Bridge Engineering Handbook

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Concrete Bridge Construction

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3.1 Introduction

This chapter focuses on the principle and practices related to construction of concrete bridges in which construction engineering contributes greatly to the successful completion of the projects. We first present the fundamentals of construction engineering and analyze the challenges and obstacles involved in such processes and then introduce the problems in relation to design, construction practices, project planning, scheduling, and control, which are the basis of future factorial improvements in effective construction engineering in the United States. Finally, we discuss prestressed concrete, high-performance concrete (HPC), and falsework in some details.

3.2 Effective Construction Engineering

The construction industry is a very competitive business, and many companies that engage in this marketplace develop proprietary technology in their field. In reality, most practical day-to-day issues are very common to the whole industry. Construction engineering is a combination of art and science and has a tendency to become more the art of applying science (engineering principles) and approaches to the construction operations (Blank and Blank 1995; Blank 1996). Construction engineering includes design, construction operation, and project management. The final product of design team effort is to
produce drawings, specifications, and special provisions for various types of bridges. A fundamental part of construction engineering is construction project management (project design, planning, scheduling, controlling, etc.).

Planning starts with analysis of the type and scope of the work to be accomplished and selection of techniques, equipment, and labor force. Scheduling includes the sequence and interrelation of operations both at a job site and with external aspects, as well as allocation of man power and equipment. Controlling consists of supervision, engineering inspection, detailed procedural instructions, record maintenance, and cost control. Good construction engineering analysis produces more valuable, effective, and applicable instructions, charts, schedules, and so on.

The objective is to plan, schedule, and control the construction process such that every construction worker and every activity contributes to accomplishing tasks with minimum waste of time and money and without interference. All construction engineering documents (charts, instructions, and drawings) must be clear, concise, definitive, and understandable by those who actually perform the work. As mentioned earlier in this section, the bridge is the final product of design team efforts. When all phases of construction engineering are completed, this product—the bridge—is ready for service loading. In all aspects of construction engineering, especially in prestressed concrete, design must be integrated for the most effective results. The historical artificial separation of the disciplines—design and construction engineering—was set forth to take advantage of the concentration of different skills in the workplace. In today’s world, the design team and construction team must be members of one team, partners with one common goal. That is the reason partnering represents a new and powerful team-building process, designed to ensure that projects become positive, ethical, and win-win experiences for all parties involved.

The highly technical nature of a prestressing operation makes it essential to perform preconstruction planning in considerable detail. Most problems associated with prestressed concrete could have been prevented by properly planning before the actual construction begins. Preconstruction planning at the beginning of the projects ensures that the structure is constructed in accordance with the plans, specifications, and special provisions and also helps detect problems that might arise during construction. It includes (1) discussions and conferences with the contractor; (2) review of the responsibilities of other parties; and (3) familiarization with the plans, specifications, and special provisions that relate to the planned work, especially if there are any unusual conditions. The preconstruction conference might include such items as scheduling, value of engineering, grade control, safety and environmental issues, access and operation considerations, falsework requirements, sequence of concrete placement, and concrete quality control (QC) and strength requirements. Preconstruction planning has been very profitable and in many cases has resulted in substantial reduction of labor costs. More often, in prestressed concrete construction the details of tendon layout, selection of prestressing system, mild-steel details, and so on, are left up to general contractors or their specialized subcontractors, with the designer showing only the final prestress and its profile and setting forth criteria. The contractors must understand the design consideration fully to select the most efficient and economical system. Such knowledge may, in many cases, provide a competitive edge, and construction engineering can play a very important role in it.

### 3.3 Construction Project Management

#### 3.3.1 General Principles

Construction project management (Fisk 1997) is a fundamental part of construction engineering. It is a feat that few, if any, individuals can accomplish alone. It may involve a highly specialized technical field or science, but it always includes human interactions, attitudes and aspects of leadership, common sense, and resourcefulness. Although no one element in construction project management can create success, failure in one of the foregoing elements will certainly be enough to promote failure and escalate costs. Today’s construction environment requires serious consultation and management of the
following life-cycle elements: design (including specifications, contract clauses, and drawings), estimating, budgeting, scheduling, procurement, bid ability–constructability–operability (BCO) review, permits and licenses, site survey, assessment and layout, preconstruction and mutual understanding conference, safety, regulatory requirements, QC, construction acceptance, coordination of technical and special support, construction changes and modifications, maintenance of progress drawing (red-lines), creating as-built drawings, and project records, among other elements.

Many construction corporations are becoming more involved in environmental restoration either under the Resource Conservation and Recovery Act or under the Comprehensive Environmental Response, Compensation, and Liability Act (otherwise commonly known as Superfund). This new involvement requires additional methodology and considerations by managers. Some elements that would otherwise be briefly covered or completely ignored under normal considerations may be addressed and required in a site’s Specific Health and Environmental Response Plan (SHERP). Some elements of the SHERP may include site health and safety staff, site hazard analysis, chemical and analytical protocol, personal protective equipment requirements and activities, instrumentation for hazard detection, medical surveillance of personnel, evacuation plans, special layout of zones (exclusion, reduction, and support), and emergency procedures.

Federal government contracting places additional demands on construction project management in terms of added requirements in the area of submittals and transmittals, contracted labor and labor standards, small disadvantaged subcontracting plans, and many other contractual certification issues, among others. Many of these government demands are recurring elements throughout the life cycle of the project, which may require adequate resource allocation (man power) not necessary under the previous scenarios.

The intricacies of construction project management require the leadership and management skills of a unique individual who is not necessarily a specialist in any one of the aforementioned elements but who has the capacity to converse and interface with specialists in various fields (i.e., chemists, geologists, surveyors, mechanics, etc.). An individual with a combination of an engineering undergraduate degree and a graduate business management degree is most likely to succeed in this environment. Field management experience can substitute for an advanced management degree.

It is the purpose of this section to discuss and elaborate elements of construction project management and to relate some field experience and considerations. The information presented here will only stimulate further discussion and is not intended to be all-inclusive.

### 3.3.2 Contract Administration

Contract administration focuses on the relationships between the involved parties during the contract performance or project duration. Owing to the nature of business, contract administration embraces numerous postaward and preaward functions. The basic goals of contract administration are to ensure that the owner is satisfied and all involved parties are compensated on time for their efforts. The degree and intensity of contract administration will vary from contact to contact, depending on the size and complexity of the effort to be performed. Since money is of the essence, too many resources can add costs and expenditures to the project, whereas insufficient resources may also cost in loss of time, in inefficiencies, and in delays. A successful construction project management program is one that has the vision and flexibility to allocate contract administrative personnel and resources wisely and that maintains a delicate balance in resources necessary to sustain required efficiencies throughout the project life cycle.

### 3.3.3 Project Design

Project design is the cornerstone of construction project management. In this phase, concepts are drawn, formulated, and created to satisfy a need or request. The design is normally supported by sound engineering calculations, estimates, and assumptions. Extensive reviews are performed to minimize
unforeseen circumstances, avoiding construction changes or modifications to the maximum extent possible in addition to verifying facts, refining or clarifying concepts, and dismissing assumptions. This phase may be the ideal time for identification and selection of the management team.

Normally, 33%, 65%, 95%, and 100% design reviews are standard practice. The final design review follows the 95% design review, which is intended to ensure that review comments have been either incorporated into the design or dismissed for consideration. Reviews include design analysis reviews and BCO reviews. It can be clearly understood from the nomenclature that a BCO encompasses all facets of a project. Bid ability relates to how the contact requirements are worded to ensure clarity of purpose or intent and understanding by potential construction contractors. Constructability concentrates on how components of the work or features of the work are assembled and how they relate to the intended final product. The main purpose of the constructability review is to answer questions such as whether a structure can be built in the manner represented in the contract drawings and specifications. Interaction between mechanical, civil, electrical, and other related fields is also considered here. Operability includes aspects of maintenance and operation, warranties, services, man power, and resource allocation during the life of the finished work.

The finished product of the design phase should include construction drawings illustrating dimensions, locations, and details of components; contract clauses and special clauses outlining specific needs of the construction contractor; specifications for mechanical, civil, and electrical or special equipment; a bidding and payment schedule with details on how parties will be compensated for work performed or equipment produced and delivered; responsibilities; and operation and maintenance (O&M) requirements. In many instances, the designer is involved throughout the construction phase for design clarification or interpretation, incorporation of construction changes or modifications to the project, and possible O&M reviews and actions. It is not uncommon to have the designer perform contract management services for the owner.

There are a number of computer software packages readily available to assist members of the management team in writing, recording, transmitting, tracking, safekeeping, and incorporating BCO comments. Accuracy of records and safekeeping of documentation regarding this process has proved to be valuable when a dispute, claim, design deficiency, or liability issue is encountered later during the project life cycle.

### 3.3.4 Planning and Scheduling

Planning and scheduling are ongoing tasks throughout the project until completion and occupancy occur by a certain date. Once the design is completed and the contractor selected to perform the work, the next logical step may be to schedule and conduct a preconstruction conference. Personnel representing the owner, designer, construction contractor, regulatory agencies, and any management/oversight agency should attend this conference. Among several key topics to discuss and understand, construction planning and scheduling is most likely to be the main subject of discussion. It is during this conference that the construction contractor may present how the work will be executed. The document here is considered the “baseline schedule.” Thereafter, the baseline schedule becomes a living document by which progress is recorded and measured. Consequently, the baseline schedule can be updated and reviewed in a timely manner and becomes the construction progress schedule. The construction progress schedule is the means by which the construction contractor records progress of work, anticipates or forecasts requirements so that proper procurement and allocation of resources can be achieved, and reports the construction status of work upwardly to the owner or other interested parties. In addition, the construction contractor may use progress schedule information to assist in increasing efficiencies or to formulate the basis of payment for services provided or rendered and to anticipate cash flow requirements. The construction progress schedule can be updated as needed, or as mutually agreed to by the parties, but for prolonged projects it is normally produced monthly.
A dedicated scheduler, proper staffing, and adequate computer and software packages are important to accomplish this task properly. On complex projects, planning and scheduling is a full-time requirement.

### 3.3.5 Safety and Environmental Considerations

Construction of any bridge is a hazardous activity by nature. No person may be required to work in surroundings or under conditions that are unsafe or dangerous to his or her health. The construction project management team must initiate and maintain a safety and health program and perform a job hazard analysis with the purpose of eliminating or reducing risks of accidents, incidents, and injuries during the performance of the work. All features of work must be evaluated and assessed to identify potential hazards and implement necessary precautions or engineer controls to prevent accidents, incidents, and injuries.

Frequent safety inspections and continued assessment are instrumental in maintaining the safety aspects and preventive measures and considerations related to the proposed features of work. In the safety area, it is important for the manager to be able to distinguish between accidents/incidents and injuries. Lack of recorded work-related injuries is not necessarily a measure of how safe the work environment is on the project site. The goal of every manager is to complete the job in an accident/incident- and injury-free manner, as every occurrence costs time and money.

Today’s construction operational speed, government involvement, and community awareness are placing more emphasis, responsibilities, and demands on the designer and construction contractor to protect the environment and human health. Environmental impact statements, storm water management, soil erosion control plans, dust control plans, odor control measures, analytical and disposal requirements, Department of Transportation (DOT) requirements for overland shipment, activity hazard analysis, and recycling are some of the many aspects that the construction project management team can no longer ignore or set aside. As with project scheduling and planning, environmental and safety aspects of construction may require significant attention from a member of the construction management team. When not properly coordinated and executed, environmental considerations and safety requirements can delay the execution of the project and cost significant amounts of money.

### 3.3.6 Implementation and Operations

Construction implementation and operations is the process by which the construction project manager balances all construction and contact activities and requirements to accomplish the tasks. The bulk of construction implementation and operations occur during the construction phase of the project. The construction project management team must operate in synchronization and maintain good communication channels to succeed in this intense and demanding phase. Many individuals in this field may contend that the implementation and operation phase of the construction starts with the site mobilization. Although it may be an indicator of actual physical activity taking place on site, construction implementation and operations may include actions and activities prior to the mobilization to the project site.

Here, a delicate balance is attempted to be maintained between all activities taking place and those activities being projected. Current activities are performed and accomplished by field personnel with close monitoring by the construction management staff. Near (~1 week ahead), intermediate (~2 to 4 weeks), and distant future (over 4 weeks) requirements are identified, planned, and scheduled to procure equipment and supplies, schedule work crews, and maintain efficiencies and progress. Coordinating progress and other meetings and conferences may take place during the implementation and operation phase.
3.3.7 Value Engineering

Some contracts include an opportunity for contractors to submit a value engineering (VE) recommendation. This recommendation is provided to either the owner or the designer. The purpose of VE is to promote or increase the value of the finished product while reducing the dollars spent or invested; in other words, to provide the desired function for the minimum costs. VE is not intended to reduce performance, reliability, maintainability, or life expectancy below the level required to perform the basic function. Important VE evaluation criteria are in terms of “collateral savings”—the measurable net reductions in the owner/agency’s overall costs of construction, operations, maintenance, and/or logistics support. In most cases, collateral savings are shared between the owner/agency and the proponent of the VE by reducing the contract price or estimated cost in the amount of the instant contract savings and by providing the proponents of the VE a share of the savings by adding the amount calculated to the contract price or fee.

3.3.8 Quality Management

During the construction of a bridge, construction quality management (CQM) plays a major role in QC and quality assurance (QA). CQM refers to all control measures and assurance activities instituted by the parties to achieve the quality established by the contract requirements and specifications. It encompasses all phases of the work, such as approval of submittals, procurements, storage of materials and equipment, coordination of subcontractor activities, and the inspections and the tests required to ensure that the specified materials are used and that installations are acceptable to produce the required product. The key elements of the CQM are the contractor quality control (CQC) and QA. To be effective, there must be a planned program of actions and lines of authority and responsibilities must be established. CQC is primarily the construction contractor’s responsibility, whereas QA is primarily performed by an independent agency (or other than the construction contractor) on behalf of the designer or owner. In some instances, QA may be performed by the designer. In this manner, a system of checks and balances is achieved, minimizing the conflicts between quality and efficiency that are normally developed during construction. Consequently, CQM is a combined responsibility.

In the CQC, the construction contractor is primarily responsible for (1) producing the quality product on time and in compliance with the terms of the contract, (2) verifying and checking the adequacy of the construction contractor’s QC program of the scope and character necessary to achieve the quality of construction outlined in the contract, and (3) producing and maintaining acceptable record of its QC activities. In the QA, the designated agency is primarily responsible for (1) establishing standards and QC requirements; (2) verifying and checking adequacy of the construction contractor’s QC (QA for acceptance), performing special tests and inspections as required in the contract, and determining that reported deficiencies have been corrected; and (3) assuring timely completion.

3.3.9 Partnership and Teamwork

A great deal of construction contract success attributes to partnering. Partnering should be undertaken and initiated at the earliest opportunity during the construction project management cycle. Some contracts may have a special clause, which is intended to encourage the construction contractor to establish clear channels of communication and effective working relationships. The best approach to partnering is for the parties to volunteer to participate.

Partnering differs from the team-building concept. Team building may encourage establishing open communications and relationships when all parties share liabilities, risk, and money exposure, but not necessarily share costs of risks. The immediate goal of partnering is to establish mutual agreements at the initial phase of the project on the following areas: identification of common goals, identification of common interests, establishment of communication, and establishment of lines of authority and decision-making commitment to cooperative problem solving, among others.
Partnering takes the elements of luck, hope, and personality out of determining project success. It facilitates workshops in which stakeholders in a specific project or program come together as a team, which results in breakthrough success for all parties involved. To increase awareness in partnership and teamwork in the Department of the Army, Philadelphia district, Corps of Engineers, Dr. Michael Blank and Capt. Jeff Barson, have initiated the “Partnering Team Award.” This award was approved by the commander of the army, Corps of Engineers (Philadelphia district).

It aimed to recognize teams (internal and external to the district) who have achieved the best exemplification of partnering and team approach to the mission accomplishment. Now it has been given annually to the team of teams, which embodies the spirit, code, and principles of effective partnering while fostering a customer-focused relationship that produces the best-quality work ahead of schedule, under budget, and with the newest and most innovative technology available.

Over the past few years, the partnering process has been well defined in published papers by different authors, equally coming from both the government and the private sectors (Kubai 1994; Godfrey 1995; Schriener 1995; Tri-Service Committee 1996; Blank et al. 1997).

Air Force, Navy and the Army have had a positive experience and have acquired skilled expertise in the implementation of partnering in their various civil works (bridges, road construction, etc.), military, and support for other (U.S. Environmental Protection Agency, Federal Aviation Administration, etc.) projects.

Another success example is the Office of Structure Construction (OSC) of the California Department of Transportation (Caltrans). Richmond field office (part of OSC) with his Structures Engineer Simon A. Blank and partnering team of Kiewit Pacific Company (a Kiewit company) contributed to achieve effective partnering in a work, which resulted not only of high quality, but was delivered in the safest manner possible in widening bridges at Highway I-80 corridor in cities of Berkeley and Emeryville in San Francisco Bay Area.

In partnership with the districts and other clients, the OSC does the following to achieve the best results in partnering:

- Administers and inspects the construction of the Caltrans transportation structures and related facilities in a safe and efficient manner
- Provides specialized equipment and training, standards, guidelines, and procedural manuals to ensure consistency of inspection and administration by statewide OSC staff
- Provides consultations on safety for OSC staff and district performing structure construction inspection work
- Conducts reviews and provides technical consultation and assistance for trenching and shorting temporary support and falsework construction reviews
- Provides technical recommendations on the preparation of structure claims and the contract change orders (CCOs)
- Provides construction engineering oversight on structure work on non-state-administrated projects
- Conducts BCO review

### 3.3.10 Project Completion and Turnover of Facility

Success in construction project management may be greatly impacted during project completion and turnover of the facilities to the user or owner. The beginning of the project completion and turnover phase may be identified by one of the following: punch list developed, prefinal inspections scheduled, support areas demobilized, and site restoration initiated, just to mention a few. Many of the problems encountered during completion of this last phase may be avoided or prevented with proper user or owner participation and involvement during the previous phases, particularly during the construction phase where changes and modifications may have altered the original design. A good practice in preventing conflicts during the completion and turnover of the facilities is to invite the owner or user
to all construction progress meetings and acceptance inspections. In this manner, the user or owner is completely integrated during the construction with ample opportunity to provide feedback and be part of the decision-making process. In addition, by active participation, the owner or user is being informed and made aware of changes, modifications, and/or problems associated with the project.

### 3.4 Major Construction Considerations

Concrete bridge construction involves site investigation; structure design; selection of materials—steel, concrete, aggregates, and mix design; workmanship of placement and curing of concrete; and handling and maintenance of the structure throughout its life. Actually, site investigations are made of any structure, regardless of how insignificant it may be. The site investigation is very important for intelligent design of the bridge structures and has significant influence on selection of the material and mix. A milestone is to investigate the fitness of the location to satisfy the requirements of the bridge structure. Thus, investigation of the competence of the foundation to carry the service load safely and an investigation of the existence of forces or substances that may attack the concrete structure can proceed. Of course, the distress or failure may have several contributing causal factors: unsuitable materials, construction methods, and loading conditions; faulty mix design; design mistakes; conditions of exposure; curing condition; or environmental factors.

### 3.5 Structural Materials

#### 3.5.1 Normal Concrete

**3.5.1.1 Important Properties**

Concrete is the only material that can be made on site and is the most dependable and versatile construction material practically used in bridge construction (Naway 2008). Good durable concrete is quality concrete that meets all structural and aesthetic requirements for a period of structure life at minimum cost. We are looking for properties such as workability in the fresh condition; strength in accordance with design, specifications, and special provisions; durability; volume stability; freedom from blemishes (scaling, rock pockets, etc.); impermeability; economy; and aesthetic appearance. Concrete, when properly designed and fabricated, can actually be crack-free, not only under normal service loads, but also under moderate overload, which is very attractive for bridges that are exposed to an especially corrosive atmosphere.

The codes and specifications usually specify the minimum required strength for various parts of a bridge structure. The required concrete strength is determined by design engineers. For cast-in-place concrete bridges, a compressive strength of 3250–5000 psi (22–33 MPa) is usual. For precast structures, compressive strength of 4000–6000 psi (27–40 MPa) is often used. For special precast, prestressed structures compressive strength of 6000–8000 psi (40–56 MPa) is used by Caltrans: whenever the 28-day compressive strength shown on the plans is greater than 3600 psi, the concrete shall be designated by strength.

If the plans show a 28-day compressive strength that is 4000 psi or greater, an additional 14 days will be allowed to obtain the specified strength. The 28-day compressive strength shown on the plans that is 3600 psi or less is shown for design information only and is not a requirement for acceptance of the concrete. Other properties of concrete are related to the strength, although not necessarily dependent on the strength.

Workability is the most important property of fresh concrete and depends on the properties and proportioning of the materials: fine and coarse aggregates, cement, water, and admixtures. Consistency, cohesiveness, and plasticity are elements of workability. Consistency is related to the fluidity of mix. Just adding water to a batch of concrete will make the concrete more fluid or “wetter,” but the quality of the concrete will diminish. Consistency increases when water is added and an average of 3% in total water
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per batch will change the slump about 1 in. (2.54 cm). Both research and practice show that workability is a maximum in concrete of medium consistency, between 3 in. (7.62 cm) and 6 in. (15.24 cm) slump. Very dry or wet mixes produce less workable concrete. Use of relatively harsh and dry mixes is allowed in structures with large cross sections, but congested areas containing much reinforcement steel and embedded items require mixes with a high degree of workability.

A good and plastic mixture is neither harsh nor sticky and will not segregate easily. Cohesiveness is not a function of slump, as very wet (high-slump) concrete lacks plasticity. On the other hand, a low-slump mix can have a high degree of plasticity. A harsh concrete lacks plasticity and cohesiveness and segregates easily.

Workability has a great effect on the cost of placing concrete. Unworkable concrete not only requires more labor and effort in placing, but also produces rock pockets and sand streaks, especially in small congested forms. It is a misconception that compaction or consolidation of concrete in the form can be done with minimum effort if concrete is fluid or liquid to flow into place. It is obvious that such concrete will flow into place but segregate badly, so that large aggregate will settle out of the mortar and excess water will rise to the top surface. Unfortunately, this error in workmanship will become apparent after days, even months later, showing up as cracks, low strength, and general inferiority of concrete. The use of high-range water-reducing admixtures (superplasticizers) allows placing of high-slump, self-leveling concrete. They increase strength of concrete and provide great workability without adding an excessive amount of water. An example of such products used in Caltrans is PolyHeed 997, which meets the requirements for a type A, water-reducing admixture specified in American Society for Testing and Materials (ASTM) C 494–92, Corps of Engineers CRD-C 87–93, and American Association of State Highway and Transportation Officials 194–87, the standard specifications for chemical admixtures for concrete.

3.5.1.2 Special Consideration for Cold Weather Construction

Cold weather can damage a concrete structure by freezing of fresh concrete before the cement has achieved final set and by repeated cycles of freezing of consequent expansion of water in pores and openings in hardened concrete. Causes of poor frost resistance include poor design of construction joints and segregation of concrete during placement; leaky formwork; poor workmanship, resulting in honeycomb and sand streaks; and insufficient or absent drainage, permitting water to accumulate against concrete. To provide resistance against frost, it is suggested to design adequate drainage. If horizontal construction joints are necessary, they should be located below the low-water or above the high-water line about 2–3 ft. (0.6–1 m). Previously placed concrete must be cleaned up. The concrete mix should have 7% (maximum) air for ½ in. (12.7 mm) or ⅞ in. (19 mm) (maximum) aggregate, ranging down to 3%–4% for cobble mixes. It is essential to use structurally sound aggregates with low porosity. The objective of frost-resistant concrete mix is to produce good concrete with smooth, dense, and impermeable surface. This can be implemented by good construction technique used in careful placement of concrete as near as possible to its final place, avoiding segregation, sand streaks, and honeycomb under proper supervision, QC, and QA.

Sudden changes in temperature can stress concrete and cause cracking or crazing. A similar condition exists when cold water is applied to freshly stripped warm concrete, particularly during hot weather. For the best results, the temperature difference should not exceed 25°F between concrete and curing water. In case when anchor bolt holes were left exposed to weather, filled with water, freezing of water exerted sufficient force to crack concrete. This may happen on the bridge pier cap under construction.

3.5.1.3 Concrete Reinforcement and Placement

The optimum condition for structural use is a medium slump of concrete and compaction by vibrators. A good concrete with low slump for the placing conditions can be ruined by insufficient or improper consolidation. Even workable concrete may not satisfy the needs of the bridge structure if it is not properly consolidated, preferably by vibration. An abrupt change in size and congestion of reinforcement not only makes proper placing of concrete difficult but also causes cracks to develop. Misplacement of
reinforcement within concrete will greatly contribute to development of structure cracks. The distress and failure of concrete are mostly caused by ignorance, carelessness, wrong assumptions, and so on.

### 3.5.1.4 Concrete Mix and Trail Batches

The objective of concrete mix designs and trail batches is to produce cost-effective concrete with sufficient workability, strength, and impermeability to meet the conditions of placing, finishing characteristics, exposure, loading, and other requirements of bridge structures. A complete discussion of concrete mixes and materials can be found in many works such as the *Concrete Construction Engineering Handbook* by Naway (2008). The purpose of trail batches is to determine strength, water–cement ratio, combined grading of aggregates, slump, type and proportioning of cement, aggregates, entrained air, and admixtures as well as scheduling of trail batches and uniformity. Trail batches should always be made for bridge structures, especially for large and important ones. They should also be made in cases where there is no adequate information available for existing materials used in concrete mixes, and they are subjected to revisions in the field as conditions require.

### 3.5.1.5 Consideration to Exposure Condition

Protection of waterfront structures should be considered when they are being designed. Designers often carefully consider structure aesthetic aspects without consideration of exposure conditions. Chemical attack is aggravated in the presence of water, especially in transporting the chemicals into the concrete through cracks, honeycombs, or pores in surfaces. Use of chamfers and fillers is a good construction practice. Chamfering helps prevent spalling and chipping from moving objects. Fillets in reentrant corners eliminate possible scours or cracking. Reinforcement should be well covered with sound concrete and in most cases 3 in. (7.62 cm) coverage is specified. First-class nonreactive and well-graded aggregates in accordance with the Uniform Building Code standard should be used. Cement type II or type Y with a low amount of C3 should be used. Careful consideration should be given to the use of an approved pozzolan with a record of successful usage in a similar exposure. Mix design should contain an adequate amount of entrained air and other parameters in accordance with specifications or a special provision for a particular project. The concrete should be workable with slump and water–cement ratio as low as possible and containing at least 560 pcy (332 kg/m³). To reduce mixing water for the same workability and, by the same token, to enhance strength and durability, a water-reducing mixture is preferred. The use of calcium chloride and type III cement for acceleration of hardening and strength development is precluded. Concrete should be handled and placed with special care to avoid segregation and prevent honeycomb and sand streaks. The proper cure should be taken for at least 7 days before exposure.

### 3.5.2 High-Performance Concrete

HPC is composed of the same materials used in normal concrete, but proportioned and mixed to yield a stronger, more durable product. HPC structures last much longer and suffer less damage from heavy traffic and climatic condition than those made with conventional concrete. To promote the use of HPC in highway structures in the United States, a group of concrete experts representing the state DOTs, academia, the highway industry, and the Federal Highway Administration (FHWA) has developed a working definition of HPC (FHWA 2005), which includes performance criteria and the standard test to evaluate performance when specifying an HPC mixture. The designer determines what levels of strength, creep, shrinkage, elasticity, freeze/thaw durability, abrasion resistance, scaling resistance, and chloride permeability are needed. The definition specifies what test grade of HPC satisfies these requirements and what to perform to confirm that the concrete meets the grade.

An example of the mix design for the 12,000-psi high-strength concrete used in the Orange County courthouse in Florida is as follows:

The Virginia and Texas DOTs have already started using HPC, that is, ultra-high-strength concrete of 12,000–15,000 psi (80–100 MPa), in bridge construction and rehabilitation of the existing bridges.
3.5.3 Steel

In the bridges, reinforcing bars shall be low-alloy steel deformed bars conforming to the requirements in ASTM Designations A 706/A 706M, except that deformed or plain billet steel bars conforming to the requirements in ASTM Designation A 615/A 615M, grade 40 or 60, may be used in other categories: slope and channel paving, minor structures, and so on. Prestressing steel shall be high-tensile wire conforming to the requirements in ASTM Designation A 421, including Supplement I; high-tensile seven-wire strands conforming to A 416; or uncoated high-strength steel bars conforming to A 722, including all supplementary requirements that are usually used.

In addition, epoxy-coated seven-wire prestressing steel strands in addition shall conform to ASTM Designation A 882/A 882M, including Supplement I and other requirements, for example, California Standard Specification (Caltrans 2010).

All prestressing steel needs to be protected against physical damage and rust or other results of corrosion at all times from manufacture to grouting or encasing in concrete. Prestressing steel that has physical damage at any time needs to be rejected. Prestressing steel for posttensioning that is installed in members prior to placing and curing of the concrete needs to be continuously protected against rust or other corrosion until grouted, by a corrosion inhibitor placed in the ducts or applied to the steel in the duct. The corrosion inhibitor should conform to the specific requirements. When steam curing is used, prestressing steel for posttensioning should not be installed until the stem curing is completed. All water used for flushing ducts should contain either quick lime (calcium oxide) or slaked lime (calcium hydroxide) in the amount of 0.01 kg/L. All compressed air used to blow out ducts should be oil free.

3.6 Construction Operations

3.6.1 Prestressing Methods

If steel reinforcement in reinforced concrete structures is tensioning against the concrete, the structure becomes a prestressed concrete structure. This can be accomplished by using pretensioning and posttensioning methods (Gerwick 1997).

3.6.1.1 Pretensioning

Pretensioning is accomplished by stressing tendons, steel wires, or strands to a predetermined amount. Whereas stress is maintained in the tendons, concrete is placed in the structure. After the concrete in the structure has hardened, the tendons are released and the concrete bonded to the tendons becomes prestressed. In pretensioning techniques, hydraulic jacks and strands composed of several wires twisted around a straight center wire are widely used. Pretensioning is a major method used in manufacture of prestressed concrete in the United States. The basic principles and some of the methods currently used in the United States were borrowed from Europe, but much has been done in the United States.
to develop and adapt manufacturing procedures. One such adaptation uses pretensioned tendons that do not pass straight through the concrete member, but are deflected or draped into a trajectory that approximates a curve. This method is very widely used in the fabrication of precast bridge girders in the United States.

### 3.6.1.2 Posttensioning

A member is called posttensioned when the tendons are tensioned after the concrete has hardened and attained sufficient strength (usually 70% final strength) to withstand the prestressing force, and each end of the tendons is anchored. Figure 3.1 shows a typical posttensioning system. A common method used in the United States to prevent tendons from bonding to the concrete during placing and curing of the concrete is to encase the tendon in a mortar-tight tube or flexible metal hose before placing it in the forms.

The metal hose or tube is referred to as a sheath or duct, and remains in the structure. After the tendons have been stressed, the void between the tendons and the duct is filled with grout. The tendons become bonded to the structural concrete and protected from corrosion. A construction engineer can use prestressing very effectively to overcome excessive temporary stresses or deflections during construction, for example, using cantilevering techniques in lieu of falsework.

Prestressing is not a fixed state of stress and deformation, but is time dependent. Both concrete and steel may be deformed inelastically under continued stress. After being precompressed, concrete continues to shorten with time (creep). Loss of moisture with time also contributes to a shortening (shrinkage). To reduce prestress losses due to creep and shrinkage and to increase the level of precompression, use of not only higher-strength steel but also higher-strength concrete that has low creep, shrinkage, and thermal response is recommended. New chemical admixtures such as high-range water-reducing admixtures (superplasticizers) and slag are used for producing HPC and ultra-high-strength concrete. The new developments are targeted to producing high-strength steel that is “stabilized” against stress relaxation, which leads to a reduction of stress in tendons, thus reducing the prestress in concrete.

**FIGURE 3.1** A typical posttensioning system.
3.6.2 Fabrication and Erection Stages

During construction, not all elements of a bridge have the same stresses that they were designed for. That is the reason it is a very important part of construction engineering to be aware of this and to make sure that appropriate steps have been taken. For example, additional reinforcement will be added to the members in the fabrication stage and delivered to the job site for erection.

In the case of cast-in-place box-girder bridge construction, the sequences of prestressing tendons have to be engineered step by step to ensure that the structure will have all parameters for future service load after completion of this stage (Caltrans 2006).

The sequence of the erection itself may produce additional stresses that structures or portions of the structures were not designed for. These stresses and the stability of structures during erection are a big concern that is often overlooked by designers and contractors—construction sequences play a very important role in the erection of a segmental type of bridge. It seems that we have to give more attention to analysis of the role of the construction engineering implementation of such erections. And, yes, sometimes the importance of construction engineering to accomplish safe and efficient fabrication and erection of bridge structures (precast, prestress girders, cast-in-pile structures) is not sufficiently emphasized by design engineers and/or fabrication contractors.

Unfortunately, we have to admit that the design drawings even for an important bridge do not include the erection scheme. And, of course, we can show many examples of misplaced erection efforts on the part of the designer, but our goal is to show why it happened and to make efforts to pay more attention to the fabrication and erection stages. Even if such an erection scheme is included in the design drawings, contractors are not supposed to rely solely on what is provided by the designer’s erection plan.

Sometimes a design can be impractical, or it may not be suitable in terms of erection contractor’s equipment and experience. Because the erection plans are very generalized and because not enough emphasis is given to the importance of this stage, it is important that the designer understands the contractor’s proposed method so that the designer can determine if these methods are compatible with the plans, specifications, and requirements of the contract. This is the time when any differences should be resolved. The designer should also discuss any contingency plan in case the contractor has problems. In many instances, the designer is involved throughout the construction phase for design and specification clarification or interpretation, incorporation of construction changes or modifications to the project, and possible O&M reviews/action.

3.6.3 Construction of Concrete Box-Girder Bridges

A successful innovative approach in the design and construction of concrete box-girder bridges is the I-680/24 project. Built in the late 1950s, the I-680/24 interchange was expected to accommodate 70,000 vehicles a day. Today it carries an estimated 380,000 vehicles. Caltrans designed the I-680/24 to eliminate the dramatic increase in congestion and driver frustration.

It was the largest freeway interchange reconstruction project in Northern California, incorporating some of the latest seismic safety features throughout the project area, and became one of the state’s most advanced freeway systems. The total cost of the I-680/24 project was $315 million.

It was built in seven phases. Phase 6 was the largest and most challenging phase of the project.

Caltrans simultaneously modified several ramps and streets serving the interchange.

The following freeway-to-freeway connectors were rebuilt to the three lanes:

- Eastbound State Route-24 to northbound I-680
- Southbound I-680 to westbound State Route-24
- Northbound and southbound I-680

The new connectors and the new on- and off-ramps throughout the project area eliminated congestion-causing traffic weaves.
Before the interchange work began, a 1 mi. temporary bypass was built in phase 3 to carry southbound I-680 traffic from Ygnacio Valley Road to Olympic Boulevard, California. This bypass begins to rise above the existing roadway at the Oakvale overcrossing, curving and descending to rejoin the permanent roadway near Olympic. When the interchange reconstruction was near completion, the bypass was removed and the materials (steel I-beams) were recycled for use in three-span bridge in the Olympic off-ramp.

Careful construction planning kept disruptions to a minimum throughout the project.

When work on phase 5 started in October 1997, Caltrans awarded a special incentive contract to R&L Brosamer, a Walnut Creek-based construction firm. The terms of the contract allow Brosamer and its subcontractors to work around the clock and in any weather to deliver scheduled work. As a result, construction activity occurred at a rapid pace.

In phase 7, Caltrans reconfigured the Monument Boulevard area into an “urban diamond interchange.” The new interchange featured northbound and southbound on- and off-ramps, controlled by an intersection with one signal under the freeway instead of the traditional two intersections on either side of the street. To minimize the weave at the junction of I-680/24, exit-only lanes for Gregory Lane and Monument Boulevard from I-680 are included as part of this construction (Figure 3.2).

An innovative concrete box girder on a straight alignment over the freeway is a pedestrian bicycle bridge with a span without a median column, which crosses I-80 in Berkeley, California. The bridge is designed to handle the seismic forces generated by the San Andreas and Hayward faults, two major faults within 3–14 km of the site (Caltrans 2002).

The bridge was erected into major phase, the first being the steel-reinforced, posttensioned lightweight concrete bridge deck on falsework. Steel arches were raised and welded in place (Figures 3.3 and 3.4). Even though the bridge is primarily being used by pedestrians and bicyclists, it was designed and constructed to accommodate vehicular traffic in case of emergencies. The steel “basket handle” arch is one of the most prominent features of the bridge. Another unusual feature is the curvature of the posttensioned box-girder span.

![Figure 3.2 Former Caltrans bridge engineer Simon Blank at the I-680/24 Interchange, Walnut Creek.](image-url)
3.6.4 Construction of High-Performance and Ultra-High-Performance Concrete Bridges

When the first U.S. HPC bridge was built under the Strategic Highway Research Program, the FHWA and the Texas DOT sponsored a workshop to showcase HPC for bridges in Houston in 1996. The Center for Transportation Research at the University of Texas at Austin also cooperated with them at the event. It was focused on the pros and cons of using HPC; mix proportioning; structural design; HPC in precast, prestressed, and cast-in-place members; long-term performance; and HPC projects in Nebraska, New Hampshire, and Virginia. The showcase took into consideration local differences in cements, aggregates, and prestressing fabricators because they have considerable impact on the design and construction of concrete structures. In Texas, concrete can be produced with compressive strength of 13,000–15,000 psi (90–100 MPa).

The first bridge to use HPC fully in all aspects of design and construction is the Louetta Road Overpass on State Highway 249 in Houston. The project consists of two U-beam bridges carrying two adjacent lanes of traffic. The spans range from 121.5 to 135.5 ft. (37–41.3 m) long. The HPC is about twice as strong as conventional concrete and expected to have a useful life of 75–100 years, roughly double the average life of a standard bridge. A longer life span means not only lower user cost, but also motorists will encounter fewer lanes closures and other delays caused by maintenance work.

FIGURE 3.3 Berkeley Pedestrian Bridge with former Caltrans bridge engineer Hamid Kondazi, who managed the construction.

FIGURE 3.4 Berkeley Pedestrian Bridge—curved eastern approach ramp.
Another Texas HPC bridge located in San Angelo carries the eastbound lanes of U.S. Route 67 over the North Concho River, U.S. Route 87, and South Orient railroad. The 954 ft. (291 m) HPC I-beam bridge runs parallel to a conventional concrete bridge. This bridge presents an ideal opportunity for comparing HPC and conventional concrete.

The first spans of the two bridges are of the same length and width, making it easy to compare the cost and performance between HPC and conventional concrete. The comparison indicates that the conventional concrete lanes of the first span require seven beams with 5.6 ft. (1.7 m) spacing, whereas the HPC span require only four beams with 11 ft. (3.4 m) spacing.

To date, more than 50 HPC bridges have been built in the United States. The Jakway Park Bridge in Buchanan County, Iowa, has earned the right to be called innovative. It is the first North American highway bridge built with a new generation of ultra-high-performance concrete PI girders, the first highway bridge to incorporate UNPC batched in a ready-mix truck with compressive strength of 29,000 psi (200 MPa).

### 3.7 Falsework

Falsework may be defined as a temporary framework on which the permanent structure is supported during its construction. The term falsework is universally associated with the construction of cast-in-place concrete structures, particularly bridge superstructures. The falsework provides a stable platform on which the forms may be built and furnish support for the bridge superstructure.

Falsework is used in both building and bridge construction. The temporary supports used in building work are commonly referred to as “shoring.” It is also important to note the difference between “formwork” and “falsework.”

Formwork is used to retain plastic concrete in its desired shape until it has hardened. It is designed to resist the fluid pressure of plastic concrete and the additional pressure generated by vibrators. Because formwork does not carry dead load of concrete, it can be removed as soon as the concrete hardens. Falsework does carry the dead load of concrete, and therefore it has to remain in place until the concrete becomes self-supporting. Plywood panels on the underside of a concrete slab serve as both a formwork and a falsework member. For design, however, such panels are considered to be forms to meet all design and specification requirements applied to them.

Bridge falsework can be classified into two types: (1) conventional systems (Figure 3.5), in which the various components (beams, posts, caps, bracings, etc.) are erected individually to form the completed system; and (2) proprietary systems, in which metal components are assembled into modular units that can be stacked, one above the other, to form a series of towers that compose the vertical load-carrying members of the system.

![Falsework at I-680/24 Interchange South-East connector, Walnut Creek.](image_url)
The contractor is responsible for designing and constructing safe and adequate falsework that provides all necessary rigidity, supports all load composed, and produces the final product (structure) according to the design plans, specifications, and special provisions. It is very important also to keep in mind that approval by the owner of falsework working drawings or falsework inspection will in no way relieve the contractor of full responsibility for the falsework. In the state of California, any falsework height that exceeds 13 ft. (4 m) or any individual falsework clear span that exceeds 17 ft. (5 m) or where provision for vehicular, pedestrian, or railroad traffic through the falsework is made, the drawings have to be signed by the registered civil engineer in the state of California.

The design drawings should include details of the falsework removal operations, methods and sequences of removal, and equipment to be used. The drawings must show the size of all load-supporting members, connections and joints, and bracing systems. For box-girder structures, the drawings must show members supporting sloping exterior girders, deck overhangs, and any attached construction walkway. All design-controlling dimensions, including beam length and spacing, post locations and spacing, overall height of falsework bents, and vertical distance between connectors in diagonal bracing must be shown.

For example, in the largest freeway interchange reconstruction project in Northern California with total cost of $315 million, Simon Blank, structure engineer at Walnut Creek field office (Caltrans), reviewed all falsework drawings and calculations submitted by the general contractor, CC Meyers, Co., and then inspected falsework construction to make sure it substantially conformed to the falsework drawings. He later inspected the falsework removal operations after completion of the construction of NE and SE connectors.

As a policy consideration, minor deviations to suit field conditions or the substitutions of materials are permitted when it is evident by inspection that the change does not increase the stresses or deflections of any falsework members beyond the allowable values, nor reduce the load-carrying capacity of the overall falsework system.

But if revision is required, the approval of revised drawings by the state engineer is also required. Any change in the approved falsework design, however minor it may appear to be, has the potential to affect adversely the structural integrity of the falsework system. Therefore, before approving any changes, the engineer has to be sure that such changes will not affect the falsework system as a whole.

References


