failures of various degrees, functional failures, failure to meet aesthetic expectations, and failure to meet economical prospects for all phases of the project life-cycle. Economical considerations during the life-cycle are e.g., cost of design efforts, budget and project duration scheduled for construction, and little maintenance cost during the service life.

In order to be on the safe side, safety concepts have been introduced into the design process. The so-called *factor of safety* is the centerpoint of these; it is dealt with in Section 3.5.2. Apart from human causes for failures during design, construction and service life, e.g. collision accidents, there can be Acts of God, such as earthquakes, floods, and storms that strike with unexpected severity. All these external influences need to be taken into consideration to design a sound structure. It can be easily imagined how difficult prediction and codification of these events in practice is. In many cases, historical data is used, e.g. designing for the worst recorded event over a period of about 100 years. Further complexity is introduced when the natural deterioration and time-dependent material behavior such as creep, shrinkage, and relaxation is considered. Load-dependent behavior is captured under the heading of fatigue, depending on the intensity, range, and frequency of imposed load cycles. Information from the applicable codes and sound engineering judgement at which stage and where failures may occur are required to implement sufficient safety.

3.1.5 The Design Process

Designing a structure is a comprehensive engineering process that spans from the very first compilation of information on the project and making the first drafts to the final preparation of shop drawings, schedules and other documents. The following sections take a closer look particularly at the steps of the first phases in the design process that are undertaken prior to generating detailed analytical calculations.

3.1.5.1 Creativity at Work

In the introduction to Section 3.1 basic traits of the design process have been mentioned, including creativity. Creativity, one of the basic requirements for the design process, shall be defined as the skill of coming up with innovative ideas for a problem based on both existing and new concepts.

Facing a difficult problem people often experience a kind of blank paper syndrome that hinders innovative work, as Petroski (1997) has noted. Once the first thoughts have been put on paper, however, it may be felt that the flow of thought will be much better. A variety of counseling literature can be found on how to overcome blockades in thinking and how to deal with problems in a creative and elegant way. They introduce special creativity techniques, e.g. the well-known brainstorming technique (Fogler and LeBlanc 1995), stressing that a stimulating atmosphere helps generating fruitful ideas. Breaking down problems into substeps will make difficult undertakings become clearer and simple to accomplish.

It is possible to stimulate the creative process in engineering through active reading of professional journals, communications with peers and similar activities. Keeping up to date with current construction projects of interest can give valuable information and helps further fostering the own creativity.

3.1.5.2 Conceptual Design

The initial phase of the design process is commonly referred to as the *conceptual design phase*. In this phase the engineer becomes familiar with the overall picture of the project and gets an impression of the required functions and imposed limitations. Sources contributing to this process are of various natures; they comprise e.g. maps and existing plans, surveying data, codes and regulations, and many more. More of these factors are discussed in Section 3.4. Moreover, throughout his career the engineer will accumulate experience in addition to the knowledge gained from studying, which will also contribute to the quality of his proposals. Melaragno (1990, p215) very fittingly speaks of a “kaleidoscope” of design ideas that exists in the designer’s mind at the beginning of working on a new project. With the information reviewed and readily available, the first sketches will be put down, using the classical instruments of the engineer, pencil and paper (Melaragno 1990). Engineers will also use Computer Aided Design and Drafting (CADD) software in following steps of the design as a comfortable and versatile tool to implement and study various designs. Simple back-of-the-envelope calculations, with which Petroski (1997) deals from a historic perspective, are used to determine the overall feasibility of a concept. Alternatives will be evaluated by means of cost estimates for material use and complexity and duration of erection works, and by elaboration on the performance of the structure in service. Documentation of the material produced and the rationale that leads to design decisions is advisable. Further in the process the underlying concept is refined, yet it will not be drastically changed anymore. Improvements to existing plans should be implemented as early as possible and be critically reflected on. The importance of these first simple drafts should not be underestimated, because the basic outline of the whole design is already determined in them. Schlaich (1995, p60) stresses the importance of the phase of conceptual design, which in his opinion “is also the most creative phase that comprises the joy of engineering.” He also observes that many costly problems that occur during construction and under service of bridges could be avoided if enough care was put in the initial phases of design (Schlaich 1995, pp54f):

> *“To an observer of the scene of structural engineering, it must be surprising how little time is usually spent on the initial phase of the design of a structure. Later phases only carry out what was initially conceived during the conceptual design. Later on, engineers proudly report of their immense mental input and computational efforts to grasp the exact forces at singular loads by refining the FEM mesh, to develop a most intricate reinforcement layout at a complicated joint, or to find the special concrete mix including superplasticizers to ensure that it will penetrate an extremely dense reinforcement cage. Looking closer at such “problems” and their sophisticated solutions, one will in most cases find their origin in a negligent conceptual design.”*

3.1.5.3 Analysis and Dimensioning

Based on a profound understanding of structural behavior, the structure will then be analyzed. Attention needs to be given to both overall system and also to structural details, such as expansion joints, hinges, and bearings. The structure will evolve to its final form by optimization of its structural members. This dimensioning process attempts to minimize the use of material while keeping the maximum stresses in the respective member well within the limitations given by allowable values from the codes. For the largely iterative process between size of members and the stresses and deformations within the structure the use of computer software is very valuable.

3.1.5.4 Design Process According to Leonhardt

Most vivid a description of the design process has been provided by Leonhardt (1984) in his book “Bridges: Aesthetics and Design”. A summary of his key thoughts as to how the initial idea evolves to a complete set of plans, specifications, detailed descriptions, estimates, and schedules will be given in the following paragraphs.

Leonhardt (1984) considers it necessary to have comprehensive information on the nature of the project and its boundary conditions in addition to skills, experience, and knowledge of the engineer himself. He urges the designer to perform a site visit to get a personal impression of the setting of the future bridge. Coming up with an initial idea, rough sketches of the bridge that capture the anticipated elevation are made first. Important features of proportioning and composition, such as span length and position of piers and abutments, shape and depth of the superstructure will become clearer in these sketches. Leonhardt continues his description with a phase of revision and criticism of these drafts in which the proportions of the structural elements can be improved. Doing more detailed sketching the superstructure cross-section and the pier shape can be drafted next. Since the bridge needs to be evaluated in its overall three-dimensional appearance, some sketches looking at the structure from different angles will greatly facilitate the impression. An important source of information that Leonhardt mentions is the professional criticism of peers. At this stage thoughts on a feasible construction method become necessary.

Refining the form of substructure and superstructure will be the next task in the design process, once the overall concept has been fixed. Substructure and superstructure members will become more detailed when producing larger drawings of them, making reasonable assumptions on the thicknesses of concrete members to provide sufficient space for reinforcement and prestressing tendons. Alternative solutions for the structural system can then be compared and evaluated. Leonhardt (1984) calls this revision stage ‘meditating on the concept’, checking that it fulfills all requirements and gives an aesthetic solution. Only when this stage, which may include more input from peers, has been accomplished, drawing detailed plans and calculating should start.

It may be added at this point that some simple so-called back-of-the-envelope calculations will already have been done earlier to support the feasibility and rough dimensioning of the planned structure. Approximations of the member dimensions and steel amounts required should be done first; later on more detailed calculations with the help of computer programs will be done. Optimization for economy is achieved with relative ease through varying single dimensions in the computer input and comparing the results. Still, Leonhardt again notes that purely economic considerations may not necessarily lead to aesthetic structures.

After having accomplished the aforementioned steps, design drawings will be produced, showing all relevant details and dimensions. Leonhardt does not specifically mention preparation of a schedule draft and a cost estimate for construction, but it can be assumed that he included these issues in the preparation of documents to be submitted for approval. Upon approval by the client and probably involvement of the public, more detailed work that takes a considerable time will be done. Comprehensive analytical calculations for all anticipated influences need to be performed. Sets of final drawings, descriptions, and specifications will be produced to prepare the project execution. Additional preparation includes the layout of temporary facilities, such as formwork, scaffolding, and necessary equipment.

3.2 CONSTRUCTION PROJECT CHARACTERISTICS

Projects are unique undertakings with certain characteristics. They are created to achieve a certain goal, e.g. manufacturing a product, and they have a defined framework of resources that are utilized to achieve the goal. Resources, as will be discussed in Section 3.2.2, can be of both concrete and immaterial nature. Apart from physical materials that are either used in the product itself or support its construction, resources such as time, space, money, and controlling need to be present for a successful project outcome.

Projects in the construction industry are unique in that in most of all cases they only have one product, i.e. the new structure as an outcome and not a large batch of similar products as in the manufacturing industry. To generate the structure, however, much planning and construction effort is necessary. On a time scale, construction projects go through several different phases, the so-called life-cycle. The project life-cycle will be explained in the following Section 3.2.1.

3.2.1 Project Life-Cycle

A closer look at the time scale shows that any construction project typically goes through several phases to produce the structure. Structures mostly have an anticipated duration of service for which they are designed. During this duration they are supposed to serve their purpose in a safe manner. The following main phases can be identified for a construction project. They are conceptualization, design, construction, and utilization.

During the conceptualization phase the owner, e.g. a Department of Transportation establishes need of the structure, e.g. a bridge, and contemplates the feasibility of his ideas. The owner also determines a time and cost frame for the project and documents these issues.

The owner's wishes, put down in descriptions and specifications are then used by the structural engineers in the conceptual design phase. Codes and regulations also need to be considered, providing information on e.g. load factors for bridge superstructures, minimum amount of reinforcement, and the like. The construction phase is planned during the design process and documented in shop drawings for all parts of the new structure, schedules, and descriptions.

Construction work on site will then proceed. Ideally, the construction will closely follow the anticipated sequence. Due to uncertainties in factors such as soil conditions, weather conditions, subcontractors meeting deadlines, and many more it is possible that changes might become necessary during the construction process. The resources that are involved in the construction phase of the project are discussed in the following Section 3.2.2.

Completion of the structure does not mark the end of the overall project life-cycle. After acceptance of the structure by the owner, it is put into service, the so-called start-up. To keep a bridge structure on an acceptable level of service a maintenance scheme is usually set up that includes regular inspections to determine need for upgrading. When the structure finally deteriorates to an extent where repairs or rehabilitation are not economical anymore, demolition and replacement mark the end of its life-cycle.

Engineering embraces the whole project life-cycle from the very first conceptualization in the design process to more detailing, calculating, the whole construction process, and finally use, maintenance, and demolition of the structure. This comprehensiveness nature can be the source of deep satisfaction for the engineer.

3.2.2 Resource Utilization

When doing the planning for carrying out a construction project it will become necessary to allocate the proper resources to the schedule. Their availability can be an important limiting factor in coming up with duration data for erection of the bridge foundations, the substructure and superstructure, and finishing work. When developing the schedule these work tasks and their interrelationships need to be anticipated. In the beginning and finishing phases of the project different types and amounts of resources will be needed than during ongoing regular construction work. Accounting for these developments during project execution will save money and effort.

Resources in this context do not only denote material items, but rather a compound of these and managerial items. Resources comprise construction materials of all kinds and laborers of different trades. Concerning materials it should be noted that they are used in two ways in construction. They form structural members and are secondly needed to construct non-structural facilities, e.g. temporary railings, scaffolding, and similar items. Moreover, pieces of equipment, such as formwork and scaffolding as well as small tools and machinery (e.g. hydraulic jacks for post-tensioning elements of segmental bridges) are necessary. On a larger scale, heavy construction equipment will be needed to work on foundations, such as excavators and drills, and for the substructure and superstructure, e.g. haulers to move earth and supply concrete and steel, and cranes and concrete pumps to bring material in place.

In order to coordinate all these construction efforts, planning and supervision is of prime importance to keep within time frame and budget. Progress in meeting deadlines needs to be measured with the real amount of work accomplished. Time and money spent on project execution only give hints on the actual project status. Quality control needs to be incorporated in these supervision efforts to ensure that all specifications are met.

It is a good comparison to think of a construction site as a mobile temporary plant, erected and powered to produce the bridge. From this it can be further derived that the third abstract dimension of project resources in addition to time and money is workspace. Site layout needs to provide easy access to the site and enough space for storage and moving of heavy equipment. Finally, construction sites require certain infrastructure installations, such as water supply, waste and wastewater removal facilities, electricity, telecommunication, office space, and rest facilities. Sometimes items such as compressed air, gas, heating and cooling devices will be needed for special means and methods of construction.

3.2.2.1 Economy

Much concern in engineering is given to achieving economical solutions. As already outlined in Section 3.1.3 engineering structures bear a certain amount of safety, i.e. overdesign to accommodate for uncertainties of all kinds. In a competitive market environment two issues are always acting contrarily – striving for reliably safe structures and the wish of building cheaper structures to generate higher profit. It is the engineer’s task to find a good balance between these two potentially conflicting wishes.

Cost savings can be achieved by several means, such as optimization of material use in the structure; partial prefabrication if cost for the precasting yard, transportation, and placement of the elements are less than cost for cast-in-place facilities on site; and schedule optimization with respect to labor allocation.

From this point of view, using concrete segmental bridges offers several advantages. Choice of prefabrication, cast-in-place fabrication of the segments, or even a combination of these techniques offer possibility for optimization of the erection procedure. As will be discussed in Section 3.7, segmental bridges with box girder superstructures have much flexibility in shape, span arrangement and alignment, making them competitive over a wide range of lengths and curvatures. Today’s variety of construction methods is described in Section 4.2. It allows matching the construction process exactly with site limitations.

Use of local materials in bridge construction for earthwork, concrete aggregates, and perhaps stone masonry contributes both to aesthetics (see Section 3.2.5) and cost cutting of the bridge project, as long distances of transportation are avoided.

3.2.2.2 Ecology

In view of limited natural resources, responsible use of these has become more and more important in engineering. The whole construction process should ideally be carried out with attention to its impact on the natural environment and on neighboring dwellings. Keeping workspace at a minimum and avoiding noise emission and pollution as required by law contribute to preservation of the natural environment for future generations. Waste and sewage disposal needs to be considered. On modern construction sites recycling systems for solid waste and wastewater have been introduced. Choice of less harmful materials reflects this increased awareness, as illustrated by asbestos removal in many buildings and replacement of lead-based paint for corrosion protection of steel structures with other substances. Larger projects usually implement environmental impact studies.

3.2.2.3 The Linn Cove Viaduct

By way of constructing bridges with the cantilevering method it is possible to minimize disturbance of the nature at the site. An interesting example is provided by Anon. (1984), reporting of the construction of Linn Cove Viaduct in North Carolina. This viaduct is located in a scenic mountainous yet very inaccessible landscape. The solution to these restrictive site conditions was use of the progressive placement method that allowed reduction of impact on the site to a minimum. More information on this method and the example will be given in Section 4.2.1.5.

3.3 AESTHETICS AND ENGINEERING

Seeing a bridge can create a variety of reactions in observers. The initial glance might create awe for its grandeur and the elegance with which it spans its way – or the impression might be the complete opposite, producing negative sensations which lead to perception of the bridge as 'ugly' and not fitting to its surroundings. Obviously, "aesthetics, as an art, cannot objectively be quantified or subjected to fixed rules. Aesthetic evaluation is an individual and subjective act, affecting each of us individually" (Maestro et al. 1995, p39).

Leonhardt (1984, p12) defines aesthetics as "the science or study of the qualities of beauty of an object, and of their perception through our senses." Hence, an aesthetic object, as Leonhardt derives, does incorporate some aesthetic values, which he calls qualities of beauty, in one way or the other. He points out that 'aesthetic' thus does not necessarily mean that the object observed is beautiful. Beauty cannot be captured in purely numerical rules, since it is subjective interpretation of the perception that makes people consider an object beautiful or not.

In the following paragraphs generic principles that are considered useful in designing aesthetically pleasing structures shall therefore be presented without attempting to limit the artistic freedom in any way. It is the engineer's challenge to design structures that overcome short-lived considerations and become timeless manifestations of engineering achievement.

3.3.1 Aesthetic Values

All bridges, regardless of their size, influence their natural and man-made environment through their very appearance in shape, color, and other aspects. The impact of a bridge on its surroundings needs to be considered carefully by the responsible engineer, keeping in mind that "aesthetics is an integral part of the design and not a frivolous and nonfunctional adornment" (Garcia 1995, p49). The attitude that building in a very economical way is not necessarily opposed by the wish to achieve high aesthetic quality still needs to be conveyed to owners and even to the engineers themselves. Putting emphasis and effort especially into the conceptual design phase can even help saving cost. Whereas larger bridges with their longer design period and bigger budget more easily facilitate aesthetic considerations during the design phase, the biggest number of bridges is of smaller scale. They are ubiquitous in the transportation system and therefore their quality should be given special attention. Melaragno (1998, p237), as already mentioned in Section 2.2.3, calls this phenomenon the “silent majority” of bridges.

German bridge engineer Schlaich (1995) puts much emphasis of the quality aspect of today’s bridges. He uses the term quality generically in that it “can be considered as perfect manufacture, construction, safety, and durability at minimum cost. At least equally important, quality also can be aesthetics, that implies compatibility with the environment including the right scale, least consumption of natural resources, reusability, and others” (Schlaich 1995, p58). Pointing especially at the many small-scale bridges, Schlaich expresses his concerns with today’s monotony in bridge design. In highway bridges many prefabricated standardized parts, e.g. prestressed standard beams are used to save cost. Garcia explains this situation as follows. “Standardization is more evident on smaller concrete bridges because special forms and shapes cannot be amortized on the project” (Garcia 1995 p52). In accordance with the previous statements it clearly becomes the structural engineer’s challenge to find aesthetically pleasing solutions even for such industrialized projects.

In conclusion, it can be said that aesthetics are of prime importance in bridges of whatever size and location as they are contributing to the standard of living of their respective communities.

3.3.2 Character and Function

In many cases of novel engineering structures the initial public reaction was far away from enthusiastic. An example certainly known is the Eiffel Tower in Paris, built from 1887 to 1889 for the Universal Exposition. Commentaries in the media disregarded the presumably monstrous tower as an “offense to French good taste” (Petroski 1997, p172). Yet it took only a short time for the tower to become an enormous success with over two million visitors during the exhibition, and by today it is the most famous landmark of Paris.

The character of a structures generally speaking denotes its unique appearance, the shape, size, and color, and what impression it coveys to spectators. Character is closely related to the primary function of bridges, namely of bridging natural or artificial obstacles within the transportation systems. If the composition of the bridge combines expression of functionality with its own identity it will be considered a successful undertaking. The superstructure and substructure need to show structural consistency in that they correspond with the construction material and clearly express the natural flow of forces in the structural system. Deviation from this simplicity in the main structural system by incorporating different types of superstructures usually is not beneficial, since the "mixture of structure types and span arrangements will be aesthetically horrendous", as Garcia (1995, p52) states. "The form of the bridge will have to be the most logical one, that one which in the simplest, clearest, and most economical way responds to its intended function, to the building materials, and to the construction methods", Maestro et al. (1995, p39) explicitly demand.

Where the structural system is simple, as e.g. in cable-stayed bridges, structural clearness is easily achieved. Box girder bridges usually convey a very clear picture of their structural function as beams; they can be haunched along their span, i.e. be of variable depth, and visibly cambered to acquire an elegant arch-like appearance. Other examples for clear structural systems can be found e.g. in concrete arches with decks supported on columns.

3.3.3 Proportions and Harmony

Proportions are relationships between the geometric measure of objects, such as the lengths, surface areas, and volumes of structural elements. Matching the apparent masses of bridge elements through careful proportioning is one of the oldest principles of aesthetic designing. Leonhardt (1984, p27) writes that in "a bridge, for instance, these relationships may be between the suspended superstructure and the supporting columns, between the depth and the span of the beam, or between the height, length, and width of the openings. Harmony is also achieved by the repetition of the same proportions in the entire structure or in its various parts."

A great deal of literature exists on this topic, beginning with ancient builders such as Vitruvius, and continuing with Palladio and other authors. Geometrical relationships in natural objects, e.g. in blossoms of flowers and even in Man himself were studied and determined to follow certain rules. Vitruvius gives a whole chapter dealing with symmetry and proportions of the human body. A well-known principle is the Golden Mean, which can be obtained by dividing a distance into two parts in such a manner that the proportion of the shorter *b* to the longer part *a* equals the proportion of the longer part *a* to the whole *a*+*b*. The Golden Mean is expressed in the following (Leonhardt 1984, p19):

$$\frac{b}{a} = \frac{a}{a+b}$$ **Equation 3-1**

which has the solution

$$a = \frac{\sqrt{5}+1}{2} b = 1.6180339887... \cdot b$$ **Equation 3-2**

Proportions played an important role in architecture of earlier times, e.g. temples and, in Christian times, cathedrals and other awe-inspiring buildings. Many proportions that have been used for these buildings are simple fractions, giving harmony and scale between the elements and the whole structure. Another area where principles of harmony are used is music.

Harmonic considerations also play a role in integration of the structure into its setting. In the eye of the beholder, strictly "parallel lines appear stiff and static, producing uncomfortable optical illusions" (Leonhardt 1984, p28), whereas e.g. a taper in the vertical axis makes bridge piers appear more graceful. 'Recipes' for designing well-proportioned tapered columns can again already be found in Vitruvius' (Morgan 1960) and Palladio's (Palladio 1570) works. Tapered design of load-carrying elements logically follows from the flow of forces, since the bottom part of supports has to carry the most weight. Other of Leonhardt's considerations deal with decreasing span length closer towards the edges of the valley and cambering horizontal superstructures to avoid the illusion of sagging. Overall slenderness of bridge beams and piers is usually considered advantageous for lightness of the visual appearance.

3.3.4 Complexity and Order

Importance of a clear structural system has already been pointed out in Section 3.3.2. This should, however, not lead to the impression that the simplest of all bridge designs will please the most. Interest arises mainly because of contrasts and accents set in the bridge. In bridges of former centuries one often finds ornamentation with pilasters and capitals, statues, lanterns, profiled articulated balustrades and protruding piers to enhance the visual impression. While these kinds of decoration are usually not found in today's bridges anymore, important lessons can be drawn from the careful application of these details. They evoke interest in the observer and serve to refine the clear appearance of the bridge in overall view of the site. In Section 3.3.3 the principle of tapering piers has already been introduced. In fact, a great number of all kinds of bridge piers can be found which carry the idea of architectural shaping further. Slight additional edges, small cutouts or inlets of other materials in the surface deviate from a purely rectangular cross section and create interest.

The order of a structure is expressed in regularly appearing patterns in structural members with their respective proportions. Introducing rhythm and symmetry in number and arrangement of structural members can be pleasing to a certain degree, but as Leonhardt (1984) writes, this should not lead to overall monotony through endless repetition. To avoid confusion and displeasure, he also gives advice to limit the number of spatial directions into which the lines and edges of the structure run. He also cautions to consider the three-dimensional appearance of substructure and superstructure. "We must also check the appearance of the design from all possible vantage points of the future observer. Often the pure elevation on the drawing board is entirely satisfactory, but in skew angle views unpleasant overlappings are found. We must also consider the effects of light and shadow" (Leonhardt 1984, p28).

3.3.5 Color and Texture

Coloring is paid much attention to by the visual arts. In entertainment and advertising colors contribute much to the image that ought to be conveyed to the audience. Although structures work in a completely different setting, they nevertheless attract people's attention. The Golden Gate Bridge in San Francisco, built from 1933 to 1937, spanning the bay with unique elegance, is much cited as an example of how a bridge can enhance its setting. Brown (1993, p105) gives a pronounced statement in his comprehensive work on bridges when he calls the red bridge spanning the San Francisco Bay "the world's largest Art Deco sculpture." Choosing a specific color strongly influences the impression that an object makes. Red usually symbolizes alert and attention, green and brown colors are related to quiet nature, yellow can stand for happiness, and blue can symbolize freshness, energy, and flow. Much literature exists on color psychology and how colors should be chosen to achieve harmony. Architects and interior designers will deliberately use colors to control the effect of objects and to create emotions. Coloring bridges helps integrating a bridge into its natural environment, e.g. through use of soft natural coloring, or it can be specially accented as a technical object through plain, intense colors and distinctive lines. In some cases bridge substructures have a distinctively darker color than the superstructure that they carry, which thus appears lighter. This effect will not only be achieved by artificial coloring, but also by the natural sun lighting at the site. Light and shadow are factors to be considered, as they create the final visual impression of the bridge shape. Barker and Puckett (1997) stress the effect of light and shadow with respect to the shape of the bridge beam. As the shape of the superstructure evolves toward a box girder with large cantilevers and perhaps even inclined webs, the visual impression of its depth will be reduced. Shadow in this case diminishes the lower parts of the bridge optically and makes the thin fascia band of the superstructure become more pronounced.

Introducing texture means adding scale to the bridge surface. It is possible to use stone cladding or inlets in members to add some distinction to the bridge and make it match better with its environment. Good integration can especially be achieved by choice of local materials and architectural styles.

The Wilson Creek Bridge in Virginia, also called “Smart Bridge” after the research site on which it is located, is presented in Chapter 5. It incorporates vertical inlets of natural stone in all faces of the piers. This so-called Hokie Stone from a local quarry adds interesting details to the high tapered piers and creates a visual connection with the typical architecture on campus of nearby Virginia Polytechnic Institute and State University. Apart from use of natural stone the piers also show architectural shaping at the pier table. The lines of the tapering vertical pier edges are carried across about half the height of the pier table while the box girder tapers in the other direction. Thus the smooth horizontal lines of the long overall superstructure girder are separated into the smaller lengths of the spans. A photograph of the pier table design of the Wilson Creek Bridge is shown in Figure 3-3.

Figure 3-3: Pier and Pier Table Design of the Wilson Creek Bridge

Texturing of bridges is very much dependent on the materials of which they are built. The two main materials for bridge superstructures, concrete and steel, come with very different characteristics with respect to texture. A description of possibilities of how to treat concrete surfaces to enhance their visual impression is given by Leonhardt (1984). He points out that using textured formwork panels less suitable for bridges. However, methods such as bush hammering in various techniques and depths as well as exposed aggregate can have an enhancing effect. These techniques of removing some of the concrete surface by means of tools require extra thickness of the cover to sufficiently protect the reinforcement embedded within against corrosion. Leonhardt is aware that the aforementioned methods may result in increased cost for finishing works, so that careful planning and consultation with the owners is necessary. Exposed concrete surfaces, when crafted carefully can remain untreated or can also be colored artificially. In addition to its normal grayish appearance, which varies with the choice of ingredients for the concrete design mixture, concrete can be colored with a variety of natural and artificial pigments that are added. Examples of colored concrete are shown in Figure 3-4.

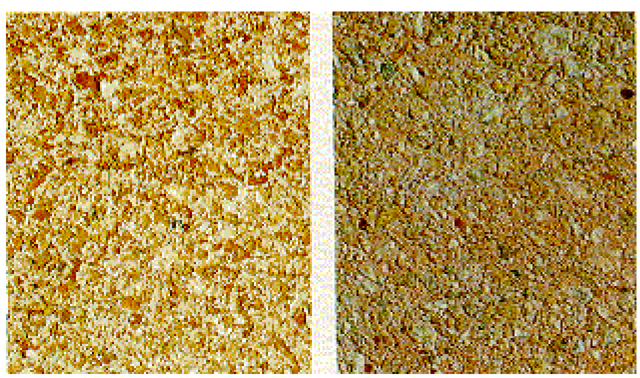

Figure 3-4: Examples of Colored Concrete (taken from Leonhardt 1984, p65)

Strongly textured rough surfaces will give the member a more rustic and solid appearance; smooth surfaces are more suitable for slender columns and beams, as Leonhardt (1984) writes. When precast segments are chosen the aforementioned techniques of texturing and coloring can be applied more easily due to the controlled environment in the plant. Surface finishing of the concrete, such as sandblasting and other texturing, coating, impregnating, and coloring will contribute both to appearance and durability of the bridge.

Steel, on the other hand, will be protectively coated with layers of paint to prevent corrosion, often using reddish or blue paints. Less than the material itself, the shape of the plates, girders, hangers, and trusswork of which steel bridges are composed will first and foremost influence the appearance of these bridges. Rivets and bolts or welding seams in more modern bridges serve to connect elements and structure the surface of steel members. External ribs and bracing, e.g. for steel box girders give the bridge superstructure a regular pattern and provide order in the horizontal and vertical lines.

3.3.6 Environmental Scale

Bridges never exist secluded from their environment; they become an integral part of it and hopefully contribute to its beauty. Natural landscapes all have a certain scale to them. Narrow valleys and wide bays, deep gorges and shallow streams all accommodate different kinds of bridges best. Long lines full of grace e.g. better fit to a wide, large-scale site, small curves more to a location full of tiny details. The specific scale of the structure should be matched with the scale of nature. Artificial landscaping in conclusion of the construction efforts will help integrating the bridge into its new setting. Both construction methods and their product need to take care of the sensitive natural environment. More information on environmental issues is given in Section 3.2.2.2.

3.4 FACTORS INFLUENCING DESIGN AND CONSTRUCTION

A wide range of data has to be compiled and considered in the design effort. These pieces of information can come from many different areas. They can deal with the site and its specific physical conditions and with the surroundings of the site. More abstract considerations, such as requirements of subcontractors and local communities need to be paid attention to when planning and executing construction work. The particular erection method chosen will require a certain sequence and will impose some technical limitations, e.g. as to the size and weight of superstructure segments. In the following sections all factors have been separated into four main categories. A diagram showing all these factors and giving examples is provided in Figure 3-5.

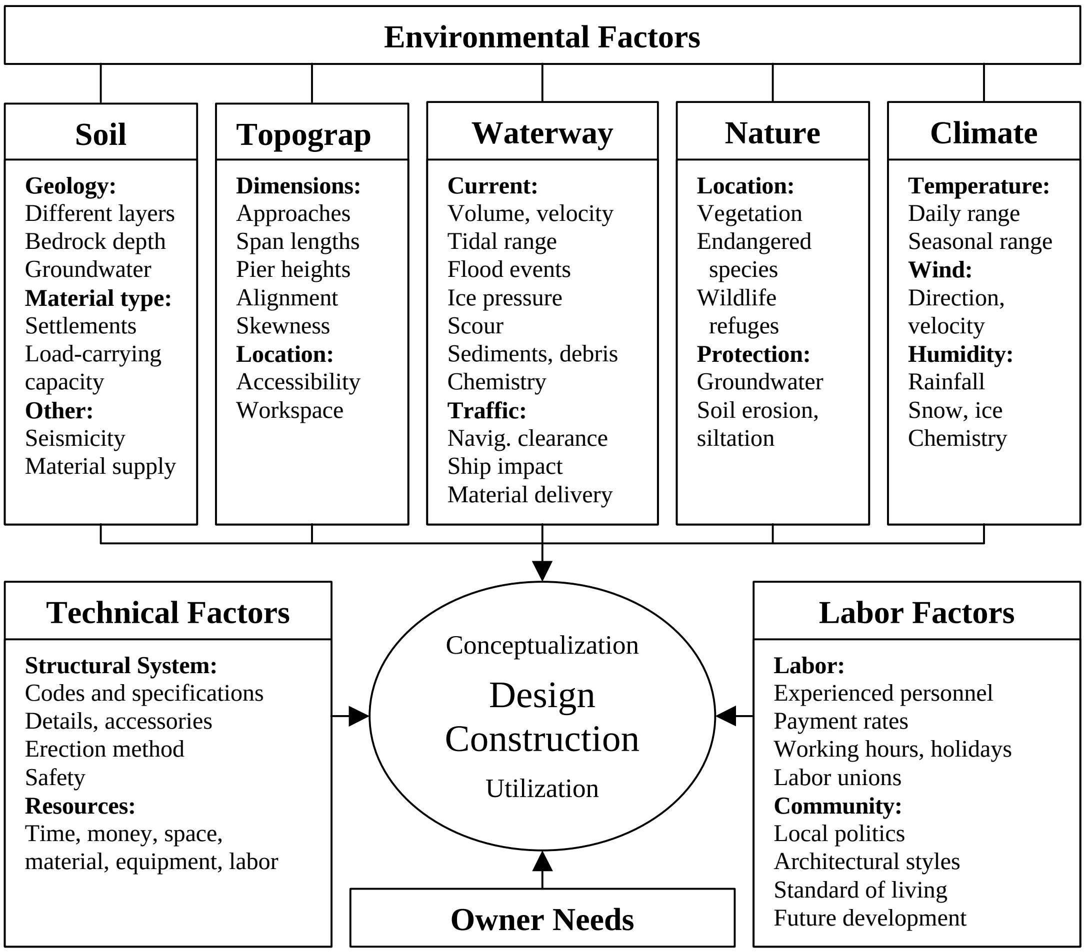

Figure 3-5: Factors Influencing Design and Construction

3.4.1 Environmental Factors

Most importantly, the site itself will influence the outcome of the design process. Many different parameters of the site will have to be acquired, recorded, and considered to properly design bridge foundations, substructure, superstructure, and approaches.

3.4.1.1 Soil Conditions

Soil conditions are determined by means of geological and hydrological maps and field investigations. The type of soil materials, thickness of layers, the level of groundwater, and the chemical and mechanical properties are needed data. With these information the load-carrying capacity of the soil, earth pressure on foundations, and the expected settlement of foundations can be calculated. Foundations and substructure need to be designed accordingly, using either flat foundations that rest on sufficiently load-bearing bedrock or using deeper pile foundations. Seismicity is another factor to be considered in certain areas. Local supplies of suitable rock and soil may be used in construction to save cost and blend with local architectural styles.

3.4.1.2 Topography

Main dimensions of the bridge, such as span length, pier height, and necessary approaches to the main spans depend on the topography of the site. Roadway alignment should ideally remain unchanged at the bridge and its approaches for reasons of driving comfort and safety. In addition to this, whenever possible the bridge should be located where the waters are narrow and should cross at an angle close to 90°, as Troitsky (1994) advises. Otherwise, longer skewed bridge spans may become necessary, making construction more difficult and leading to higher cost. Aesthetics of such a bridge, e.g. pier positioning will also require more work to achieve a satisfying result. With respect to the construction itself the topography determines accessibility of the site and how much workspace for heavy machinery exists.

3.4.1.3 River Crossing

In case the waterways are fitting, provision of larger amounts of material and prefabricated elements can be done by use of barges, which can also accommodate lifting devices, e.g. to place precast elements of a segmental bridge. Ship traffic sets limitations for both construction work and the finished bridge in that it requires navigation clearances and widths that cannot be obstructed. For this reason, cantilevering of the bridge spans is often a very viable method of construction. The special load case of ship impact on the bridge structure also needs to be considered to ensure stability of superstructure and substructure even in this catastrophic case.

The nature of the waters to be crossed determines design of foundations and substructure. They need to be strong enough to resist the varying flow of water, including the impacts of high tides, flood events, and ice. Scour, abrasion of the foundations through debris, and the amount of sediments carried with the current need to be taken in account so that that the stability of the bridge will not be affected. Deep foundations and banks of riprap at the piers are some measures that help alleviating this hazard.

3.4.1.4 Protection of the Environment

The closer surroundings of the bridge site can require special protection during construction if e.g. sensitive vegetation, wildlife refuges for endangered species or groundwater protection areas are present. Erosion and siltation protection is usually required during the construction process.

3.4.1.5 Climate

Local climatic conditions need to be researched, especially to get data of temperature levels and temperature ranges daily and over the year, rainfall and snowfall or ice, and winds with their primary directions and speeds. Heavy storms have been the cause some of the most prominent structural failures in the history of bridge engineering, such as the Tay Bridge in 1879 and the Tacoma Narrows Bridge in 1940, which are presented in Sections 2.1.4.8 and 2.1.5.6. Extremely adverse natural events, such as tornadoes and earthquakes may additionally have to be dealt with.

In addition to these factors, the ambient chemistry of the environment and the waterway will play a role for the durability of materials. Concrete and steel can be affected through aggressive industrial emissions and salts from deicing detergents and seawater. The shape of the superstructure determines the exposed surface areas that can be affected by these chemicals. In comparison with other types of load-carrying members, such as T-girders supporting the deck and coffered slabs, the application of closed cross-sections offers the advantage of having less surface area that can be affected.

3.4.2 Technical Factors

Technical considerations for bridge construction primarily deal with design of members and their materials and methods of putting them into place in a safe manner. Economical limits are set by the financial and time frame under which the whole bridge project shall be carried out. The available workspace and the labor force also influence project execution. Codes and regulations, specifications, safety regulations of the Occupational Safety and Health Administration (OSHA), which is overseen by the U.S. Department of Labor, union labor regulations, and other sources provide information for design and construction efforts.

3.4.2.1 Structural Type and Erection Method

The structural type of the bridge will have strong implications on the choice of a feasible erection method for a particular project. Depending on the erection method and site restraints the structural engineer develops a detailed erection sequence and allocates necessary equipment. Depending on the bridge location, availability of construction materials and heavy equipment from local suppliers will have to be investigated. Larger contractors will often employ construction equipment from their own fleet.

As mentioned earlier, cable-stayed bridges can be erected best with the cantilevering method. More erection techniques for segmental bridges, specifically concrete box girders, will be discussed in Section 4.2. Afterwards, dealing with the construction loads introduced by the erection technique will be examined closer in Section 4.3.

3.4.2.2 Construction Details

The various Departments of Transportation mostly have standardized details for bridges, such as drainage gutters and pipes, drip noses, curbs, parapets, sidewalks, railings, lighting, and information systems. Apart from information on standard bridge furniture, also called accessories, the Departments of Transportation also provide specifications for e.g. piers and abutments and for the materials for pavement layers, the wearing surface, slope protection, and other elements of the structure (VDOT 1997c).

Special attention is required for the two structural details expansion joints and bearings. They need to be designed so that they can easily be inspected and replaced if necessary. Specialized certified manufacturers supply the aforementioned details. Durability for a long service life is an important goal to be met. Reduced corrosion and ease of repair can be accomplished through e.g. high quality of materials and their finishing and design of modular elements that can be replaced one by one.

3.4.3 Labor Factors

Not only when a construction company is working on projects in foreign countries the local culture needs to be taken into account. Any community has attributes that influence the construction process and therefore need to be taken into account during the preparation phase. The availability of experienced local work force and their habits of working, with respect to e.g. working times, holidays, levels of payment, and presence of trade unions and their regulations becomes an important factor in carrying out the work on time and within budget. Local preferences in architectural styles are amongst the factors to be considered from the very beginning of the design process.

3.4.4 Owner Needs

Apart from environmental, technical, and labor factors the owner of the structure plays a major role in design and construction process. It is the owner's need of a new facility that initiates the construction project at all. For bridge projects this need could have reasons such as replacement of an old bridge due to its deterioration or building of new routes within the existing transportation system. Wishes of the owner concerning the layout of the structure have priority for structural engineers. In case of Departments of Transportation these issues are put down in comprehensive manuals with specifications that become part of the bidding and contract documents.

For anticipation of future growth of traffic the social and economical development of the region needs to be researched. Not only the frequency of traffic, but also its dimensions in weight and speed will play a role when designing the transportation system.

3.5 CHARACTERISTICS OF STRUCTURAL ENGINEERING

The following section will deal with the nature and typical tasks of structural engineering and issues related to design of bridges. A definition of structural engineering is provided by Petroski (1992, p40), who cites that it "is the science and art of designing and making, with economy and elegance, buildings, bridges, frameworks, and other similar structures so that they can safely resist the forces to which they may be subjected." Structural engineers typically perform mathematical analysis of models of structures that are based on assumptions on the geometry, structural details, materials properties, and loads. In these calculations they include factors of safety to account for uncertainties in the assumptions.

Afterwards, issues pertaining to cast-in-place cantilevering construction of segmental concrete bridges will be presented. Different aspects of this erection method, e.g. the characteristics of cantilevering will be explained. Finally, quality aspects of the erection method are addressed.

3.5.1 Modeling Reality

It is important to realize that in engineering in most cases – except for field measurements of the behavior of a real structure – abstract models are used. Simple graphical models of structures are widely used in the classic beam and truss theory to visualize the flow of forces and analyze its effects. From these models, equations describing their behavior can be derived and solved for the unknown parameters. Contributing to the wide use of graphical representations is that they are easily communicated amongst peers, as the language of the engineer is the drawing.

As is discussed in the following paragraphs, the author of this thesis has conceptualized generic structural design concepts in the diagram shown in Figure 3-6. Features of a real structure are represented on the left side of the diagram; a model representation of the structure is found on the opposite side. Transferring reality into a model will necessarily include idealizations and assumptions to simplify the real structure for purpose of analysis. Even a most exact numerical solution of an analysis – given that the results are checked for numerical errors – can only be as good and valid as the assumptions on which it is based. Yet absolute accuracy cannot be achieved with engineering calculations because the solutions obtained are based on models – simplifications – of reality only. In a passage on analysis of structural systems Barker and Puckett (1997, pp256f) state the importance of "the engineer's responsibility to understand the assumptions and their applicability to the system under study", i.e. how results from the model are interpreted and applied to the real structure that is to be built. They further point at the cyclical, iterative nature of the structural design process, which is represented through feedback loops within the cycle. Which features of a structure are specifically modeled depends on the desired information that the model analysis shall give.

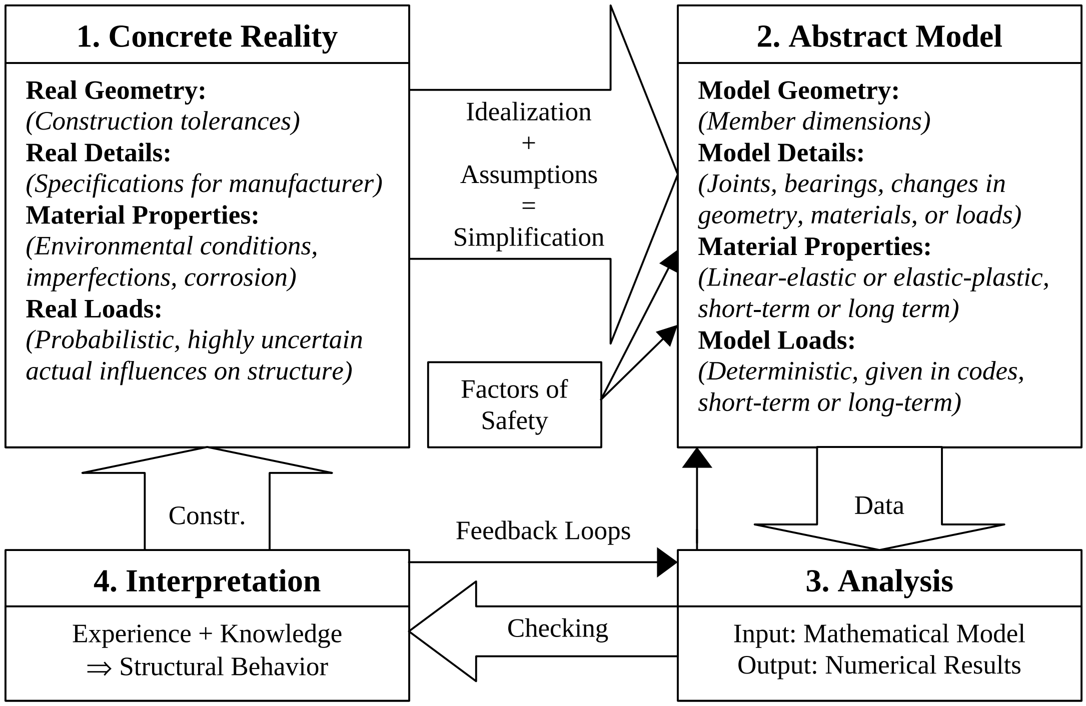

Figure 3-6: Modeling Reality

Any real existing structure comprises four main elements, namely its geometry and boundary conditions, structural details, e.g. bearings and expansion joints, material properties, and any loads on the structure.

The exact geometry of the structure is variable within the tolerances of fabrication. Boundary conditions denote the integration of the structure into its environment, especially through the interaction between its foundations and the specific soil on site. Structural details need to fulfill manufacturing specifications as to their performance during the service life. Material properties are variable due to flaws and imperfections during fabrication. Furthermore, materials change in their behavior depending on environmental conditions, such as temperature and moisture, and depending on time and loads, revealing the phenomena creep, shrinkage, relaxation, and fatigue. More complicated to predict are the loads that will influence the structure. Loads on the structure vary considerable during construction process and service life. During construction, the resistance of the incomplete structure has not reached its final state. This relationship between the structure under erection and the load steps occurring will be examined in Section 4.3. A comprehensive list of loads on foundations, substructure, and superstructure as they appear in the AASHTO (American Association of State Highway and Transportation Officials) Standard Specifications for Highway Bridges is given in Melaragno (1998).

Any modeling effort of the real structures needs to include the aforementioned four elements. Member dimensions will usually be taken from plans and specifications. Often it can be sufficient to model several subsystems of the three-dimensional structure in two-dimensional planes with transitory conditions between them, thus simplifying the calculation effort. Details, such as joints and supports as well as changes in geometry, materials, or loads will be idealized to make them easier to analyze. These inconsistencies of the structure are generally difficult to model accurately, especially with Finite Element Programs (FEM). FEM programs use discrete analysis, modeling the structure as a network of incremental elements. Care should be taken to represent these points of interest correctly as they often attract stress concentrations and possible flaws during construction.

A very common idealization is to model bearings as element that allow free frictionless displacements and rotations in certain planes while being completely fixed in other directions. These boundary conditions in structures can be captured in mathematical equations. Material properties are expressed with mathematical functions, such as the well-known stress-strain relationship for the linear-elastic and elastic-plastic range.

Short-time influences on the materials, e.g. expansion and contraction under changes of temperature and long-term time-dependent influences, such as creep, shrinkage, and relaxation and load-dependent influences, such as fatigue can be modeled if necessary for the analysis. Loads and other actions that have to be considered during the analysis are given in current design codes and specifications.

3.5.2 Factor of Safety

Nowadays' structures in developed countries are mostly on a very high level of safety, meaning that at least structural failures occur extremely rarely. Modern design philosophy, as outlined in

Menn (1990), distinguishes between two separate limit states, the *Ultimate Limit State* (ULS) and the *Serviceability Limit State* (SLS) that were mentioned in Section 3.1.3. For both limit states the limits of stresses and deflections can be set in codes. During structural analysis it has to be verified that the structure will fulfill the limits under any anticipated combination of load cases.

Structures are by nature overdesigned to some extent. This margin of additional capacity of structures is meant to account for the limited accuracy and uncertainty in assumptions for geometry, structural details, material properties, and loads. All these factors show statistical variability in real life, e.g. flaws in materials. This error margin is an accepted risk in engineering and does not in itself imply any lack of quality of the engineering work.

Factors of safety are found in codes and are calibrated by expert committees to a certain level of safety, meaning a very small, yet existing probability of failure. Zero risk of failure is by definition impossible, as structures become immensely massive and expensive the smaller the risk of structural failure becomes. Kranakis (1997, p85) fittingly calls the factor of safety "a factor of ignorance, a 'guesstimate' ", yet very suitable for the engineering community to work with. Determining how safe is safe enough, i.e. meaning what standardized numerical values for factors of safety should be used, is the task of code committees.

As structures can fail in rather complex ways, detailed analysis of possible modes of failure is necessary. Different *modes of failure* exist from the structural point of view because of redundancy built into the structural system. Petroski (1992, p92) gives the technical term for this redundancy, "alternate load paths". Failure of a single structural member, e.g. a bridge pier may not necessarily cause total collapse of the structure. The loads can often distribute between other load-carrying members. As there will probably be one mode of structural failure more probable than other, being the weakest link in the chain of structural safety, the overall level of safety of the structure can be determined by finding this element.

The most basic concept in structural design is outlined by Barker and Puckett (1997) and other authors. A structure will safely serve its purpose and carry the loads imposed as long as its resistance R is greater than the most unfavorable combination of actions S that causes stresses in the structure. Expressed in a simple way this means that the materials in their geometric configuration need to withstand the stresses imposed by different load combinations. The following equation expresses this basic concept of structural safety (MacGregor 1997, p14):

$$fR_n \geq a_1 S_1 + a_2 S_2 + \cdots$$ **Equation 3-3**

with

ϕ = strength reduction factor (less than 1)

R_n = nominal resistance [i.e. computed]

α_i = load factor (greater than 1)

S_i = load effects based on the specific loads

On both sides, for material properties as well as for loads, factors are implemented in the calculations. They are provided because of the uncertainty pertaining to the exact nature of materials and loads. On the resistance side, these factors ϕ are called *strength reduction factors*, on the load side these factors α are called *load factors* (MacGregor 1997). MacGregor in this context also notes that the ACI (American Concrete Institute) Code 318, applicable for concrete buildings denotes the right side of the equation with the symbol *U*.

In exactly the same manner, the *Load and Resistance Factor Design* (LRFD) approach for steel structures as implemented takes the aforementioned statistical nature of materials and loads into account, including load combinations with partial safety factors both on the material side and on the load side (Barker and Puckett 1997).

Clearly, to introduce increased safety, these factors for design purposes lower the assumed resistance of the structure and increase the anticipated loads. Code committees calibrate these factors based on empirical knowledge from field data and engineering judgment.

3.5.3 Structural Analysis

Once the modeling process has been completed, structural analysis can begin. The four components of the model – geometry, structural details, material properties, and loads – are expressed in terms of variables in mathematical equations for "equilibrium, compatibility, and material response, in conjunction with the assumptions", thus forming what Barker and Puckett (1997, p257) call a mathematical model of the structure. Solving the obtained system of equations will produce numerical results for the values of the unknown variables. Checking the magnitude of these values for errors is an important step within the design process. Afterwards, the results are interpreted in terms of stresses and displacements by the engineer who is examining the structural behavior and applied to the given project, e.g. to determine the camber necessary for a bridge or to come up with an appropriate sequence of prestressing the tendons. Profound engineering knowledge and experience from previous projects help in this process. In most cases the design process will be a team effort due to the wide range of work that had to be done. Most important is good communication between the team participants and awareness of the philosophy behind the construction process.

Loads on structures can occur in many different forms. A more generic term for influences on structures is action. An *action* is defined by Liebenberg (1992, p69) as follows:

> *"An action is an assembly of concentrated or distributed forces (direct actions [in italics]), or imposed or constrained deformations (indirect actions [in italics]), applied to a structure due to a single cause. An action is considered to be a single action if it is stochastically independent, in time and space, of any other assembly of forces, or imposed or constrained deformations, acting on the structure. Actions can be qualitatively classified according to their variation in time, or space, or according to their dynamic nature."*

From this definition actions can be dead load and live loads, wind and snow loads, thermal gradients, water currents and ice loads on substructures, seismicity, foundation settlements, and the like. The safety of the structure under these actions is captured in the *Ultimate Limit State* (ULS), after which "any increase in load, however small, results in loss of equilibrium and hence in collapse of the structure" (Menn 1990, p93).

Care needs to be taken in use of analytical tools as e.g. computer programs for structural analysis. Structural failures have already occurred because of overconfidence in computer models of the structure, an issue that was addressed in Section 3.5.2. A well-known example is the failure and sinking of Norwegian oil platform Sleipner A in 1991, a massive concrete structure, of which Petroski (1997) reports that the reason lay in incorrect representation of adjoining cells in the analysis, which led to underestimation of stresses in the seams.

Using computer programs does only help to solve the complex systems of equations with mathematical algorithms. Development of better software tools made very complex structural calculations possible. However, responsibility for the accuracy of the model input and correct interpretation always remains at the engineers who are using computer tools. In today's technical environment the abundant presence of computers makes it possible to forget about their purpose in engineering, to perform calculation operations that would be too tedious for manual calculation. It is appropriate to think of computers as data processing systems that only support the engineers in their tasks. Petroski (1992) discusses the problem of uncritical use of computers in engineering. He states that the ability to quickly perform almost any calculation may foster less critical use of the many numerical computer-generated results. It is the engineer who has to interpret the numerous data obtained for stresses and deformations in terms of real structural behavior.

In addition to that, Petroski (1992) shows concern with the accuracy of computer software available. Engineers analyzing structural models with computer software have repeatedly failed to ensure structural safety, which led to failures such as the roof of the Hartford Civic Center in 1978. Computer software generally is a black box often based on unknown algorithms and assumptions within the program code that may not be clearly expressed in computer manuals. It could only contribute to the quality of structures if engineers used the time they saved through use of computers for elaborate calculations for careful checks of computer outputs based on a sound knowledge of structural behavior (Petroski 1992). This discussion is best captured by Professor Richard Barker's philosophy, which says: "… you are to assume that computer results are incorrect unless proven otherwise…" (Barker 1999).

3.6 CHARACTERISTICS OF CAST-IN-PLACE SEGMENTAL CANTILEVER CONSTRUCTION

Cast-in-place prestressed cantilever bridges have been built for almost half a century. For the first time this technique was used in 1950 by German engineer Ulrich Finsterwalder for the Lahn Bridge at Balduinstein that has a span of 62 m, as Fletcher (1984) reports. The following sections specifically deal with erection of bridge superstructures with the cast-in-place segmental cantilever construction. Technical terms of the heading will be defined and explained with their characteristics to show how these techniques in their combination generate a very feasible means of construction.

3.6.1 Segmental Construction

Segmental construction is “a method of construction in which primary load-carrying members are composed of individual members called segments post-tensioned together” (Podolny and Muller 1982, p10). For the analytical calculations, information on the planned segmentation and use of precast or cast-in-place segments is most important. When cast in place, the different ages and concrete strength of the segments need to be considered. Podolny and Muller (1982) caution to keep the segments as regular in their geometry and as straight in alignment as possible, with including only little obstruction through e.g. diaphragms.

Segmental construction follows logically from the technical limitations of erection methods and the construction equipment. Cranes, concrete pumps, form travelers, and other pieces of equipment have certain limitations as to the volume and weight of material that they can handle at one time. A major advantage of segmental construction is the ease with which it can be adapted to the specific project and the capacity of available equipment, allowing optimization for economical construction.

Subsequent placement of segments divides the overall construction process into smaller repetitive steps that facilitate a learning process (Fletcher 1984) and project management. Segmental construction leads to economic and rapid erection of the bridge superstructure.

Several well-tried, feasible erection methods exist for segmental bridges and give the designer ample choice in coming up with a method suitable for the specific project. Combinations of the erection methods that are described in Section 4.2 are also possible if necessary.

Subdivision of the superstructure into elements can exist along the longitudinal and in the transverse direction. Separation in the vertical axis is found less frequently. It is used e.g. in composite bridge superstructures that comprise steel trusses or box girders with a concrete deck slab. Longitudinally divided segments are load-carrying members that span the complete length of one bridge span, e.g. in form of several parallel prestressed AASHTO (American Association of State Highway and Transportation Officials) girders, which will be covered with a deck.

Of prime interest in this study is segmentation in the transverse plane. These segments have the full width of the superstructure. For the common type of box girders the segments are usually 3 to 5 m long (Fletcher 1984) and can weigh up to 250 tons in precast cantilevering construction (Podolny and Muller 1982) or up to 300 tons for cast-in-place cantilevering construction (Fletcher 1984). Other lengths and weights are used for incremental launching, which will be discussed in Section 4.2.3.

3.6.2 Cantilevering Method

A cantilever is a horizontal beam with a fixed support at one of its ends. To begin with the discussion of characteristics of the cast-in-place cantilevering method, it is useful to take a brief look at a simple beam theory model shown in Figure 3-7, which can similarly be found in any textbook on mechanics of deformable bodies. In this two-dimensional graphical model of the structural system a horizontal line depicts the longitudinal axis of the beam. For simple calculation of the beam deflection under load one needs to know the beam length, its modulus of elasticity as a material parameter, and the moment of inertia of the beam cross-section need to be known. Loads on the beam can occur in form of loads and moments that can be singular or distributed over the beam length in a uniform or variable manner. With these information it is possible to determine the deflection of the beam and the resulting angle of the previously horizontal beam at any point along its length. The results obtained by this approach are easily accessible, yet they are the output of a modeling process that has been undertaken. More information on the concept of modeling reality is given in Section 3.5.1.

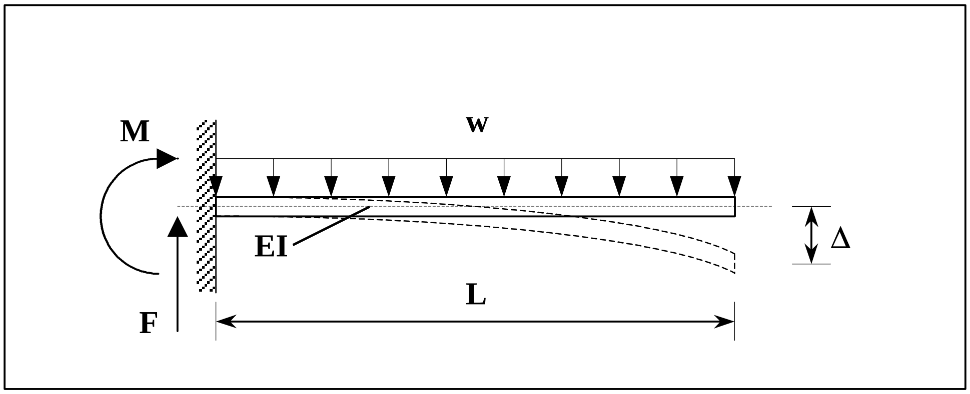

Figure 3-7: Uniformly Loaded Cantilever Beam

When structural analysis is performed on a cantilever system, the modeling approach is used in that all major influences are examined separately and are finally superposed to come up with the overall system behavior. Taking the example of a free cantilever of continuous cross-section that is composed of segments with different ages and is held together with prestressing tendons the effect of each of these factors is calculated separately as shown in Figure 3-8. The cantilever system is loaded through its own dead load and an anticipated uniform live load under service, which will in turn create the well-known parabolic moment curve for a cantilever beam. Post-tensioning tendons are used within the cantilever beam to compensate for the dead load moment figure. For simplification is shall be assumed that the prestressing tendons that are added with every new segment are all located at the same eccentricity from the neutral axis of the cantilever beam cross-section. Assuming further that all tendons are straight without curvature (as would be used in real bridge structures), the superposition of the moments from all post-tensioning tendons provides a stepped moment envelope that compensates the dead load moment figure.

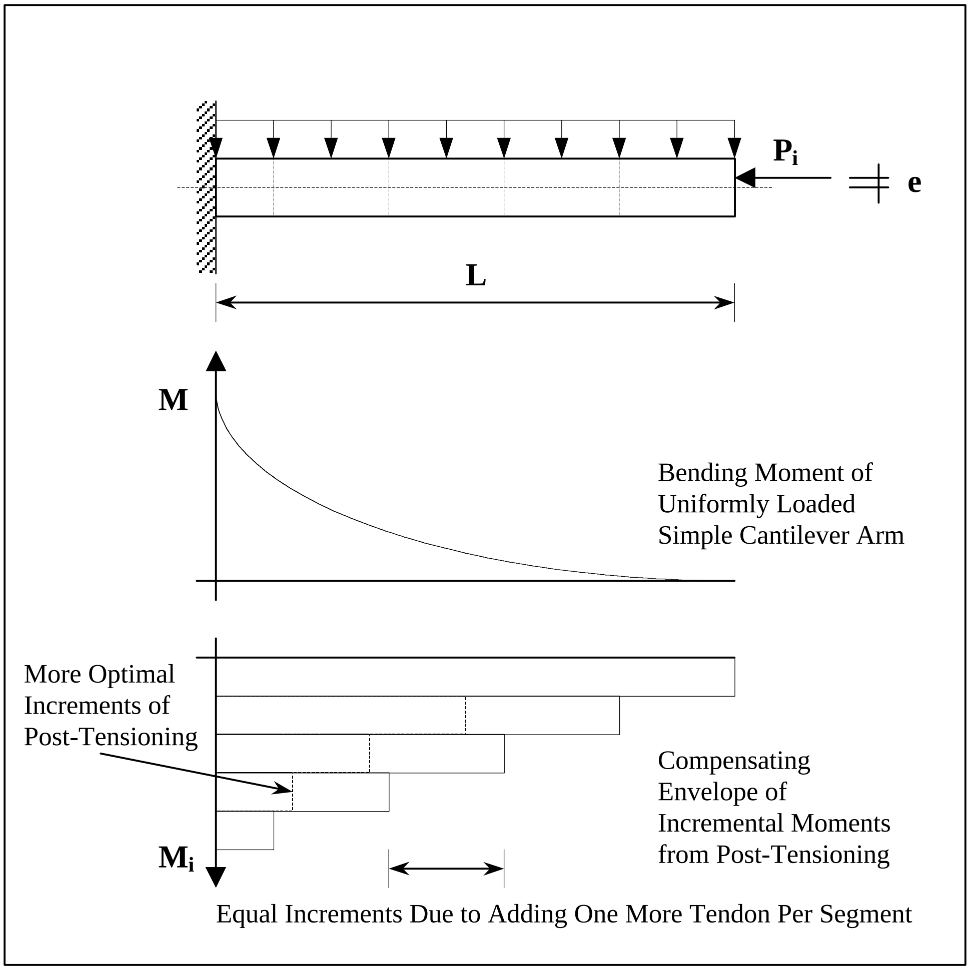

Figure 3-8: Post-Tensioning of Segmental Cantilever

Two major points in time are examined to determine long-term stresses and deformations of the structural system based on time-dependent material properties, i.e. creep and shrinkage of concrete and relaxation of steel. These dates are the end of construction (EOC) and the assumed ‘infinity’, usually chosen to be day 10,000 after beginning construction. Before end of construction the cantilever system of the bridge will have changed to a continuous system, in some cases if midspan hinges. Moment redistribution from supports towards the spans will take place. Different segment ages will certainly play a role when determining stresses and deformations of the structural system at the end of construction. For ‘infinity’, however, the relative differences in segment ages are usually small enough to be neglected in structural analysis.

It is relatively easy to give a rough estimate of moment values for the completed structural system. Figure 3-9 illustrates the procedure that is outlined in the following. The range in which the overall bending moment values will be is given by idealized states of the structural system at end of construction and at ‘infinity’. When the structural system has just reached continuity, all bending moments at the supports are still at their maximum and no moment redistribution has taken place so far, i.e. moments at the midspan closures are still zero. Moments will slowly redistribute in the structural system depending on time-dependent material properties from this state to the state at ‘infinity’. However, time-dependent effects usually show asymptotic behavior. Hence, the idealized state of ‘infinity’ will never be reached. The idealized state of ‘infinity’ is given by the continuous structural system, assuming that all elements were cast and loaded at the same times. Calculation of this simple structurally indeterminate system under the assumed dead load and live loads generates a moment diagram with certain moment values for supports and spans. Taking the results from the two idealized systems as upper and lower limits, an initial impression of the dimension of moment values in the real structure with its time-dependent material properties has been generated.

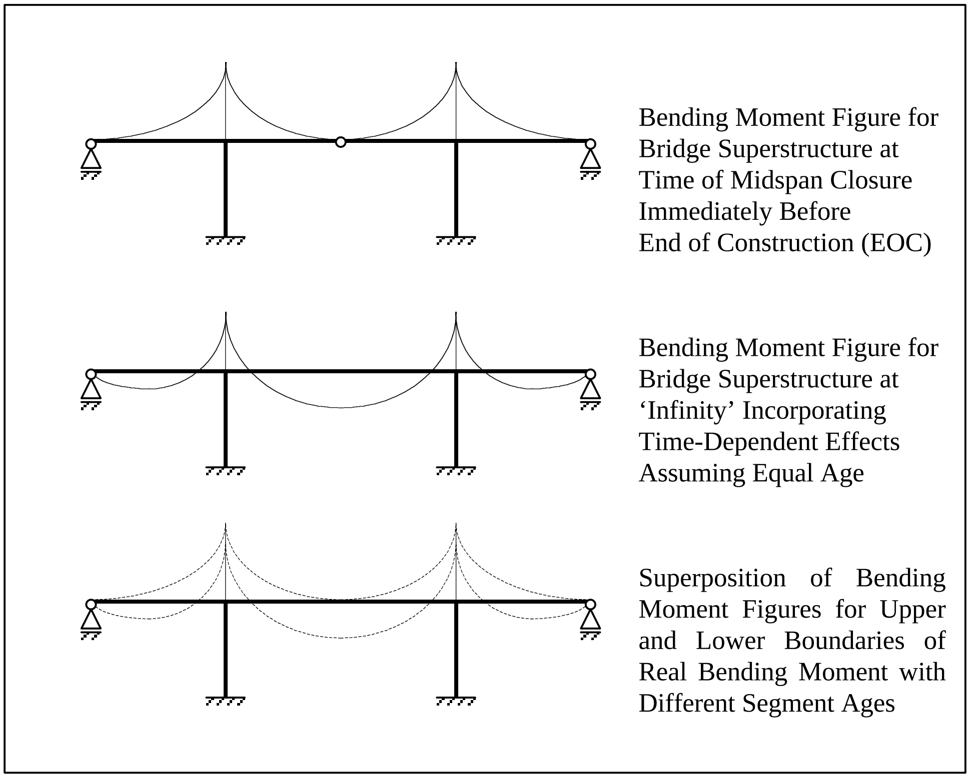

Figure 3-9: Upper and Lower Boundaries for Long-Term Bending Moments

3.6.2.1 Cantilevering Defined

Cantilevering means placing segments progressively into their final position at the tip of the self-supporting superstructure. Cantilevering of the spans always begins at one of the supports, which are piers or abutments, counterweighted by another emerging span as in Balanced Cantilever Construction or a massive abutment (Mathivat 1983, p30) or supported by stay cables as it is often used in the progressive placement method. More specific information on cantilevering construction and its advantages will be given in Section 4.2.1. More information pertaining to cast-in-place construction will be addressed in the following Section 3.6.3.

Several authors have taken a closer look at the cantilevering method and examined the critical topic of prestress losses in segmental construction, with emphasis on cast-in-place construction.

As opposed to precast construction, where segments are usually placed into the superstructure and stressed together at a later age, cast-in-place construction features early loading of a newly cast segment. The following paragraphs will outline the effects that segmental construction with cast-in-place cantilevering generates and in what way they need to be considered in structural analysis of the chosen erection sequence. Figure 3-10, which is based on information from Barker and Puckett (1997), Bishara and Papakonstantinou (1990), and Shiu and Russell (1987), provides a comprehensive scheme depicting these effects and their interrelationships.

3.6.2.2 Low Strength of Young Concrete

The simple, self-supporting structural system remains a cantilever during construction until closure of the spans at midspan. This beam-type structural system is even statically determinate and thus facilitates structural analysis. Special attention, however, has to be paid to the stepwise change in length of the cantilever that occurs as new segments are added. Especially when using the cast-in-place method, strength development of every segment needs to be considered. Here, segments are usually stressed shortly after casting, sometimes only two days after placement. At this point of time the concrete has reached only part of the compressive strength that is specified for an age of 28 days, usually between about 40 and 50 % (MacGregor 1997). Strength developed by the concrete at ages more than 28 days is usually not taken into consideration for analytical calculations in structural design. The actual compressive strength of newly cast segments is determined by running laboratory tests on samples that were obtained during actual casting and have been cured under field conditions. Precast segments, having been stored for an additional time before being installed have usually developed a higher strength than cast-in-place segments by the time they are placed in the superstructure.

Within segments themselves the concrete age is usually assumed to be identical, since different lifts are placed within a relatively brief time interval. There is, however, the possibility that the segments are partially fabricated from precast elements, e.g. the webs, or that the top slab is cast later than the rest of the segment section, as mentioned in Section 4.2.1.2. Moreover, very

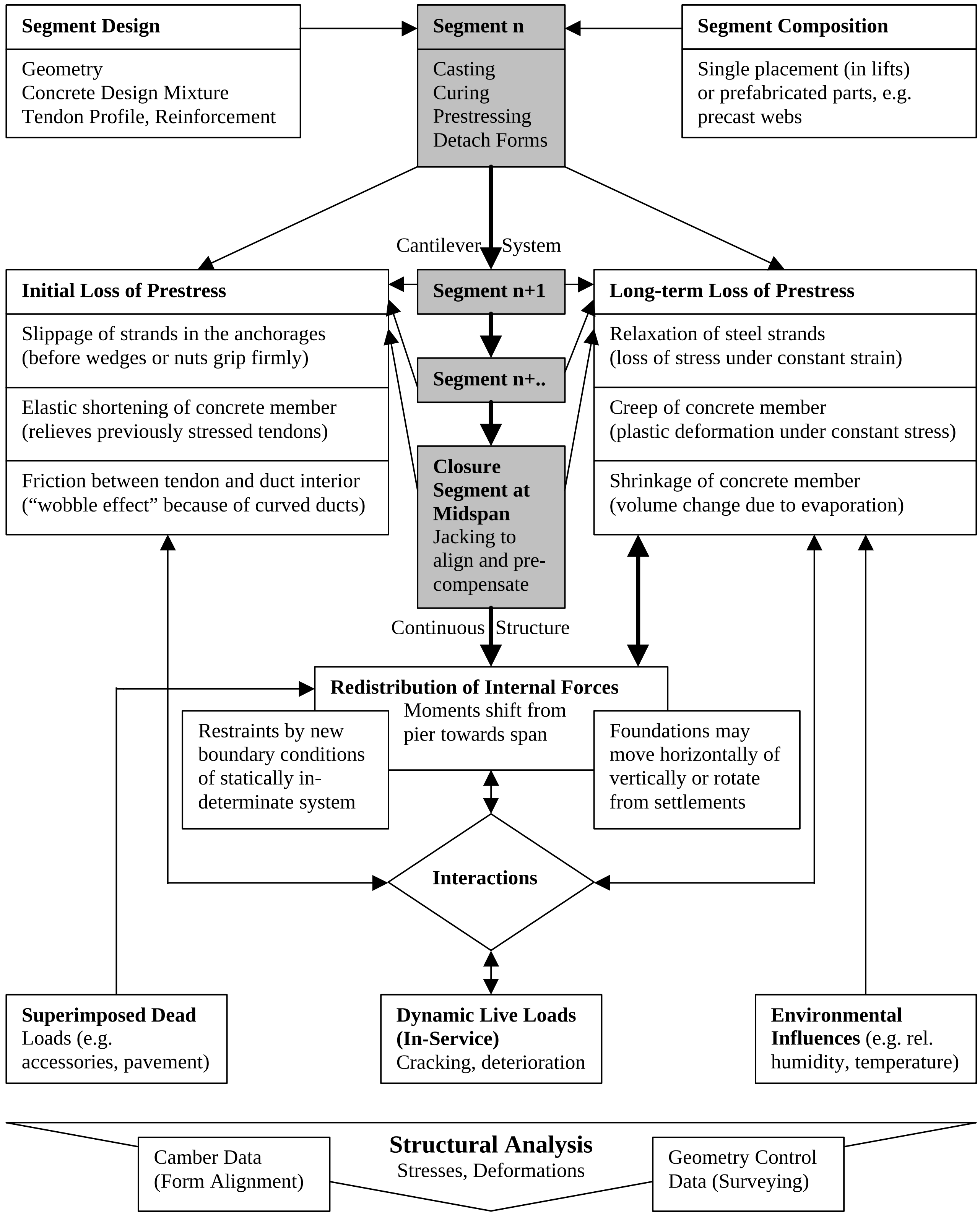

Figure 3-10: Effects in Cast-In-Place Segmental Cantilever Construction

massive segments, e.g. pier tables, may have to be cast in several individual concrete placements operations, each composed of many small lifts. Between these placements, new reinforcement and prestressing tendons with their ducts may have to be installed, and formwork may have to be added. In such cases the strengths can even differ within one segment of the bridge superstructure and have to be taken into account in the structural analysis.

3.6.2.3 Prestress Losses Through Elastic Shortening

In case the bridge superstructure is constructed by cantilevering, the process of adding segments influences the prestressing forces in the tendons. Elastic shortening of all previously installed segments occurs and reduces the applied prestressing force that causes this shortening, as determined by the modulus of elasticity of the particular segment. Shiu and Russell (1987, p654) pronounce that losses in prestress "due to elastic shortening is a major concern in the total prestress losses for segmental balanced cantilever construction." They further capture this influence in the following (Shiu and Russell 1987, p649):

> *"Use of segmental construction results in complex load histories on individual post-tensioned elements. Post-tensioning of newly erected segments unavoidably relieves a certain portion of prestressing in the previous segments through elastic shortening. This means that the prestress level changes as construction progresses. Estimation of prestress losses at each construction event becomes necessary for a proper control of concrete stress levels and geometry control. Consequently, calculations of prestress losses are very time-consuming and tedious."*

Because of the elastic shortening effect it may be chosen to first apply only a fraction of the final prestressing force that is enough to carry one or a few subsequent elements. During construction of these, the segment will gain further strength and more prestressing can be applied to provide full load-carrying capacity for the growing cantilever.

3.6.2.4 Prestress Losses Through Time-Dependent Effects

Along with the lower strength of young concrete and early, stepwise application of loads on the bridge segments comes increased susceptibility of the loaded concrete to time-dependent effects. Bishara and Papakonstantinou (1990, p1249) describe the relationship between segmental construction and time-dependent effects:

> *"During the construction process, a particular segment is loaded incrementally at different ages, with each age corresponding to the time a new segment is added to the system. Thus, for predicting effect of creep of concrete for a segment at any time t, the duration of loading of the segment by the following segments must be included in the creep coefficient."*

Calculations of prestress losses involve "uncertainties due to interactions between factors" as listed in Table 4-1 and in addition to that "environmental influence [e.g. ambient air and concrete temperature and humidity] on time-dependent material properties changes conditions of stresses continuously" (Shiu and Russell 1987, p649). Further factors that are mentioned in Shiu and Russell (1987) are the still ongoing development of concrete strength (creep recovery) that may compensate for some of the time-dependent effects, the thickness of the concrete member, and the type of concrete with its characteristic stress-strain relationship and own dead load. Segment age at the time of loading, i.e. prestressing, is critical for further development of time-dependent effects.

Shiu and Russell (1987) analyzed prestress losses of a segmental concrete box girder bridge in northern Illinois, the Kishwaukee River Bridge. It consists of two parallel five-span superstructures that were built with Balanced Cantilever Construction. The authors (Shiu and Russell 1987, p650) report that "field measurements, laboratory tests, and analytical evaluations" were undertaken for various segment locations. For the laboratory analysis cylinder samples were taken from these segments and were cured under controlled laboratory conditions or cured outdoors under field conditions. Afterwards, results were compared with results from calculations with the then actual simplified formulas as provided by the Prestressed Concrete Institute (PCI) and the American Association of State Highway and Transportation Officials (AASHTO). Considerable deviations were found between these results. Actual measurements showed that both shrinkage and creep were slightly less in concrete samples from the

Kishwaukee Bridge that were cured under field conditions than for curing in the laboratory. However, "distinct seasonal fluctuations were noted for outdoor shrinkage values" (Shiu and Russell 1987, p650).

3.6.2.5 Redistribution of Internal Forces

Even more interesting is the effect that time-dependent effects of material properties have on the overall structural system. Bishara and Papakonstantinou (1990, p1247) express how redistribution within the system takes place over a long time after continuity of the structural system has been reached:

> *"Particularly, for cast-in-place cantilever bridges, the internal forces and the associated deformations are influenced by the different ages of the segments. After continuity is achieved, time-dependent deformations cause redistribution of these internal forces. Time-dependent foundation displacements [i.e. vertical and horizontal movements and rotations] induce internal forces in the continuous system that are a function of both the rate of the displacements and the rate of creep of concrete."*

Redistribution within the structural system, Bishara and Papakonstantinou (1990, p1253) state, "is caused by the fact that displacements (i.e. deflections and rotations) that would have continued to take place in the statically determinate system due to shrinkage, creep, and relaxation effects become restrained by the imposed boundary conditions of the indeterminate completed structure." In the previously statically determinate cantilever arms bending moments increased towards the fixed support at the piers and were zero at the cantilever tip, since every segment has to support all following ones. With casting, curing, and post-tensioning of the closure segment at midspan the moments will redistribute to some extent from the piers towards the span girder, resulting in a different stress distribution in the segments. Shiu and Russell (1987, pp652f) in their investigation into prestress losses in construction of the Kishwaukee Bridge further found with respect to the amount of moment redistribution:

> *"A substantial decrease of prestress loss due to elastic lengthening was noted at 462 days which corresponded to the weight of the closure segments at the instrumented span. This negative prestress loss accounted for almost 50 % of the*

> *total prestress loss. (…) Substantially bigger prestress losses were recorded for the segment next to the pier than segments at quarter span and midspan. Higher prestress losses can be attributed to moment redistribution from the negative moment region at the pier support to the positive moment region at midspan."*

With respect to the continuous statical system that exists after closure at midspan and stressing of the so-called continuity tendons, Bishara and Papakonstantinou (1990, pp1252f) give a list of factors influencing forces in the completed structure itself:

- *"(1) Long-time effects of the girder weight and the prestressing forces of the balanced cantilever system;*
- *(2) forces induced by the continuity tendons;*
- *(3) superimposed dead load (weight of the wearing surface, sidewalks, and handrails [i.e. from bridge deck and accessories]);*
- *(4) forces caused by foundation movements occurring after continuity;*
- *(5) live loads; and*
- *(6) forces caused by environmental effects (temperature, wind, etc.)."*

3.6.2.6 Further Considerations

Factors that are considered in an algorithm developed by Bishara and Papakonstantinou (1990, p1247) are "effects caused by differences in ages of bridge segments, shrinkage and creep of concrete, relaxation and curvature of prestressing tendons, and vertical and horizontal support movements as well as their rotations." The two latter issues, tendon material properties and tendon profile, as well as changes in the boundary conditions of the statical system by displacement or rotation of foundations need to be considered in structural analysis. Displacements or rotations of the foundations will be calculated from measured actual soil properties at the site. The authors (Bishara and Papakonstantinou 1990, p1261) observe that "effect of tendon curvature in computing prestress losses is often neglected in segmental cantilever bridges", however, can contribute a considerable amount to prestress losses.

Further factors are mentioned in Bishara and Papakonstantinou (1990, p1249), who derive and present formulas to calculate creep that incorporate a special reduction coefficient “to take into account the effect of compression steel, movement of neutral axis, progressive cracking in reinforced concrete flexural members and effect of nontensioned steel in prestressed concrete flexural members.” In addition to that, coefficients are introduced to take the particular curing process of the concrete into consideration. Also, so-called ambient conditions of the immediate environment of the structure are considered by a correction factor, which results from multiplying factors for “ambient relative humidity effect;… minimum thickness effect;… slump effect;… percentage of fines effect;… air content effect;… effect of difference of age of segments when loaded“ (Bishara and Papakonstantinou 1990, p1249).

In their study the authors finally note the additional effect of the form traveler itself, which is a temporary load during construction and should be considered accordingly. After finishing cantilevering operations, “the form travelers are dismantled, resulting in an upward deflection. (…) Since the form traveler stays at the same position as long as it is needed for a segment to be constructed, it introduces time-dependent deflections” (Bishara and Papakonstantinou 1990, p1252).

In summary, displacements (again, the authors refer with this term to both deflections and rotations) are obtained from superposition of “initial displacement due to dead load;… displacement due to prestressing force after instantaneous losses;… long-term displacement due to dead load;… additional long-term displacement due to long-term prestress losses;… long-term displacement due to foundation movements; and … displacement of the same nodal point *n* due to live loads” (Bishara and Papakonstantinou 1990, p1250).

3.6.2.7 Importance of Accounting for Prestress Losses and Conclusion

Bishara and Papakonstantinou (1990) describe the development of an algorithm for computer analysis of cast-in-place bridges. In particular, they examine bridges with box girder superstructures that are built with Balanced Cantilever Construction and they discuss aspects to be considered in structural analysis that arise from cast-in-place balanced cantilevering. Results that they obtained in their analysis are compared with more simplified analytical methods, in which e.g. the design concrete strength of segments is used, disregarding the individual segment ages, or in which an average age is used. The authors (Bishara and Papakonstantinou 1990) conclude from these comparisons that effects described hereafter definitely need to be considered. Many of the effects contributing to prestress losses share the common characteristic that they are asymptotic over time and are therefore represented by exponential mathematical functions, as e.g. in the study described in this paragraph.

The importance of calculation of prestress losses is easily understood with the concepts from Figure 3-2. Loss of prestressing force in the tendons does not immediately affect the structural safety, but can influence "serviceability of the structural member such as camber, deflection, and crack control" (Shiu and Russell 1987, p649).

Shiu and Russell (1987) also note that in order to properly meet both cantilever arms at the planned midspan elevation, camber of these needs to be controlled closely by calculation of prestress losses. Results obtained from these calculations will be used in a twofold manner. They serve to determine the alignment and camber of the formwork during ongoing casting of the cantilever. The camber is necessary to account for any deflections that arise during construction and in the finished structure, so that the structure arrives at the planned alignment on the long run. The second use of the calculation results is that they are reference values to be compared with actual surveying data for geometry control.

Different ages of segments in two cantilever arms that are to form one span of the superstructure will display different time-dependent deflections (Bishara and Papakonstantinou 1990). Such differences in segment ages for corresponding segments in the two cantilever arms can be caused by the particular construction schedule. It is possible that e.g. there is only one work crew for installing reinforcement and another crew for placement of concrete to save on labor cost. The crews would switch working between both cantilever ends so that the cantilever would grow one step at a time, first on one side, then on the other, and so forth.

Care should be taken that jacking the cantilever arms together for horizontal and vertical alignment is avoided if possible. Thorough analysis of the construction stages including all effects outlined in previous paragraphs and incorporating the results in the planned camber will contribute to avoiding these additional stresses imposed on the structure. There is, however, another reason why jacking may be used on the cantilever arms, it may be chosen to jack them apart to decrease “the effects of long-term creep and shrinkage of the superstructure on the substructure” (Matt et al. 1988, p37).

3.6.3 Cast-In-Place Construction

Cast-in-place construction, as opposed to precast construction where the segments are prefabricated in a casting plant, denotes a construction process where the segments are progressively cast on site into their final position in the structure.

Describing the analogy between cast-in-place construction and precast construction will help gain understanding of the differences in on-site operations for both methods. Precast erection is first and foremost a lifting activity. It requires lifting equipment, i.e. a large crane or a launching gantry that lifts and transports the load, i.e. the prefabricated segment along a path, in this case from the storage yard to the tip of the cantilever. The capacity of the equipment depends on the moment that is created by the product of load and radius of the crane boom and needs to consider the size of the segment in comparison with the available workspace.

Cast-in-place erection, on the other hand, is primarily a placing activity. This method requires placing equipment, i.e. a form traveler or some kind of traveling falsework. Concrete is delivered to the casting site with buckets, pumps, or other means and is placed into the forms. Required capacity of the form traveler depends on the size and weight of the heaviest segment to be supported during casting and curing.

3.6.3.1 Cast-In-Place Construction Applied to Cantilevering

In the following paragraph the focus of attention shall be put on cast-in-place construction applied to the cantilevering method. For cantilevering with cast-in-place segments, form travelers are implemented. Thus, high cost for erection of a precasting plant is avoided. Moreover, transportation and storage of the heavy precast segments is avoided and no heavy-duty erection cranes need to be employed. Podolny and Muller (1982) point out that particularly for very long structures with many spans precasting can result in cost savings because the project then will be large enough for amortization of casting, transport, and erection.

Menn (1990) gives information that cast-in-place cantilever construction is economical for a range of span-lengths of about 70 m to more than 250 m. Compared with precasting larger segments are possible in cast-in-place erection. Here the form traveler needs to have the capacity of supporting the heaviest of all segments while it has not gained any strength of its own. This specified capacity determines the cost of the form traveler as Podolny and Muller (1982) spell out. More detailed information on form travelers is given in Section 4.2.2.1.

Cast-in-place construction requires careful consideration of the construction stages. It can easily be understood that for a cantilever every newly cast segment needs to support all subsequently cast ones. Concrete develops strength with time after casting. Commonly the 28-day strength of concrete is specified and tested, which is the strength after four workweeks. Later gains in strength are usually not taken into consideration when doing the structural analysis. They add, however, some additional strength to the structure. In a cast-in-place cantilever the segments will necessarily have ages that differ from each other by the duration of a casting cycle. From this difference in age follows a difference in concrete strength.

Cast-in-place cantilevering will usually have larger deflections than precast cantilevers because those segments are stored for some time before being placed in the bridge superstructure (Mathivat 1983). To achieve rapid construction in cast-in-place construction it will be tried to minimize the cycle time for casting. The casting process is described in further detail in Section 4.2.1.2. British engineer Fletcher (1984, p17) gives information that the casting cycle time "generally settles down to one pour per shutter [i.e. form traveler] per week." At the same time he cautions to consider some factors that influence this scheduling estimate:

- Learning effects take place because of the repetitive nature of casting steps;
- Form traveler adjustment takes longer when segments change geometry, e.g. the box girder depth or flange width;
- Form traveler adjustment takes longer for incorporation of special details, as e.g. "for any in-span diaphragms, for the effect of having to incorporate bottom flange tendons and anchorages near midspan" (Fletcher 1984, p17);
- Furthermore, speed of reinforcement and tendon installation and speed of concrete placement depend on the size of the segment.

Matt et al. (1988) with their description of construction of the Gateway Bridge in Brisbane, Australia provide another example of a cast-in-place bridge. The main span of this bridge was constructed with Balanced Cantilever Construction, and the authors note that the span length of 260 m "has approached the limits of balanced cantilever construction of solid-web box-girders" (Matt et al. 1988, p41). They state that through use of "trussed girders and higher strength concrete, the weight could be further reduced", making erection of bridges with Balanced Cantilever Construction economical "with a cable-stayed solution for spans on the order of 300 m" (Matt et al. 1988, p42). The average cycle time for casting of a segment of the main span of the Gateway Bridge was seven days.

From the previous information two factors that are critical to the casting progress can be derived:

- Strength development of the previously cast segments;
- Necessary adjustments for changing girder geometry, diaphragms, and reinforcement layout.

3.6.3.2 Quality Control

The basic conclusion for cast-in-place cantilever construction is that the lower limit for cycle time depends on the concrete strength. Quicker casting would lead to structural failure. Quality of every segment in the cantilevering chain of cast-in-place segments is critical to the structural integrity of the superstructure. As Fletcher (1984, p15) writes, the cast-in-place “cantilever construction demands high quality consistent concrete.” Continuous supervision and quality control of the ongoing casting is therefore necessary to ensure that every segment has gained at least the specified strength by the beginning of the subsequent casting cycle.

3.6.3.3 Durability

The goal to be achieved in cast-in-place cantilevering is high early strength. Achieving strong and durable concrete depends on the concrete ingredients, on its age and consolidation when placing it, and on proper curing. Admixtures can assist in obtaining early strength. Manuals on concrete technology and codes give further information on today’s concrete design mixtures and various methods of placement, curing, and testing. For cantilevering Mathivat (1983) gives examples of feasible curing methods, as e.g. concrete preheating and steam curing.

3.6.3.4 Camber

The growing cantilever beam will deflect during cantilevering because of its dead load, the live load of form traveler and construction material, and because of temperature gradients in the box girder and wind load. Mathivat (1983) writes that the stepwise prestressing sequence will also contribute to deflections. More deflections will occur through the deflection of the form traveler itself, as Podolny and Muller (1982) mention. They continue their list of causes for deflections after construction with superimposed dead loads, meaning bridge accessories, the foundation settlements, and substructure deformations under superstructure loads. Live loads from the future traffic also need to be included.

Superposition of all these influences will generate the total deflection curve and hence the camber can be planned. Deflection compensation by cambering the superstructure is necessary for the following reasons:

- Ensuring that the two cantilever beams meet at the same midspan elevation so that casting the closure segment is not hindered. It is, however, possible to jack the two cantilever beams into alignment to correct minor misalignments before casting the closure segment.
- Giving the bridge in service the visual appearance of strength. Sagging below the vertical plane would also be detrimental to the riding comfort.

3.7 CONSTRUCTABILITY OF BOX GIRDERS

Concrete bridge superstructures can have very different configurations. They can be composed of slabs only for small-span bridges, precast girders that carry the deck slab, solid coffered slabs, and a variety of box cross-sections. The following sections describe the characteristics of box girders and advantages that made box girders a most widely used type of bridge superstructure. Although primarily concrete box girders are dealt with, many features are also valid for box girders made from steel.

3.7.1 Characteristics of Box Girders

Prestressed box girder bridges, according to Troitsky (1994), have been used after their introduction in Europe in Canada since 1964 and in the U.S. since 1973.

Box girders are hollow beam-type structures that consist of webs, top and bottom slab, often with cantilevering flanges at the top slab to provide a wide deck. Diaphragms at various locations within the box girder are provided to internally stiffen them. Characteristics and advantages of box girders in comparison with other superstructure systems are shown in Figure 3-11.

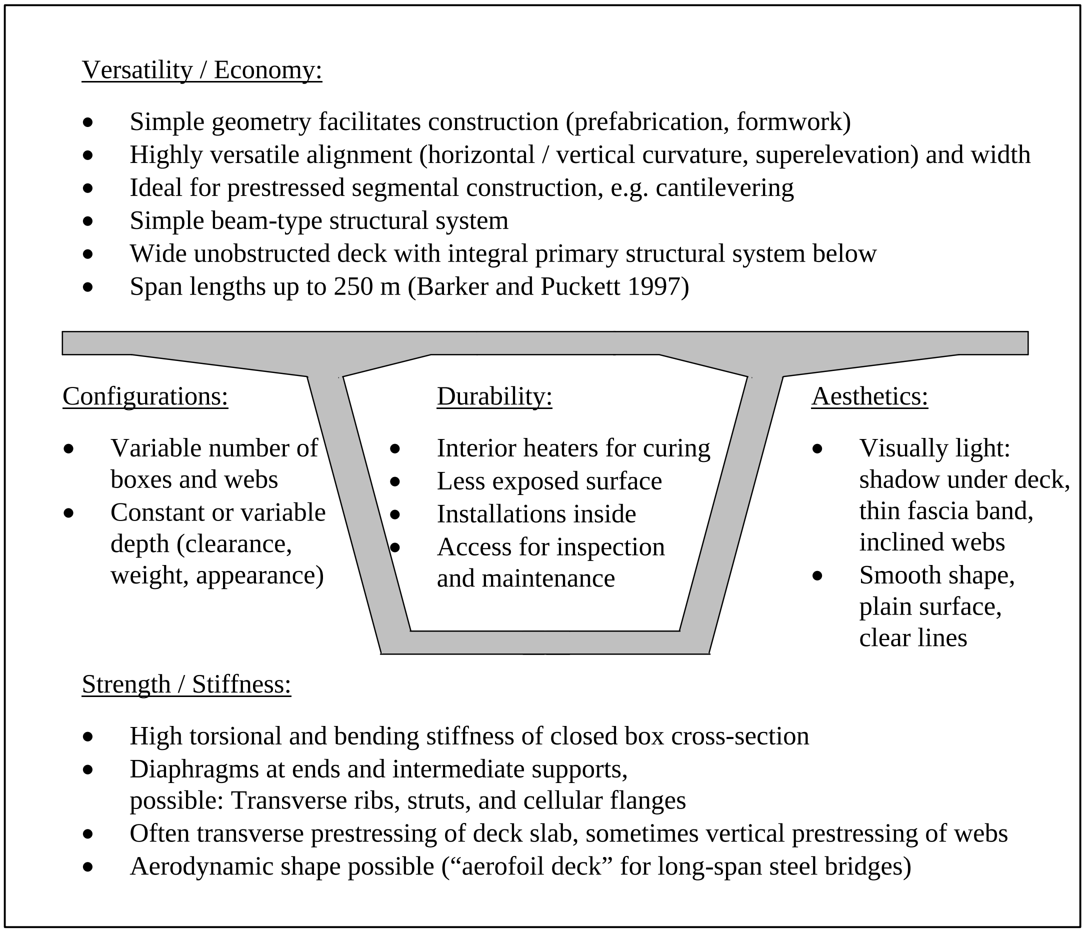

Figure 3-11: Features of Box Girders

3.7.1.1 Webs

Webs are often more massive than flanges since “they have to accommodate the torsional shear stress which is additive to the vertical shear force” (Lee 1971, p404). Enough space for longitudinal prestressing cables and for the necessary shear reinforcement needs to be provided. Sometimes, vertical prestressing of the webs is done close to supports to withstand shear forces, as Podolny and Muller (1982) point out in one of their bridge descriptions. The webs of modern box girders are often inclined outwards, which has several reasons: Lee (1971) specifically names the reduced size of the bottom slab while providing sufficient support for the deck that withstands bending moments in the transverse plane, and less visual obstruction and a more slender appearance. Corners of the box girders, e.g. between webs and top slab are often provided with small haunches. These haunches shall enable a better "flow of shear stress from one element to another" (Lee 1971, p402).

3.7.1.2 Diaphragms

Intermediate stiffeners, such as diaphragms are usually only located at the ends of the box girder at the abutments and over support to accommodate the flow of forces from the box into the substructure. Diaphragms at intermediate positions within the box are usually not necessary, "only in very large box girders or in box girders having thin concrete webs" (Lee 1971, p405) they may be incorporated to avoid distortion.

3.7.1.3 Structural Behavior

Bouwkamp et al. (1971, p18) write that box girders provide "a smooth, functional structure with a high resistance to torsional moments." They specifically point at the high torsional stiffness of the closed cross-section of box girders, making them suitable for many project conditions, including curved and skewed arrangements that induce eccentric loads into the structure.

Box girders also have good bending resistance in the longitudinal plane. Because of their inherent stiffness, box girders can be smaller than the width of the roadway that they support.

Comprehensive sample calculations and formula dealing with the specific behavior of box girders can be found in standard textbooks of bridge engineering, such as Menn (1990) and Barker and Puckett (1997). For analytical purposes the box cross-section is often idealized as consisting of thin slabs of constant thickness so that they can be analyzed based on classical beam theory as Menn points out (1990), even if they are thicker at their connections.

3.7.2 Implementation of Box Girders

Lee (1971) describes the variety of possible box girder configurations that can be achieved by altering the number of whole boxes and webs in these boxes. Most common is the box girder with a single box enclosed by two webs because of economical reasons. O'Connor (1971, pp227f) lists parameters that determine the particular box girder:

> *"(a) the shape of the cross section;*
>
> *(b) the ratio of the longitudinal dimension, or span [length], to the maximum cross-sectional dimension [i.e. depth];*
>
> *(c) a typical ratio of the width to thickness of a wall; and*
>
> *d) the diaphragm spacing, possibly expressed as a fraction of the span [length]."*

Its relatively simple geometry facilitates a rapid construction process by using formwork repeatedly, as in a form traveler for cast-in-place fabrication, or by prefabricating segments in a casting plant.

3.7.2.1 Width

Box girders are very versatile in alignment and can be adapted to a great variety of horizontal and vertical curves (camber) and superelevations in the transverse plane. O'Connor (1971, p228) notes their high torsional stiffness of closed box girder cross-section. The width of the box girder may even be adjusted to the required number of lanes for the roadways by varying the width of the cantilever flanges without affecting the box itself. As Fletcher (1984, p15) explains, bridge widths are normally between 10 and 12 m, 22 and 24 m, or 28 and 30 m, respectively, relating to "a carriageway of one, two or three lanes in each direction."

The wide deck, although integral with the primary structural system below, remains unobstructed from load-carrying member in any case. Transverse prestressing is used to provide enough stiffening against transverse bending moments in the wide cantilevering flanges.

3.7.2.2 Depth

The box girders need not only have a constant depth, but can also be varied in depth along the longitudinal axis of the bridge. Fletcher (1984) gives average values for the ratio of girder depth to span length of 1:17 at the supports and 1:50 at midspan. Less depth of the girders at midspan means less dead load and will lead to a more equal stress level throughout the bridge superstructure, since continuous depth leads to high bending moments at the supports. It will also provide more clearance below the bridge. Most people consider the appearance of a gently curved soffit that becomes more slender towards its middle pleasing. Cost for formwork, on the other hand, will be higher than for box girders with constant depth because of the necessary geometrical adjustments.

3.7.2.3 Span Length

Menn (1990) gives the economical range of span length for cast-in-place cantilevering as about 70 to 250 m, with major cost factors being the comparatively large pier heads and the form travelers cantilevering from these. With span lengths of up to 250 m technically feasible for a girder superstructure, much longer spans can be achieved in cable-stayed bridges and suspension bridges with steel box girders (Barker and Puckett 1997). In these long bridges, aerodynamic shaping of the boxes is strongly advised. Information on the development of these special so-called aerofoil cross-sections for long-span steel superstructures has already been given in Section 2.2.3.1.

3.7.2.4 Durability

With regards to durability, box girders have several advantages. Their closed cross-section will have less concrete surface directly exposed, thus reducing corrosion due to environmental conditions. However, according to Melaragno (1998) corrosion could also occur inside the girder because of condensation. Inspection and maintenance works inside the girder can be easily done with access through manholes at the piers or abutments. Mathivat (1983) gives information that initially tendon anchorages were located in the joints of segments so that they could hardly be accessed after placement of further segments. Nowadays, however, the common trend is to implement internally accessible anchorages in concrete blocks, so-called blisters on the inside of the box girder.

Other installations, such as gutter pipes and electric cables for lighting can also be situated within the box to preserve the plain outside appearance of the superstructure. Apart from these permanent installations the room inside can also be used to place a heater during cast-in-place construction if necessary, which helps with the curing process in addition to thermally insulated formwork and preheating of the concrete ingredients (Mathivat 1983).

3.7.2.5 Appearance

Box girders are generally considered attractive in terms of their appearance. The whole superstructure expresses simplicity (Muller and McCallister 1988) through its clear horizontal lines and the plain unobstructed surfaces. The closed box girder surfaces will also accumulate much fewer dirt than e.g. open truss systems with many edges and nodes. Visual lightness is achieved by a thin fascia band at the edge of the flanges that contracts with the girder lying in the shadow below the deck. Inclined webs even reinforce this effect and make the girder seem more slender (Barker and Puckett 1997).