Chapter 10 – STRUCTURAL DESIGN

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CHAPTER 10

STRUCTURAL DESIGN

10.1 GENERAL

The purpose of this chapter is to provide standards, guidance and techniques for designing bridges, retaining walls, tunnels, large span culverts and other structural items. Also see Chapter 1 for general policies and guidance. The goal of a structural design is to produce a structure that:

- Serves the purpose for which it is intended;
- Is capable of co-existing within its immediate environment without causing adverse impacts (i.e., visual, physical); and
- Is economical from both a maintenance and construction point of view.

Structural design requires a solid understanding of the techniques of structural analysis and the behavior of a structure under various loading conditions. Structural design also requires knowledge of concrete, steel and timber material properties.

Awareness of factors related to other engineering fields (e.g., hydraulics, soils) is necessary to ensure that the structure functions without affecting or being affected by its environment in a detrimental way. Finally, the importance of aesthetic appeal must be recognized to make the structure an extension of nature rather than an intrusion on nature.

The Federal Lands Highway Office of Bridges and Structures (FLH Bridge) employs a staff of professional structural/bridge engineers and technicians who develop plans, specifications, and estimates (PS&E) for projects and provide construction support and occasionally oversee the actual construction.

Since structural elements do not normally comprise the entire highway project, the structural engineer will generally function as part of a design team.

The Project Manager has the overall responsibility for seeing that all aspects of the project are addressed.

However, the structural designer must obtain supporting data from the environmental, geotechnical, roadway design, survey, and hydraulics staff and coordinate the structural design with these technical units. The structural engineer is responsible for the following:

- Developing bridge type, size and location (TS&L);
- Designing bridges, retaining walls and other structures;
- Preparing complete PS&E for structures;
- Providing technical assistance to construction staff;
- Reviewing contract shop drawings; and
- Providing technical assistance to other agencies as requested.

Refer to [EFLHD – CFLHD – WFLHD] Division Supplements for more information.

10.1.1 BRIDGES

Bridges are the most common major structure encountered in highway engineering and the most varied in design. Bridges range from simple designs (e.g., a timber deck on stringers that are supported at each end) to very complex designs (e.g., segmental, cable-stayed, suspension bridges). Span lengths can vary from 20 ft [6 m] to hundreds of feet [meters]. Each bridge location is different and in most cases it is necessary to custom-fit a bridge structure into its surroundings. This generally precludes the use of wholly standardized plans and specifications in the design of bridges and requires that each bridge be handled individually.

Structural engineering work consists of designing new structures and repairing or rehabilitating existing ones. Bridges include both simple and continuous span structures constructed of reinforced concrete, prestressed concrete, steel, timber or a combination of these materials. Span lengths generally range from 20 ft [6 m] to approximately 200 ft [60 m]. As a general rule, slab-type superstructures (i.e., cast-in-place, precast, prestressed units) are economical for span lengths up to 50 ft [15 m]. Conventional composite superstructures consisting of a deck slab supported by steel stringers or concrete beams are commonly used for spans up to 100 ft [30 m]. For span lengths ranging between 100 ft and 150 ft [30 m and 46 m] a prestressed concrete bulb-tee or composite steel plate girder can be used. Structures with span lengths greater than 150 ft [46 m] require special consideration.

Bridge rehabilitation includes repairs, reconstructs, replaces or retrofits of various structural components, such as railing system, joints, deck, superstructures, substructures, etc. The most common bridge rehabilitation involves the repair of concrete decks that have been damaged by corrosion of the steel reinforcing in the deck. The type of repair needed depends on the level of concrete and steel deterioration. A deck that is severely deteriorated may have to be entirely replaced, whereas one that is moderately deteriorated could be made usable by removing and replacing all unsound materials. For decks in the initial stages of deterioration, one preventive solution may be to install a cathodic protection system to stop further corrosion.

10.1.2 SPECIAL DESIGNS

The structural engineer may occasionally become involved with certain types of bridges or other structures that differ from those normally handled and would therefore be considered special designs. This category includes major bridges having exceptionally long spans and/or requiring unique design and construction techniques. Examples are cable-stayed bridges, segmental bridges, long-span box girder bridges, and arch bridges. Designing these types of structures often requires specific expertise.

In general, certain structures (e.g., box culverts, sign supports) lend themselves to a standardized design. This enables the roadway designer to handle these types of structures with little or no assistance from the structural engineer. Occasionally, standard designs or plans are not entirely applicable to the conditions encountered and a modified or custom design is necessary.

An example of a modified standard design would be a box culvert that is required to have dimensions larger than what are detailed in the standard plans. The structural engineer would then be responsible for developing plans and specifications for the structure. It is therefore important that the structural engineer understand the principles governing the design of these structures and also that the engineer recognize the factors that influence their design.

In addition to the structure itself, the structural engineer is sometimes called upon to design structural components for guardrails, sign supports, lighting supports, pedestrian screening, etc.

The following provides brief descriptions for the design of retaining walls, tunnels and culverts:

1. **Retaining Walls**. The retaining wall as a highway structure serves one of two functions:
    - To maintain the stability of a roadway embankment in fill areas, or
    - To prevent unstable material from sloughing off onto the roadway surface in cut areas.

    The design of retaining walls is normally carried out by the structural engineer.
2. **Tunnels**. Because of their high construction costs, highway tunnels have limited use and should only be considered when other more cost-effective alternatives are not practical. The successful design of a tunnel is dependent upon a comprehensive geologic study performed by qualified geotechnical engineers to determine the presence of faults, badly fractured rock, seams, water, etc. It is vital that the structural engineer work closely with the geotechnical engineers to determine requirements for lining, drainage and methods of excavation.
3. **Culverts**. Culverts with clear spans greater than 10 ft [3 m] are generally described as large culverts and are in most instances designed for a specific site condition by a structural engineer. While these structures are described as culverts, they are in most cases not used as drainage structures, but are used to pass farm livestock, farm machinery, industrial equipment or people through an earth embankment. Typically, these large culverts are low profile steel arch superspans with spans from 20 ft to 40 ft [6 m to 12 m], rigid frame reinforced concrete box structures with spans in the 13 ft to 18 ft [4 m to 5.5 m] range and precast prestressed concrete low profile arch structures with spans in the 29.5 ft to 40 ft [9 m to 12 m] range.

10.2 GUIDANCE AND REFERENCES

The FLH Program includes a wide variety of bridge types, site conditions and design loadings. Accordingly, the bridge engineer relies on a wide variety of references for assistance, as described in the following subsections.

10.2.1 PROFESSIONAL ASSISTANCE

The primary source of professional assistance is the FLH Bridge Engineer, Team Leaders, and senior structural engineers within the design office. These individuals can provide not only technical guidance, but also can explain the correlation between theory and specifications.

Additional professional assistances are available from the Office of Infrastructure, Bridge Technology in the Federal Highway Administration, Washington, DC, the Federal Highway Administration Resource Center and the Office of Research Development and Technology at Turner-Fairbank Highway Research Center, Virginia. State highway departments are also a source of excellent professional assistance.

As a matter of good office practice, all outside contacts should be informally discussed with the FLH Team Leader prior to making contact and the items discussed should be documented in the design notes or in the design files.

10.2.2 DESIGN SPECIFICATIONS AND GUIDELINES

The primary design specification for all highway bridges on public roads in the United States is the *LRFD Bridge Design Specifications* published by American Association of State Highway Transportation Officials (AASHTO) unless approval to use the AASHTO *Standard Specifications for Highway Bridges* is granted by the FLH Bridge Engineer and/or supervisory Team Leaders. The *LRFD Bridge Design Specifications* is the primary design specification for all FLH bridges. AASHTO *LRFD Specifications* set forth minimum requirements that are consistent with current practice and certain modifications may be necessary to suit local conditions. AASHTO *LRFD Specifications* apply to ordinary highway bridges, but supplemental specifications may be required for unusual types and for bridges with spans longer than allowed in the AASHTO *LRFD Specifications*.

Interim Specifications are published yearly by AASHTO and have the same status as the *LRFD Specifications*. *Interim LRFD Specifications* are revisions that have been approved by at least a two-thirds majority of the members of the AASHTO Subcommittee on Bridges and Structures. FLH Bridge policy is to apply *Interim Specifications* to all design projects started after the issuance of the *Interim Specifications*. *Interim Specifications* shall not apply to projects retroactively.

The following AASHTO specifications, including current revisions, apply to all FLH bridge projects:

1. LRFD Bridge Design Specifications, AASHTO, current edition.
2. Standard Specifications for Highway Bridges, AASHTO, current edition.
3. Guide Specifications for Horizontally Curved Steel Girder Highway Bridges, AASHTO, current edition.
4. *LRFD Moveable Highway Bridges Design Specifications*, AASHTO, current edition.
5. *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals*, AASHTO, current edition.
6. *Bridge Welding Code*, AASHTO/AWS D1.1 & D1.5, current edition.
7. *Guide Specifications for Design and Construction of Segmental Concrete Bridges,* AASHTO, current edition.
8. *LRFD Guide Specifications for the Design of Pedestrian Bridges*, AASHTO, current edition.
9. *Guide Specifications for Seismic Isolation Design,* AASHTO, current edition.
10. *Guide Specifications for LRFD Seismic Bridge Design,* AASHTO, current edition.
11. *Guide Specifications for Design of FRP Pedestrian Bridges, AASHTO,* current edition.

The following specifications offer insight to and clarification of many of the AASHTO *Specifications*:

1. Building Code Requirements for Reinforced Concrete and Commentary, ACI 318M, American Concrete Institute, current edition.
2. *Ontario (Canada) Highway Bridge Design Code and Commentary*, Ministry of Government Services, Toronto, Ontario, current edition.
3. *AISC Specification for the Design, Fabrication and Erection of Structural Steel for Buildings and AISC Code of Standard Practice*, current edition (found in *Manual of Steel Construction*, American Institute of Steel Construction).
4. *National Design Specification for Wood Construction and Design Values for Wood Construction*, National Forest Products Association, current edition.
5. *Design Standard Specifications for Structural Glued Laminated Timber*, American Institute of Timber Construction, current edition.
6. *Structural Welding Code-Steel*, American Welding Society, current edition.
7. *Manual for Railway Engineering*, American Railway Engineering and Maintenance of Way Association (AREMA), current edition.

10.2.3 DESIGN EXAMPLES

Engineers with minimal experience should rely on the design notes and project plans of previous bridge projects. Care should always be exercised to select projects designed and checked by experienced structural engineers. Also, previous notes should not be followed in a cookbook manner, but rather, they should be used in conjunction with current AASHTO *LRFD Bridge Design Specifications*.

Design engineers should always review new projects with the project Team Leader before work is started. At this time, a similar example project to be used for guidance can be selected and discussed.

10.2.4 TECHNICAL REFERENCES

State-of-the-art bridge design involves the practical application of the principles of many varied disciplines. The following references are listed to provide entry-level structural engineers with theoretical background and assistance in practical bridge design. These references should not necessarily be considered FLH Bridge policy. Experienced structural engineers may also find the listing useful for a personal library.

10.2.4.1 Structural Analysis

The following references apply to structural analysis:

1. Moments, Shears, and Reactions for Continuous Highway Bridges, American Institute of Steel Construction.
2. Timoshenko, S., *Strength of Materials*, 2 volumes, 3rd ed., New York. D., Van Nostrand Company, 1958.
3. Roark, Raymond J. and Young, Warren C., *Formulas for Stress and Strain*, New York, McGraw-Hill Book Company, 1975.
4. Wang, Chukia K., *Statically Indeterminate Structures*, Chukia K. Wang, New York, McGraw-Hill Book Company, 1953.
5. Gaylord Jr., Edwin H. and Gaylord, Charles, *Structural Engineer Handbook*, 2nd ed., New York, McGraw-Hill Book Company, 1979.
6. Gere, James J. and Weaver Jr., William, *Analysis of Framed Structures*, Princeton, NJ. D. Van Nostrand Company, 1965.
7. Gere, James M., *Moment Distribution*, Princeton, NJ, D. Van Nostrand Company, 1963.
8. *Continuous Concrete Bridges*, 2nd ed., Portland Cement Association.
9. *Handbook of Frame Constants*, Portland Cement Association, 1958.

10. Carpenter, Samuel T., *Structural Mechanism*, Salt Lake City, John Wiley and Sons, 1960.

11. Ketter, Robert L.; Lee, George C.; and Prawel, Sherwood P., *Structural Analysis and Design*, New York, McGraw-Hill Book Company, 1979.

10.2.4.2 Reinforced Concrete

The following references apply to reinforced concrete:

1. *ACI Manual of Concrete Practice*, American Concrete Institute, current edition..
2. *Design of Highway Bridges: Based on AASHTO LRFD, Bridge Design Specifications,* Richard M. Barker, Jay A. Puckett, current edition.
3. *CRSI Handbook*, Concrete Reinforcing Steel Institute, current edition.
4. *AASHTO LRFD Strut-and-Tie Model Design Examples*, Portland Cement Association (PCA).
5. FHWA/NHI LRFD Design Example for Prestressed Concrete Superstructure Bridge with Commentary.
6. *Manual of Standard Practice*, Concrete Reinforcing Steel Institute, current edition.
7. *Reinforcing Bar Detailing*, Concrete Reinforcing Steel Institute, current edition.

10.2.4.3 Structural Steel

The following references apply to structural steel:

1. Design *of Highway Bridges: Based on AASHTO LRFD, Bridge Design Specifications,* Richard M. Barker, Jay A. Puckett, current edition.
2. *FHWA/NHI LRFD Design Example for Steel Superstructure Bridge with Commentary*
3. Fischer, John W., *Bridge Fatigue Guide*, American Institute of Steel Construction, 1977.
4. Fischer, John W., *Fatigue and Fracture in Steel Bridges*, Salt Lake City, John Wiley and Sons, 1984.
5. *FHWA/NSBA* Three-Span Continuous Composite I-Girder Steel Bridge Design Example.
6. *AASHTO/NSBA Steel Bridge Collaboration – Fabrication, Detailing and Constructability Guidelines,* current edition.
7. *FHWA Steel Bridge Design Handbook,* FHWA, 2012.

10.2.4.4 Prestressed Concrete

The following references apply to prestressed concrete:

1. *Post-Tensioning Manual*, Post-Tensioning Institute, current edition.
2. *Post-Tensioned Box Girder Bridge Manual*, Post-Tensioning Institute, current edition.

3. *Precast Segmental Box Girder Bridge Manual*, Post-Tensioning Institute and Prestressed Concrete Institute, current edition.
4. *Design of Highway Bridges: Based on AASHTO LRFD, Bridge Design Specifications,* Richard M. Barker, Jay A. Puckett, current edition.
5. *PCI Bridge Design Manual, Volumes One and Two*, current edition.
6. *PCI Design Handbook, Precast and Prestressed Concrete*, Prestressed Concrete Institute, current edition.
7. FHWA/NHI LRFD Design Example for Prestressed Concrete Superstructure Bridge with Commentary

10.2.4.5 Timber

The following references apply to timber:

1. *Timber Bridges: Design, Construction, Inspection and Maintenance*, US Department of Agriculture, US Forest Service, current edition.
2. *Timber Construction Manual*, American Institute of Timber Construction, Salt Lake City, John Wiley and Sons.
3. *Weyerhaeuser Glulam Wood Bridge Systems*, Weyerhaeuser Company, 1980.
4. *Design of Highway Bridges: Based on AASHTO LRFD, Bridge Design Specifications,* Richard M. Barker, Jay A. Puckett, current edition.
5. *Timber Design and Construction Handbook*, Timber Engineering Company, New York, McGraw-Hill Book Company, 1956 (out of print).
6. *National Design Specification (NDS) for Wood Construction*, American Forest and Paper Association, current edition.

10.2.4.6 Foundations

The following references apply to foundations:

1. Bowles, Joseph E., *Foundation Analysis and Design*, New York, McGraw-Hill Book Company, 1988.
2. Terzaghi, Karl and Peck, Ralph B., *Soil Mechanics in Engineering Practice*, Salt Lake City, John Wiley and Sons, 1967.
3. *Bridge Substructure and Foundation Design*, Petros P. Xanthakos, current edition.
4. *Design and Construction of Driven Pile Foundations Reference Manual*, FHWA, 2006.
5. *Design of Highway Bridges: Based on AASHTO LRFD, Bridge Design Specifications,* Richard M. Barker, Jay A. Puckett, current edition.
6. *FHWA/NHI LRFD Design Example for Steel Superstructure Bridge with Commentary*.
7. *LRFD for Highway Bridge Substructures and Earth Retaining Structures Reference Manual, FHWA,* current edition.

8. *Design of Piles and Drilled Shafts Under Lateral Load*, DOT, FHWA, 1987.

9. *Drilled Shafts: Construction Procedures and LRFD Design Methods Reference Manual,* FHWA, 2010.

10. *Steel Sheet Piling Design Manual*, US Steel, Updated and reprinted by DOT, FHWA, July 1984.

11. FHWA/NHI LRFD Design Example for Prestressed Concrete Superstructure Bridge with Commentary.

12. *Geosynthetic Reinforced Soil Integrated Bridge System Interim Implementation Guide,* FHWA, 2011.

13. *Geosynthetic Reinforced Soil Integrated Bridge System Synthesis Report,* FHWA, 2011.

14. *Micropile Design and Construction Reference Manual*, FHWA, 2005.

15. *Technical Manual for Design and Construction of Road Tunnels – Civil Elements Reference Manual,* FHWA, 2009.

10.2.4.7 Seismic/Dynamic Analysis

The following references apply to seismic and/or dynamic analysis:

1. Newmark, Nathan M. and Rosenblueth E., *Fundamentals of Earthquake Engineering*, Englewood Cliffs, NJ, Prentice-Hall, 1971.

2. Weigel, Robert L., *Earthquake Engineering*, Englewood Cliffs, NJ, Prentice-Hall, 1970.

3. *Seismic Design of Highway Bridges - Workshop Manual*, DOT, FHWA, Office of Research and Development, Implementation Division, January 1981.

4. *Caltrans SEISMIC Bridge Design Specification and Commentary*, California Department of Transportation, Office of Structure Design, current edition.

5. *Seismic Analysis and Design of the AISI LRFD Design Examples of Steel Highway Bridges*, AISI.

6. *Seismic Design of Bridges – Design Examples No. 1-7, FHWA, 1996.*

10.2.4.8 Construction/Load Rating/Miscellaneous

The following references apply to construction and load rating:

1. LRFD, Bridge Construction Specifications, AASHTO, current edition

2. *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-XX.*

3. *California Falsework Manual*, California Department of Transportation, Division of Structures, current edition.

4. *California Trenching and Shoring Manual*, California Department of Transportation, current edition.

5. *Construction Handbook for Bridge Temporary Works*, FHWA, current edition.
6. *Guide Specifications for Highway Construction,* AASHTO, current edition.
7. *Guide Design Specifications for Bridge Temporary Works*, AASHTO, current edition.
8. *Synthesis of Falsework, Forming, and Scaffolding for Highway Bridge Structures,* FHWA.
9. *Manual for Bridge Evaluation,* AASHTO, current edition.
10. Hurd, M.K., *Formwork for Concrete*, American Concrete Institute, current edition.
11. *Design of Bridge Deck Drainage (HEC-21)*, FHWA, current edition.

10.3 INVESTIGATION

In the development of structural design plans and specifications, the structural engineer will be confronted with data and comments obtained from several different types of investigations and reviews. This information may include bridge safety inspection structural condition data reports, bridge site survey information and several levels of field review. Also refer to Section 4.3 for general guidance when beginning the investigation.

10.3.1 BRIDGE SITE PLANS

A bridge site plan is developed when a new or replacement bridge is required. The purpose of the site plan is to provide the structural engineer with a graphic representation of the topography at the site so the required type, size and length of bridge can be determined for the site.

Bridge site topography can have a significant effect on the method of construction. The structural engineer must be aware of the possibilities and limitations that are presented by the existing conditions. Topographic maps assist the designer in determining quantities of excavation for estimating purposes.

The site plan shows the contours of the terrain as well as roads, streams or other significant features in the immediate area of the proposed bridge. Survey teams taking extensive topographic field measurements collect this data. The plans should be drawn using a scale appropriate for the total length of the proposed bridge. Contours are generally drawn at 1 ft or 3 ft [0.5 m or 1 m] intervals.

10.3.2 HYDRAULIC ANALYSIS

In cases where a bridge crosses a river, stream or flood plain, it is usually necessary to perform a hydraulic investigation and analysis. This is generally accomplished concurrently with the development of the site plan since hydraulic information is needed in deciding what type of structure is practical for the crossing. The structural engineer is interested in the high water elevation and flow velocity for flood conditions with a specified frequency of occurrence.

Typically, bridges are designed to handle a 50-year flood, which is a flood of a magnitude that it is expected to occur no more frequently than once in 50 years. For some large, high-cost structures, the design might be based on a 100-year flood to lessen the risk of flood damage. For detailed information with regard to the hydraulic design of bridges, see Chapter 7.

10.3.3 GEOTECHNICAL INVESTIGATION

Geotechnical investigations should be performed after the site plan has been developed and preliminary determinations have been made regarding the type and length of the proposed structure and the location of the foundations for the structure. The purpose of the investigation is to identify the composition of the underlying stratum, determine whether the preliminary location is acceptable as a foundation site and determine what type of foundation design is most appropriate.

Most often the investigation consists of extracting and analyzing core samples of the substratum. Core drilling is normally performed to the depth necessary to reach solid rock. For small bridges on flat terrain, a single core is sometimes sufficient. For bridges longer than approximately 100 ft [30 m] or bridges located on hilly terrain, a more comprehensive study is typically needed. It is desirable to obtain at least one core at each foundation site.

After analyzing the data, the geotechnical engineer should provide a report containing recommendations for the type of foundation needed along with allowable bearing capacities and any other pertinent information. The structural engineer receives a copy of this report to assist in developing the final design of the foundations. For detailed information with regard to the geotechnical design of bridges, see Chapter 6.

10.3.4 BRIDGE INSPECTION PROGRAM

All bridges over 20 ft [6.1 m] located on public roads are required by law to be inspected at regular intervals not to exceed two years. The inspections must be in accordance with the *National Bridge Inspection Standards and Guidelines* as set forth in Title 23, CFR, Part 650, Subpart C.

FLH Bridge administers a bridge inspection program for the National Park Service and other Federal agencies. Bridge structures are reviewed for condition and structural adequacy.

Basic data that can be found in a typical inspection report includes the following:

- Photographs of the roadway and profile view of the bridge;
- A written description and photographs of deficiencies found during the inspection;
- Basic physical dimensions of the bridge;
- A structural load capacity rating, where applicable;
- Special scour studies; and
- BIP reports and other BIP documents in the Intranet.

In many instances, data found in these reports is the basis for the development of preliminary bridge repair plans.

10.3.5 DECK SURVEY

A deck survey may be performed to further assess the structural condition of the bridge deck. The information is used by the structural engineer to determine if the deck can be repaired and where applicable, the most suitable method of repair.

A deck survey may be composed of several types of investigations, which can be classified as either destructive or nondestructive. Half-cell potential readings, ground penetrating radar, and delamination readings are classified as non-destructive since they provide information without actually damaging the deck.

Destructive methods, such as collecting deck core samples for evaluation and testing, are generally used only when non-destructive methods are not sufficient to adequately assess the condition of the deck. Destructive methods yield data that can be used to evaluate the internal condition of the deck.

Chloride tests and petrographic analysis are conducted on the core samples to determine the level of chloride contamination, ASR, etc. In addition, split-tensile tests can be performed on the cores to give an indication of the strength of the existing concrete.

10.3.6 BRIDGES WITHIN RESURFACING, RESTORATION, OR REHABILITATION (RRR) PROJECTS

Decisions are made to retain or replace any bridge within the limits of a non-freeway resurfacing, restoration, or rehabilitation (RRR) project. See the applicable chapter of the AASHTO *Green Book*. When a bridge requires replacement, design a new bridge in accordance with AASHTO LRFD structural standards for bridges. Select widths consistent with current standards to which the highway may be upgraded in the near future. Review recent bridge inspection reports to determine if the bridge is structurally and functionally adequate.

When a bridge is to remain in place, determine which treatment, if any, is required for operational and structural adequacy. The following scenarios provide a brief summary of the order of treatment to maintain operational and structural adequacy:

- Repair the railing.
- Replace/upgrade the railing and the existing deck.
- Deck/railing replacement.
- New Designs.

The following conditions require that no work or minor rehabilitation be performed for a RRR project:

- The bridge clear roadway width is equal to or greater than the minimum surfacing or approach traveled way widths.
- The bridge crash records indicate that crash problems do not exist and the approach is gradually narrowed to meet the bridge clear roadway width in advance of the bridge. Where crash problems exist; make an analysis to determine the necessary corrective action (e.g., providing improved transitions, rehabilitation, widening, replacement).
- The bridge railings, including the approach rail, meet or are made to meet adequate strength and geometric standards. In all cases where a structure is to remain in-place, check the bridge rail for adequacy.

- A reasonable or adequate alternative route does not exist and the load carrying capacity is sufficient to carry school buses and vital service vehicles.

Consider major rehabilitation for the following conditions:

- Deck replacement, to the extent practical, is designed in accordance with current AASHTO LRFD Bridge Design Specifications unless approval to use the AASHTO Standard Specifications for Highway Bridges is granted by the FLH Bridge Engineer or Team Leader;
- Rehabilitation meets current AASHTO LRFD safety standards;
- Bridge railing is to be upgraded to current standards (NCHRP 350). On some occasions, this requirement is difficult to meet due to the existing condition or original design, geometry or material of the existing deck or rail which does not allow a rehabilitation meeting the current standards; and/or
- The approach roadway width does not meet current AASHTO geometric standards and the bridge is to be widened to meet the geometric standards for the highway if it were reconstructed. The decision to rehabilitate or replace may be decided by established cost guidelines, life cycle cost analysis, or may be subjective. However, when the total cost of rehabilitation is expected to exceed 50 percent of the cost of reconstructing the structure to current standards, consider replacing the structure.
- Vertical clearances at existing underpass structures will require adjustment when the clearance after resurfacing work is less than the minimums required. Do not reduce surfacing depths or eliminate surfacing in the vicinity of the bridge to avoid pavement removal or structure modification.

All signing and markings for bridges shall be in accordance with the *MUTCD*.

10.3.7 FIELD REVIEWS

Two levels of field reviews are generally required in the development of plans for bridge repair, replacement or new construction. The first field review is designed to involve the responsible agencies in the design concepts and parameters that will be used in the development of plans and specifications for the given project. Basic information to be supplied by the structural engineer at this review is a proposed bridge type, size and location (TS&L) drawing for replacement and new bridge projects. Drawings depicting proposed repair methods shall be provided for bridge repair projects.

The second level of field review, commonly known as a plan-in-hand review, should be performed when the bridge drawings are approximately 70 percent complete. The purpose of this review is to verify that all items covered in the drawings will be compatible with the existing field conditions and to confirm that all design, safety and specific client agency needs are properly addressed in the final design documents.

10.3.8 NON-DESTRUCTIVE EVALUATION (NDE)

Non-destructive testing is particularly useful for evaluating in-service bridges, since the bridges can remain intact and open to traffic during the inspection and evaluation. Different NDE testing methods can be applied to some problems but the best method is chosen based on test specimens and testing techniques. Other non-destructive testing is available and can be performed to determine level of deterioration or acquire needed information to assess the condition of elements. Some of these NDE tests are shown in Exhibit 10.3-A.

Exhibit 10.3-A SAMPLE NDE TESTS

Test / Technique	Applications	Operating Principle
Hammer, Rotary Percussion, Chain Drag	Debonding, Delamination in concrete	Variation in acoustic sounding of tested concrete element
Ground-Penetrating Radar (GPR)	Concrete Cover/thickness, Honeycombing, Void beneath slab, Embedded utilities, Post-tensioning location, Ungrouted cell in masonry	Use of electromagnetic impulse signals
R-Meter, Pachometer (Covermeter)	Concrete cover, Rebar location	Generates a magnetic field and determines its intensity
Electric Potential (Half Cell)	Corrosion	Use of electrical potentials as indication of possible corrosion
Impulse Response	Honeycomb, Void beneath slab, Delamination, Grouted ducts, Debonding, Stress transfer, pile length	Use of stress wave generated by low-strain impact
Impact-Echo	Concrete cover/thickness, Crack location, Post-tensioning, Void beneath slab, Delamination, Grouted ducts, Debonding	Use of transient stress wave generated by elastic impact
Ultrasonic Pulse Velocity	Compressive strength, Modulus of elasticity, Delamination, Crack location, Honeycomb, Crack detection, Internal flaws, Sub-surface damage	Use of stress wave

Test / Technique	Applications	Operating Principle
Acoustic Emission	Structural performance, Crack growth, Damage evaluation, Timber decay	Use of sound wave from dynamic motions inside a solid
Ultrasonic Thickness Meters (D-Meter)	Detect thickness of steel	Uses straight beam transducers to detect thickness of test parts
Dye Penetrant	Existence and size of surface flaws in steel members	The dye dried out and reveals the irregularities, hence reveals the extent and size of the surface flaw
Magnetic Particle	Surface gouges, cracks, and holes in ferromagnetic materials	Dye penetrates and reveals irregularities, extent and magnitude
Moisture Meters	Timber moisture content/decay	Use electrodes to measure moisture content

10.4 DESIGN PROCESS

The design process involves two stages. The initial or preliminary design effort establishes the proposed structure type and layout. The final design effort develops detailed contract plans to be used to construct the facility. Both of these stages require the skills of a structural engineer.

In the preliminary design process, a structure is selected which economically fulfills the structural, functional, aesthetic and other relevant requirements of a given site. Coordinate the structure selection with the overall project preliminary design process, see Section 4.5.2.12.10.

The development of the preliminary plan requires the consideration of many different factors. The following are some of the more common of these factors:

1. **Economic**. When preparing the preliminary plan, consider the initial and maintenance costs.
2. **Site Requirements**. The following factor should be considered when reviewing the project site:
   - Topography,
   - Horizontal and vertical alignment,
   - Superelevation,
   - Deck geometrics,
   - Proposed or existing utilities, and
   - Orientation with respect to the stream (skew considerations).
3. **Hydraulic**. Consider the following factors when preparing the hydraulic design:
   - Stream flow (i.e., Q_{50}, Q_{100});
   - Risk assessment;
   - Passage of debris;
   - Scour;
   - Pier and bank protection;
   - Permit requirements;
   - Deck drainage; and
   - Culverts (as alternatives).
4. **Structural**. Factors to be considered with regards to the structural aspects of a project include:
   - Span ratios (AASHTO LRFD Table 2.5.2.6.3-1),
   - Horizontal and vertical clearances,
   - Limitations on structural depth,
   - Future widening,
   - Slope treatment,
   - Foundation and groundwater conditions,
   - Anticipated differential settlement,
   - Eliminate deck joints if feasible,
   - Use high performance materials (i.e., HPC, HPS) when possible,
   - Inspection access,
   - Future Maintenance,

- Incorporating new technology,
- Precast bridge element systems,
- Abutment and pier configuration type, and
- Types of loads

5. **Environmental**. Consider the following environmental factors for the preliminary planning stage:
   - Aesthetics and compatibility with surroundings,
   - Similarity to adjacent structures,
   - Extent of exposure to the public, and
   - Construction constraints with respect to species.
6. **Construction**. During the preliminary stage, consider the following factors for future construction:
   - Access to site,
   - Duration of construction,
   - Constraint of construction season,
   - Detours or stage construction,
   - Extent of falsework and falsework clearances,
   - Erection problems,
   - Ease of construction,
   - Restrictions due to weather, and
   - Availability of local material and fabricator.
7. **Safety**. Consider the following safety factors for the project:
   - Traffic convenience,
   - Density and speed of traffic,
   - Approach guardrail type and connection to structure,
   - Bridge rail type (crash tested rails), and
   - Design speed and traffic type.
8. **Other**. Consider any recommendations resulting from interdisciplinary team studies or special requests by an owner.

In making the recommendation for type of structure, full consideration should be given to the above factors. Economy is generally the best justification for a selection. However, some of the above considerations may outweigh differences in cost. In the final analysis, the owner must be satisfied that the proper structure has been selected.

The final design process begins with the approval, by all interested parties, of the bridge TS&L drawing. Using the information shown on the drawing, and following the design specifications, the structural engineer makes a comprehensive analysis and design of the bridge. This design is then the basis for the preparation of detailed contract plans to be included in the complete project plans.

The final design of bridges requires meticulous attention to details and a high degree of responsibility. Irresponsible design can result in construction difficulties, reduced service life of the structure and higher maintenance costs. In the extreme case, poor design can result in the collapse of the bridge either during construction or in service.

It is FLH Bridge intent that a complete and independent check is made of all structural design work. This means that one structural engineer designs the bridge and a second structural engineer performs an independent structural analysis of the bridge.

The information that is provided in the following sections applies to both preliminary design and to final design.

10.4.1 GENERAL FEATURES

The FLH Program involves a wide variety of bridge types from single lane forest development roads to high volume urban arterials. The general features, including widths, clearances, railings and approaches of these structures are normally controlled by the roadway standards of the client agency. All necessary general features should be shown on the bridge TS&L and should be agreed upon before final design begins. Before design proceeds, establish the project design criteria for the project development.

10.4.1.1 Bridge Widths and Clearances

Single-lane bridges should be a minimum of 14 ft [4.3 m] wide, face-of-rail to face-of-rail.

Multiple lane bridges should be as wide as the approach roadway plus the offset to the face of the approach guardrail.

Vertical clearances for interchange structures should meet AASHTO *Specifications* or be consistent with other bridges on the route.

10.4.1.2 Bridge Railings and Approach Railings

Railings meeting both the geometric and structural requirements of AASHTO *LRFD Specifications* and NCHRP 350 should be provided for all bridges

The use of approach railing on all bridges is required. The approach railing should be connected to the bridge railing system with connecting details that will develop the full strength of the approach railing.

All concrete parapet-type bridge railings should be detailed with joints as follows:

- At the point of maximum positive movement of all spans,
- At or near the centerline of all piers,
- In between the above locations so that the length of rail segments does not exceed 25 ft [7.6 m], and

- At bridge expansion joints.

At these locations, joints should be detailed normal to the rails or radial on curved bridges. Joint filler material should be a minimum 0.5 in [12 mm] thick. Reinforcement should not extend through the joint.

Joints for special design concrete railings should be located as necessary to control cracking due to flexure or temperature changes.

At the ends of the bridges, between the superstructure and substructure elements, railing joints should be compatible with deck joints, expansion assumptions, etc.

All steel bridge railings should have joints located as described above. Joints or splices should be designed to allow movement that maintains the full strength of the railing.

10.4.1.3 Hydraulic Considerations

Most bridges are designed to pass, without damage, 50-year flood design (Q_{50}) flows; however, the effects of 100-year flood design (Q_{100}) flows should be evaluated. Normally, there are only minor differences between these two flows and most structures will pass both without damage. For details concerning other hydraulic considerations for scour, clearances and slope protection, see Chapter 7.

10.4.2 LOADS

For loads and load factors, see Section 3 of the AASHTO *LRFD Bridge Design Specifications*.

10.4.3 DECKS, RAILS, DECK JOINTS AND DRAINS

The roadway surface of bridges that support and contain vehicular traffic consists of the deck, rails, deck joints and drains. This surface must not only provide a good riding surface but also must also provide durability against abrasive deterioration and repetitive cycles of loading in flexure and shear.

10.4.3.1 Deck Design

Transversely reinforced concrete slabs are the most commonly used bridge deck and are a significant portion of bridge design in terms of dollar investment.

These slabs also make-up the one portion of the bridge that has the most common and expensive maintenance problems. Heavy wheel loads, excessive use of deicing salts, studded tires and poor construction control are contributing factors to structure damage.

Edge support for transversely reinforced slabs is normally provided by steel or concrete cast-in-place end diaphragms. These diaphragms are often placed only between girders. Caution should be exercised to provide an edge support on slab overhangs where a substantial length of overhang might exist and where moments due to wheel loads might be a major portion of the total moment requirement. Cast-in-place decks on structural steel superstructures are another place where edge support might not naturally be provided. Edge support should be designed for each condition to be capable of carrying a wheel load.

Placement of transverse slab reinforcing on skewed bridges is a subject of some debate. A reasonable rule used by many designers, however, places the reinforcement on the skew for up to 20 degrees, and for 20 degrees or greater, places the reinforcing normal to the roadway with variable length bars at the skewed ends. For reinforcement placed on the skew, the span should be increased to the skewed length and the area of reinforcement increased for the spacing normal to the skew. For skew angles greater than 30°, additional reinforcement shall be placed in the slab end zones at abutments and conventional deck joints.

In continuous slab over intermediate pier or bent, provide supplemental longitudinal reinforcing in the top of slabs. Such reinforcing shall be minimum No. 5 [15.875 mm] bars placed between the longitudinal temperature bars, and shall extend minimum 30% of the span length from the center line of the pier.

The AASHTO *LRFD Specifications* require a 2 in [50 mm] cover over the top reinforcing steel and a 1 in [25 mm] cover over the bottom reinforcement in deck slabs. Both the positive moment bottom reinforcement and the negative moment top reinforcement should be designed. It is common practice to make the top and bottom reinforcement the same to avoid confusion during construction. It is FLH Bridge policy that the cover over the top and bottom reinforcing steel in deck slabs shall be 2.5 in [65 mm] and 1 in [25 mm] respectively, and all reinforcing steel connecting to the deck slabs shall be epoxy-coated. The purpose is to ensure that a minimum of covers of concrete would be provided over all reinforcing steel. It is also recommended to use low permeability High Performance Concrete (HPC) when possible. Both recommendations, combined with the use of epoxy-coated reinforcing steel, should be used when appropriate.

10.4.4 RAIL DESIGN

Bridge railings are an extremely important part of any structure and should be carefully designed and detailed. Railing loads are specified in AASHTO *LRFD Bridge Design Specifications*. The application of these loads to the deck overhang is also covered in the AASHTO *LRFD Specifications*. It is FLH Bridge practice to research FLH, state, and local rail types for consistency of selection, ease of construction and maintenance.

The method of connection of rails to decks should allow for ease of deck construction, for alignment and for ease of rail repair or replacement.

For rail repairing projects no crash worthy check is required. For rail replacement projects AASHTO Standard Specifications is used for bridges built before 2000. Either use 10 kips

[44.5 kN] load or engineering judgment for the analysis. For deck and rail replacement, use AASHTO LRFD for the crash worthy check. For the new design, follow AASHTO LRFD.

10.4.5 DECK JOINT DESIGN

The designer should carefully consider accommodating all bridge movements for deck joint designs.

These movements include but are not limited to the following:

- Temperature expansion and contraction,
- Concrete shrinkage and creep,
- Live load rotation,
- Effects of prestressing, and
- Foundation movements.

Deck joints should be avoided whenever possible since they are often sources of maintenance problems due to leakage of roadway water and contaminants as well as improper performance.

When possible, jointless integral or semi-integral abutments should be used to eliminate deck joints at the ends of bridges. For jointless abutments where spans contributing to expansion at the abutment in question are less than 100 ft [30 m] long, no provision for expansion is required. For spans with more than 100 ft [30 m] spans contributing to expansion at the abutment in question and are more than 100 ft [30 m] long, an expansion joint should be provided at the end of each approach slab (sleeper slab is required).

Deck joints between abutments are not desirable for the reasons mentioned. In general, they should only be used to separate different superstructure types, relieve frame-type restraint forces or when the designer feels the provision for movement is critical.

For movements of less than 4 in [100 mm], the designer can select any of a number of proprietary joints according to the manufacturer's recommendations. It is recommended that on skewed joints, an interlocking type strip or gland seal be used. The joint should be detailed so drainage is properly handled at curbs, sidewalks, parapets, etc. On the plans, the joint width setting at the temperature anticipated during construction should be shown as well as adjustments for other construction temperatures.

For movements more than 4 in [100 mm], a special design is required.

10.4.5.1 Deck Drains

Every bridge should be analyzed for deck drainage considering width of bridge, superelevation or crown, profile grade, wingwalls, rail type and geographic location. Consideration should be given to locating bridge deck drains between toes of embankments and installing drainage structures, catch basins, etc., off the bridge or placement of scuppers on the deck if required.

Deck drains over abutment fill slopes should be avoided. These drains have caused severe erosion on many previous projects. Where deck drains must be provided over abutment fill slopes, the plans must include an erosion control measure to be built at the time of bridge construction.

10.4.5.2 Analysis of Bridge Structures

The analysis of bridge structures begins with an approved TS&L drawing, the AASHTO *LRFD Bridge Design Specifications* and established Bridge Design Criteria for the project. Using these three documents, the design engineer begins by making a preliminary estimate of the members and end conditions. This assumed structure is then analyzed for the design loads and only the critical sections are designed. This design is then compared with the assumed (estimated) sections.

If necessary, the structure is modified and the new structure is again analyzed. This process continues until the optimum design is attained. At this point, the entire structure is designed for all sections and the plans can be produced.

Typically, the design is monitored at each stop for consistency, economic feasibility and practicality of construction. The designer must never forget the original purpose of the structure and the objectives of the FLH Bridge partners.

10.4.5.3 Preliminary Sizing and Structure Modeling

The preliminary sizing of the bridge members is aided by previously similar designs as well as the depth-to-span criteria listed under Sections 10.4.5 through 10.4.8. This is a critical point in the design process since a wise choice here will reduce the analysis/design iterations mentioned. Experience is invaluable at this stage, so assistance from the FLH Bridge Engineer and the senior structural engineers is highly recommended. On certain structures, final design of the deck and traffic rails is now possible. This will help to finalize a portion of the dead load.

Structural analysis is the determination of displacements and stresses due to the known loads. For analysis purposes, the bridge structure must be idealized or modeled as to how the various parts interact to carry the loads to the supports.

In all structural analysis, the following three fundamental relationships must be satisfied:

- Equilibrium,
- Compatibility of displacements, and
- Consistency of displacements with the respective stress/strain relationships.

When sizing members, consideration should be given to live load deflection criteria.

The simplest structure type to analyze is the determinate structure, which needs only the equations of equilibrium for complete solution.

The indeterminate structure requires compatibility and stress/strain relationships in addition to the equilibrium equations for complete solution. This requires significantly more effort than the determinate structure.

For each member in the bridge structure, the designer must decide whether a simplified determinate model will be adequate or whether a more complicated, time consuming indeterminate model is required. For example, a pile cap is often analyzed for 0.8 times the simple span moment to approximate the moments from a more difficult indeterminate solution, and the simple span shears are increased by 20 percent to account for continuity. By contrast, a bridge to be built at a high seismic location must be modeled with a sophisticated three-dimensional mathematical model to permit the required dynamic analysis.

Structure modeling for bridge members and complete structures can only be briefly introduced in this chapter. The inexperienced structural engineer is referred to the many references listed in Section 10.2 as well as professional assistance from the sources listed in the same section.

The engineer should always make certain that the modeling assumptions adequately represent the members or structures' true behavior for the particular design being conducted.

10.4.5.4 Simplified Methods of Analysis (Hand Method)

Before the development of computer structural analysis aids, many techniques for hand analysis were developed. These hand analysis techniques continue to be valuable tools for the structural engineer. These techniques serve to train inexperienced engineers in the structural theory behind the computer programs. They also provide a means to check and understand the results of computer analyses.

Moment distribution is a simple, fast and accurate method of analyzing continuous girders and frames. It was first taught by Professor Hardy Cross in 1924 and continues to be the bridge engineer's most powerful hand analysis tool. Two excellent references are the *Manual of Bridge Design Practice*, 3rd edition by Caltrans and *Moment Distribution* by J.M. Gere. Moment distribution can easily accommodate the frequent variable moment-of-inertia member types encountered by use of aids for stiffness and carryover factors as well as fixed-end moments for various loadings. The analogous column procedure can be used to develop these for members and loadings not covered by the aids.

For computation of deflections, the moment area and conjugate beam procedures prove very useful. Another deflection computation method that can be extended for calculation of buckling loads and beam-column problems is Newmark's method. These methods are described in *Structural Mechanics* by Samuel Carpenter and *Structural Analysis* by Harold Laursen.

Moments, Shears and Reactions for Continuous Highway Bridges by AISC provides complete moments, shears and reactions for certain continuous beam type members. It provides coefficients for determining influence lines that can be used for both dead and live loads.

The elastic center method can be used to analyze arches and rigid frames. It is described in *Structural Mechanics* by Samuel Carpenter, Section 14 of *Manual of Bridge Design Practice*, 3rd

Edition, by Caltrans and *Analysis of Arches, Rigid Frames and Sewer Sections* by the Portland Cement Association.

For indeterminate frame type structures, the following procedure for hand analysis has proven helpful:

1. **Calculate Stiffness**. From assumed member sizes, calculate stiffness and carryover factors.
2. **Perform Moment Distributions**. Perform moment distributions for unit fixed-end moments at all member ends individually and tabulate the results.
3. **Calculate Dead and Live-Load Moments**. Calculate dead load and live load moments and shears at critical superstructure sections using the above unit distributions multiplied by the fixed-end moments for dead and live loads.
4. **Check Critical Superstructure Sections**. Check the critical superstructure sections for adequacy for the assumed member sizes. (If not adequate, a change at this point will not require much effort.)
5. **Design Superstructure**. When critical superstructure sections are adequate, design the substructure. (Changes at this point to the substructure members will not waste much previous effort and reanalysis can be done.)
6. **Compute Dead Load Moments and Shears**. When substructure design is complete, compute dead load moments and shears for the superstructure at all tenth-point locations.
7. **Develop Influence Lines**. Develop and draw influence lines for moments at the tenth points. Live load moments and shears can be obtained semigraphically from these.
8. **Produce Moments and Shears**. Finally, produce the required envelopes of moments and shears for the completion of the superstructure design.

10.4.5.5 Refined Methods of Analysis (Computer Method)

The computer has become an invaluable aid to the bridge engineer. It permits better analysis in much less time than hand methods. It provides the engineer more flexibility to change member sizes and investigate different support conditions, various loading conditions and various modeling assumptions, than possible with time-consuming hand analyses.

Use of this greater analysis power removes the tedium of hand analysis and allows much more flexibility; but demands that the responsible engineer become familiar with each program, its capabilities and limitations, and verify the results of each analysis. This responsible use of computer tools is essential to maintain professional control of a bridge analysis and design project. The computer cannot substitute for an engineer’s education, experience, judgment and responsibility.

It is FLH Bridge policy to encourage the responsible use of state-of-the-art computer tools for analysis and design of bridge structures.

Some recommendations for responsible use of this tool are as follows:

- Determine program authors, original purpose and history of usage and revisions in order to evaluate the authenticity of reliability, available technical support for and the maturity of the program;
- Obtain complete user documentation as well as sample problem input and output;
- Strive to become familiar with and understand the program's flow and internal algorithms to the greatest extent possible;
- Obtain training and technical support from program authors or experienced users;
- Obtain education in unfamiliar program analysis techniques;
- When using very complicated programs for the first time, obtain a check run from the same program by the author or an experienced user;
- Always correlate the program output results (at least at critical sections) to a rough hand analysis in which you have confidence;
- When reasonable correlation does not exist, determine the cause and pursue better correlation or understanding before using the program further;
- Document helpful notes on input, usage, problem areas, correlation results, etc., for aiding novices and repeat users; and
- Avoid becoming overconfident with any program and always verify its results.

A very real danger exists in irresponsible computer usage. Engineers should spend their early career development time learning not just the usage of computer programs, but also the structural theory fundamentals.

In the FLH Bridge Office, engineers are taught the classical hand analysis techniques described previously along with proper computer usage. Development of these hand skills has shown to provide an excellent theoretical as well as practical application base for the development of responsible bridge engineers.

The following are some FLH approved computer programs:

1. **CONSPAN.** A comprehensive program for the AASHTO Standard and LRFD design, bridge load rating and analysis of simple- and multiple-span precast and prestressed bridge beams.
2. **Structural Analysis Program (SAP)**. A large, general-purpose, elastic finite element program for static, dynamic and nonlinear analysis.
3. **RC-PIER.** An integrated tool for the AASHTO Standard and LRFD analysis and design of reinforced concrete bridge substructures and foundations.
4. **CONBOX.** Specifically developed for the analysis and design of post-tensioned and cast-in-place reinforced concrete box girder and slab bridges constructed on falsework.
5. **LARSA**. Analyzes steel, concrete segmental, composite and cable-stayed bridges.

6. **Bridge Rating and Analysis of Structural Systems (BRASS)**. Analyzes and designs reinforced concrete box culverts; steel, timber, reinforced concrete or prestressed girders; and, reinforced concrete piers. The program is a comprehensive system for rating simple and continuous truss and girder floor beam stringer type bridges.
7. **MDX.** A computer program for curved and straight steel bridge design and rating for compliance with AASHTO LRFD specifications.
8. **LPILE and APILE.** LPILE is a program for the analysis of piles and drilled shafts under lateral loads. APILE is a program for the analysis of the axial capacity of driven piles.
9. **spColumn.** A program for the design and investigation of reinforced concrete sections subject to combined axial and flexural loads. Formerly it was pcaColumn, PCACOL, and IrrCOL.

10.4.6 REINFORCED CONCRETE DESIGN

Almost every bridge designed in the United States today uses reinforced concrete in some element. This may be footings, substructure elements (e.g., piers, abutments), retaining walls, girders, decks or rails. Many bridges consist entirely of reinforced concrete. Since its introduction over 150 years ago, concrete has been the most widely used construction material in the history of civilization. The major advantage in the use of concrete for bridges is its ability to be used in a wide variety of configurations and to have variable content.

10.4.6.1 Structural Types

The following is a list of the more common types of reinforced concrete bridge structures. Each design has distinctive characteristics and attributes.

1. **Reinforced Concrete Slab Bridge**. The following applies:
   a. **Structural**. Refer to Section 2.5.2.6.3 of the AASHTO *LRFD Bridge Design Specifications* for the span-to-depth ratios.
   b. **Appearance**. Neat and simple; desirable for low, short spans.
   c. **Construction**. Details and formwork simplest.
   d. **Traffic**. May be impeded by falsework if cast-in-place due to reduced clearances. Guardrail should protect falsework openings for traffic lanes.
   e. **Construction time**. Shortest of any cast-in-place construction.
   f. **Maintenance**. Very little except at hinges. Future widening may be difficult.
2. **Reinforced Concrete T-Beam Bridge**. The following applies:
   a. **Structural**. Refer to Section 2.5.2.6.3 of the AASHTO *LRFD Bridge Design Specifications* for the span-to-depth ratios.
   b. **Appearance**. Cluttered in view from bottom; elevation is neat and simple.
   c. **Construction**. Requires good finish on all surfaces; formwork is complicated.

d. **Traffic**. May be impeded by falsework if cast-in-place due to reduced clearances. Guardrail should protect falsework openings for traffic lanes.

e. **Construction time**. More than for slabs due to forming, but not excessively long.

f. **Maintenance**. Low, except that bearing and hinge details may require attention.

3. **Reinforced Concrete Box Girder Bridge**. The following applies:

a. **Structural**. Refer to Section 2.5.2.6.3 of the AASHTO *LRFD Bridge Design Specifications* for the span-to-depth ratios. High torsional resistance makes it suitable on curved alignment.

b. **Appearance**. Neat and clean lines from all views; utilities, pipes and conduits can be concealed.

c. **Construction**. Rough form finish is satisfactory on inside surfaces; formwork is complicated.

d. **Traffic**. May be impeded by falsework due to reduced clearances. Guardrail should protect falsework openings for traffic lanes.

e. **Construction Time**. More than for slabs or T-beams due to staging of concrete placement, but still not excessively long.

f. **Maintenance**. Low, except that bearing and hinge details may give some trouble. Future widening may be difficult.

4. **Rigid-Frame Bridges**. The following applies:

a. **Structural**. Integral rigid negative-moment knees greatly reduce the positive span moment and overturning moment at foundation level.

Single rigid portal frames will adapt to narrow water channels, railways, subways and divided or undivided highways underneath.

Double-span rigid frames suitable for divided multilane highways underneath with sufficient small or medium width for triple-span support rigid frames (with or without side spans) are possible to accommodate multilane, divided highways with a wider center mall or median.

Advantage of variable moment of inertia can be easily incorporated. Preliminary proportioning can start with a thickness at the knee equal to approximately twice that at the crown.

b. **Appearance**. Graceful and clean; well-adjusted to stone facing.

c. **Construction**. Usually requiring curved formwork for variable depth.

d. **Traffic**. May be impeded by falsework due to reduced clearances. Guardrail should protect falsework openings for traffic lanes.

e. **Construction Time**. Similar to that of other types.

f. **Maintenance**. Low, except for potential backfill settlement. Limited flexibility for future widening.

5. **Arch Bridges**. The following applies:

a. **Structural**. Horizontal reactions created by an arch greatly reduce the otherwise large, positive moment in the center. Constant depth for small spans and variable moment of inertia for medium and long spans. Spans as long as 1000 ft [300 m] have been built. Rise-to-span ratio varies with topography. Thickness at spring lines usually is slightly more than twice that at the crown. Filled spandrels are used only with short spans.

b. For medium and long deck spans, open spandrels with roadways carried by columns are the rule. In a through-arch, the center deck usually is carried by hangers and side decks by columns. Use long single spans over deep waterways and shorter multiple spans over wide, shallow waters with rock bottoms.

c. **Appearances**. Graceful and attractive, especially over deep gorges, ravines or a large waterway.

d. **Construction**. Either falsework or cantilever methods can be used.

e. **Traffic**. When traffic cannot be diverted, the cantilever method may be used instead of falsework.

f. **Construction Time**. Usually longer than for other structures. Use prefabricated blocks and post-tensioning when shorter time is desired.

g. **Maintenance.** Low.

10.4.6.2 General Requirements and Materials

Concrete to be used for nonprestressed structures will normally have a 28-day compressive strength (f'_c) of 4 ksi to 5 ksi [28 MPa to 35 MPa]. The strength required will be based on the member use and product availability from local sources. Poor quality local aggregates often limit the strength of available concrete. Coordinate with team leader on type of concrete to be used.

Grade 60 [Grade 420] reinforcing is typically used in the design. All reinforcing steel should conform to Section 709 of the Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-XX.

10.4.6.3 Analysis

All members of statically determinate or indeterminate structures should be designed for the maximum effects of all loads as determined by elastic analysis. Instead of elastic analysis, any acceptable method may be used that takes into account the nonlinear behavior of reinforced concrete, when subjected to bending moments approaching the ultimate. The FLH Bridge

Engineer should approve the use of these more exact methods of analysis on a case-by-case basis. Consider the following:

1. **Expansion and Contraction**. When designing and detailing reinforced concrete structures, the design engineer should always keep in mind the degree of restraint in members of the bridge. Highly restrained members will almost always crack due to shrinkage or temperature changes. Carefully located construction joints can reduce shrinkage stresses. Stresses due to temperature changes can be controlled by adjusting the stiffness of the structure and by the location of joints.

   Creep and shrinkage of concrete are time-dependent deformations and must be included in the design of bridge structures. Short-term loading (live loads) on a concrete bridge induces elastic deformations. Dead loads or superimposed dead loads, however, are long-term effects that must be considered.

   Creep of concrete is the phenomenon in which the deformation continues with time under constant load. This response can be related to the initial elastic deformation or strain.

   Shrinkage is defined as the volume change in the concrete with respect to time.

10.4.6.4 Design

The AASHTO *LRFD Bridge Design Specifications* should be used on all new construction projects unless approval to use the AASHTO *Standard Specifications for Highway Bridges* is granted by the FLH Bridge Engineer. On rehabilitation or widening projects, the use of the AASHTO *Standard Specifications for Highway Bridges* will be decided on a case-by-case basis by the FLH Team Leader.

10.4.6.5 Specifications, Design Aids and Policies

The technical references listed in Section 10.2.4 will clarify and guide the usage of the AASHTO *LRFD Bridge Design Specifications*. Current AASHTO *LRFD Specifications* are necessary since bridge design is dynamic in nature (i.e., research and development of new technologies force changes in both design specifications as well as construction methods).

10.4.7 STRUCTURAL STEEL DESIGN

Although true structural steel was used for the eye-bars of suspension bridges in the early 1800’s, it was not until about 1870 that the first all steel bridge was constructed. Today, there is a wide variety of steels available for bridge design. The bridge engineer needs to have a working knowledge of the physical properties of these steels in order to make a proper selection.

10.4.7.1 Structural Types

The following is a list of the more common types of structural steel bridges. Each design has distinctive characteristics and attributes:

1. **Composite Wide Flange Beam**. The following applies:
   a. **Structural**. This structure type has low dead load that may be of value when foundation conditions are poor. Refer to Section 2.5.2.6.3 of the AASHTO LRFD Bridge Design Specifications for the span-to-depth ratios. Larger sizes of wide flange beams may not be available in many areas.
   b. **Appearance**. Can be attractive. Best for simple spans.
   c. **Construction**. Details and form work simple. Partial length cover plates welded to bottom flange will improve economics.
   d. **Traffic**. Minimal traffic problems; limited to short periods of time for erection and installation of protection nets if required.
   e. **Construction Time**. On the job, very short, but procurement of steel may cause delay.
   f. **Maintenance**. Painted steel structures require routine maintenance depending on environmental conditions. Weathering steel eliminates the need for painting. The savings in initial and future maintenance painting offsets its higher cost. Weathering steel should be carefully considered in desert climates, coastal areas or in areas subject to heavy use of deicing salts. Weathering steel may cause straining of concrete piers and abutments.
2. **Composite Welded Girder**. The following applies:
   a. *Structural*. This structure type has low dead load, which may be of value when foundation conditions are poor. Refer to Section 2.5.2.6.3 of the AASHTO LRFD Bridge Design Specifications for the span-to-depth ratios. Can be adapted to curved alignment. Competitive with precast concrete girders.
   b. *Appearance*. Can be made to look attractive. Girders can be curved to follow alignment.
   c. *Construction*. Details and formwork simple. Transportation of prefabricated girders may be a problem.
   d. *Traffic*. Same as for composite wide flange beam.
   e. *Construction Time*. Short time on the project, but procurement and fabrication of steel may cause delay.
   f. *Maintenance*. Same as for Composite Wide Flange Beam.
3. **Structural Steel Box Girder**
   a. *Structural*. Use multiple boxes for spans up to 200 ft [60 m] and single box for longer spans. Use depth-span ratio of 0.045 for continuous spans, and 0.060 for simple spans. More expensive than steel "I" girder. More economical in the upper range of usable span and where depth may be limited. Steel box girder

superstructure is an option for spans ranging between 200 ft and 300 ft [60 m and 90 m]. Its high torsional resistance makes it suitable on curved alignment.

b. *Appearance*. Generally pleasing. Better than steel or precast concrete girders.

c. *Construction*. Very complicated welding and welding details. Because of the many opportunities for welding and detail errors that can give rise to fatigue failures, the steel box should only be used in very special circumstances.

d. *Traffic*. Erection requires substantial falsework bents at splice locations.

e. *Construction Time*. Procurement of steel and extensive fabrication requires considerable time.

f. *Maintenance*. Same as for composite wide flange beam.

4. **Steel Railroad Structure**. The following applies:

a. *Structural*. Reinforced concrete deck preferred. Steel plate deck may be used. Deck type structures are more economical than through girder structures. Depth-span ratio is 0.10 for deck type (not including the 2 ft [0.61 m] from top of rail to bottom of ballast). Through girder structures requires substantial deck thickness from top of rail to bottom of ballast. Depth-span ratio of through girders is 0.13.

b. *Appearance*. Can be attractive.

c. *Construction*. Details simple. Shop Fabricated.

d. *Traffic*. Minimal traffic problems.

e. *Construction Time*. Same as for Composite Welded Girder.

f. *Maintenance*. Same as for composite wide flange beam.

10.4.7.2 General Requirements and Materials

All structural steel should conform to Section 717 of the *Standard Specifications For Construction of Roads and Bridges on Federal Highway Projects, FPXX*. The use of High Performance Steel (HPS) should be considered where possible. The use of weathering steel should be decided by the project team in conjunction with the maintaining agency.

In general, bolts for structural steel bridges shall be fabricated from ASTM A 325M (Type 1) (AASHTO M 164M) steel and should be used with painted steel. Type 3 bolts conforming to ASTM A 325M (AASHTO M 164M) should be used with weathering steel. On rehab projects rivets should be replaced with high strength ribbed bolts to provide snug fit in the hole.

The use of high strength ASTM A 490M (AASHTO M 253M) bolts should be used only when necessary.

10.4.7.3 Design

In the past, steel bridge design was relatively simple. Usually, the structure was only required to span an obstacle by the simplest and most direct means. Material stresses were kept quite low.

Today, however, steel bridges are required to match the highway alignment, which often results in curved structures. Economic considerations require the use of steels to their maximum, resulting in very high material stresses. This means that the design details for steel bridges are of utmost importance. Current specifications become very complex and should be carefully adhered to for all steel bridge design. Consider the following:

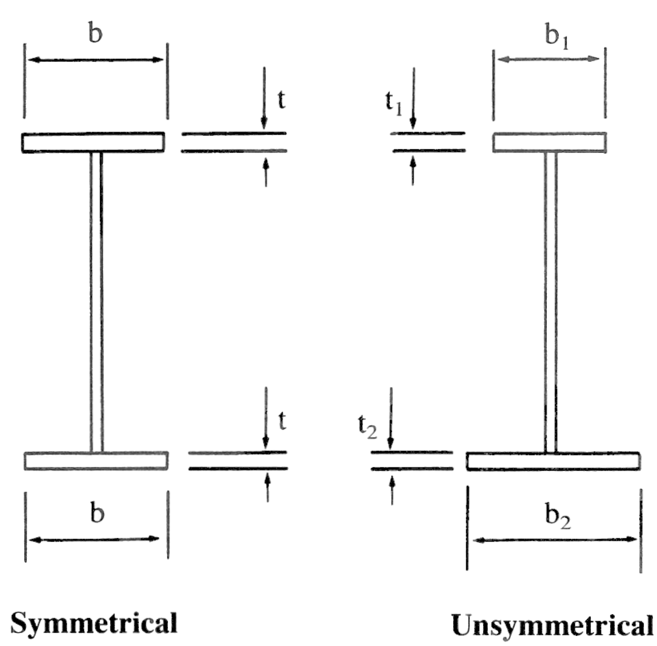
1. **Fatigue and Fracture Considerations**. Refer to Section 6.6 of the AASHTO *LRFD Bridge Design Specifications* for the fatigue and fracture design provisions.

2. **Efficient Girder Depths**. The first step in the design of a steel bridge is to determine the most efficient web depth. The determination of this depth is based on several parameters. Girders may be classified as either symmetrical or unsymmetrical as shown in Exhibit 10.4-A. Usually the weight and cost of a girder should decrease as the girder depth increases. Very deep girders with small flanges may become unstable and difficult to fabricate, transport and erect. The additional cost due to difficult fabrication, transportation and erection, which can easily overweight the cost savings due to the steel weight reduction. An economical web is a web that does not require stiffeners. Transverse stiffeners can be eliminated or reduced by thickening the web.

   In addition to being classified as symmetrical or unsymmetrical, steel members can be further categorized as follows:

   - Compact,
   - Noncompact,
   - Braced,
   - Unbraced,
   - Transversely stiffened, and/or
   - Longitudinally stiffened.

Exhibit 10.4-A GIRDER CLASSIFICATION



3. **Deflection**. The contract drawings should show the design camber necessary to compensate for deflection due to dead load, superimposed dead load and for vertical curvature required by the profile grade. Live load deflection must be checked.
4. **Splices**. Field splices should be bolted splices and designed by the AASHTO *LRFD Bridge Design Specifications*. Field splices are generally located near points of dead load contraflexure. Field welded splices of primary structural members should be avoided.
5. **Diaphragms, Cross Frames and Lateral Bracing**. Diaphragms and cross frames should be placed as stated in Section 6.7.4 of the AASHTO *LRFD Bridge Design Specifications*. The need for lateral bracing should be investigated in accordance with Section 6.7.5 of the AASHTO *LRFD Bridge Design Specifications*.
6. **Composite Deck Design**. Concrete deck slabs should be made composite with steel girders for the entire length of simple spans. For continuous spans, if shear connectors are not provided in the negative moment region, additional shear connectors should be placed in the region of the points of permanent dead load contraflexure (for detailed explanation, refer to AASHTO LRFD Section 6.10.10). This is generally achieved with welded stud or channel shear connectors.

10.4.7.4 Specifications, Design Aids and Policies

The technical references listed in Section 10.2.4 will clarify and guide the usage of the AASHTO *LRFD Bridge Design Specifications*. The current AASHTO *LRFD Specifications* are necessary since bridge design is dynamic in nature (i.e., research and development of new technologies force changes in both design specifications as well as construction methods).

10.4.8 PRESTRESSED CONCRETE

The first prestressed concrete bridge in the United States was constructed in 1949. Since 1960, most bridges in the United States with a span range of 60 ft to 120 ft [18 m to 36 m] have been constructed with prestressed concrete. In the late 1970's, post-tensioned continuous or cantilever bridges with spans of 150 ft to 660 ft [45 m to 200 m] have gained in popularity.

10.4.8.1 Structural Types

The following list of features of the more common structures provides information to assist in the preliminary selection and sizing of members:

1. **Cast-in-Place Concrete Slab**. The following applies:
   a. **Structural**. Used for spans up to 66 ft [20 m]. Recommended for conditions where very low span-to-depth ratio is required. Can be used for either simple or continuous spans. The depth span ratio is 0.030 for simple and continuous spans. More expensive than reinforced concrete slabs.
   b. **Appearance**. Same as reinforced concrete slabs.

c. **Construction**. More difficult than reinforced concrete slabs.

d. **Traffic**. May be impeded by falsework due to reduced clearances. Guide rail should protect falsework openings for traffic lanes.

e. **Construction Time**. Shortest of cast-in-place construction; longer than precast slabs.

f. **Maintenance**. Very little.

2. **Precast Prestressed Concrete Slab**. The following applies:

   a. **Structural**. Adjacent prestressed concrete slabs can be used to a maximum span of about 55 ft [17 m]. Not recommended for long multi-span structures because of difficulties in camber control resulting in undesirable riding qualities. Economical where many spans are involved or in areas remotely located from concrete batch plants.

   b. **Appearance**. Same as reinforced concrete slab.

   c. **Construction**. Details and formwork very simple. Shop fabrication methods employed.

   d. **Traffic**. Very little interference except during erection.

   e. **Construction Time**. On site, very short. Very little time required for plant fabrication.

   f. **Maintenance**. Very little.

3. **Precast prestressed Concrete Girder**. The following applies:

   a. **Structural**. Prestressed concrete box beams can span up to 120 ft [37 m]. Prestressed concrete I-beams and bulb-tee beams can span up to 150 ft [46 m]. For longer spans, spliced prestressed concrete girders should be considered. Refer to Section 2.5.2.6.3 of the AASHTO *LRFD Bridge Design Specifications* for the span-to-depth ratios. Feasibility to transport and erect girders longer than 130 ft [40 m] should be investigated. Precast prestressed concrete girders are competitive with steel girders and very economical in areas near precasting plants.

   b. **Appearance**. Similar in appearance to T-beams. Straight girders on curved alignment can look awkward.

   c. **Construction**. Require careful handling and transporting after fabrication. Fabrication plants nationwide cast a wide variety of sections in addition to standard AASHTO sections.

   d. **Traffic**. Same as prestressed slabs.

   e. **Construction Time**. Same as steel girders. Fabrication may require additional time.

   f. **Maintenance**. Very little except at hinges or joints.

4. **Cast-in-Place Box Girder (Post-Tensioned)**. The following applies:

   a. **Structural**. Requires detailed stress analysis. Refer to Section 2.5.2.6.3 of the AASHTO *LRFD Bridge Design Specifications* for the span-to-depth ratios. High torsional resistance makes it desirable on curved alignment. Dead load deflections minimized. Desirable for simple spans over 150 ft [46 m]. Long-term shortening of structure must be provided for. About the same as conventionally reinforced box girder. Used for spans up to 600 ft [180 m].

   b. **Appearance**. Better than conventional box girder because of shallow depth. All other qualities of conventional box girder exist. Excellent in metropolitan areas. Can be used in combination with conventional box girders in long structures with varying span lengths to maintain constant structure depth.

   c. **Construction**. Same as conventional box girder.

   d. **Traffic**. May be impeded by falsework due to reduced clearances. Guardrail should protect falsework openings for traffic lanes.

   e. **Construction Time**. Longest for any prestressed concrete structure due to delay before tensioning is allow to proceed.

   f. **Maintenance**. Very little except at joints or hinges.

10.4.8.2 General Requirements and Materials

Concrete in prestressed members is subject to higher stress levels than concrete in nonprestressed, reinforced members. Therefore, on all projects under the jurisdiction of FLH, the minimum compressive strength at the time of initial prestress must be f'_{ci} = 4.0 ksi [27.5 MPa] or 0.6 $f'_{c.}$

Prestressing steel strands are available in diameters from 0.25 in to 0.6 in [6.4 mm to 15.2 mm], in grades of 250 ksi or 270 ksi [1720 MPa or 1860 MPa], and as either stress-relieved or low-relaxation. The grade or strand indicates the ultimate strength and the type of strand (i.e., stress-relieved or low-relaxation) and defines the manufacturing process and prestress loss characteristics. Only low-relaxation prestressing steel strands should be used.

If a prestressing firm opts to change the size and pattern of the strands, any changes must be redesigned by the manufacturer and checked by the government. These changes should be shown on the fabrication plans and submitted for approval.

Properties and strengths of seven-wire, grade 270 ksi [1860 MPa] strand are shown on Exhibit 10.4-B.

Exhibit 10.4-B PROPERTIES OF PRESTRESSING STRAND

(US Customary)

Seven-Wire-Strand, f'_S = 270 ksi					
Nominal Diameter, in	3/8	7/16	1/2	9/16	0.600
Area, in^2 [A^*_S]	0.085	0.115	0.153	0.192	0.217
Weight, lb/ft	0.29	0.40	0.52	0.65	0.74
0.7 f'_S A^*_S, kips	16.1	21.7	28.9	36.3	41.0
0.75 f'_S A^*_S, kips	17.2	23.3	31.0	38.9	44.0
0.8 f'_S A^*_S, kips	18.4	24.8	33.0	41.4	46.9
f'_S A^*_S, kips	23.0	31.0	41.3	51.8	58.6

Note: f'_s = Ultimate strength of 270 ksi

(Metric)

Seven-Wire-Strand, f'_S = 1860 MPa					
Nominal Diameter, mm	9.5	11.1	12.7	14.3	15.2
Area, mm^2 [A^*_S]	54.8	74.2	98.7	123.9	138.7
Mass, kg/m	0.43	0.60	0.79	0.97	1.12
0.7 f'_S A^*_S, kN	71.6	96.5	128.6	161.5	181.0
0.75 f'_S A^*_S, kN	76.5	103.6	137.9	173.0	193.5
0.8 f'_S A^*_S, kN	81.8	110.3	146.8	184.2	206.8
f'_S A^*_S, kN	102.0	137.9	183.7	230.4	258.4

Note: f'_s = Ultimate strength of 1860 MPa

10.4.8.3 Analysis

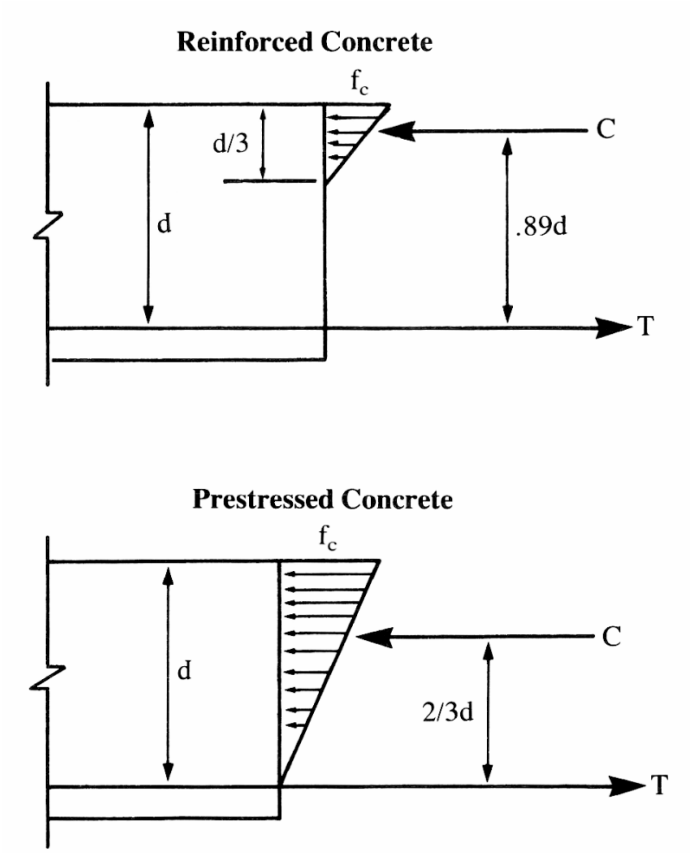
Stresses are introduced into the concrete opposite to the stresses resulting from loads acting on the structure. The stresses are introduced in a manner that allowable stresses will not be exceeded. Compressive stresses are induced in the face of the member where tensile stresses tend to develop due to loads. These induced stresses result from a compressive force that is transmitted to the concrete from the prestressing steel.

Prestressed concrete makes full use of the compressive strength of the concrete and the tensile strength of the prestressing steel. Ordinary reinforced concrete does not use the concrete to its full advantage. For comparison purposes (using the same allowable concrete stress), see

Exhibit 10.4-C The resulting moment for the reinforced concrete section is calculated in the normal manner, and the resisting moment shown for the prestressed section is approximately the net resisting moment for applied loads after prestressing.

As shown in Exhibit 10.4-C, a prestressed section with beams of the same depth can resist more than twice the moment that the reinforced concrete section can resist. Furthermore, the allowable stress can be doubled for the prestressed section, thus making the resisting moment over four times that of the reinforced concrete section. The prestressed section makes use of the entire concrete area; however, the reinforced section uses about one-third of the area while two-thirds is being used to hold the reinforcing steel away from the working section, resist shearing stresses and develop the bond between the concrete and reinforcing steel.

Exhibit 10.4-C CONCRETE BEAM STRESSES



Two advantages of a prestressed concrete structure are the reduction of both concrete and steel quantities. Other advantages of a prestressed concrete structure are as follows:

- A considerable reduction in depth of section, not only relative to reinforced concrete, but also relative to structural steel.
- A reduction in the cracking of concrete within a known range of load. This results in greater durability under severe conditions of exposure.
- A prestressed structure that has maximum rigidity under working loads and maximum flexibility under excessive overloads.

- The capacity to support a load in excess of the design load in which cracks appear but disappear completely on removal of the excess load.
- A definite reduction in diagonal tension. An important factor in reinforced concrete but often less severe in prestressed concrete.
- Use of pretested structural materials. During the prestressing operations, the steel is tested to a stress that will never again be reached under design loads. The same applies to the concrete, in many cases. This type of in-place testing is impossible in ordinary reinforced concrete structures.
- Added flexibility for construction.

There are two methods of applying a prestressing force. Pretensioning is tensioning of the steel that is done before the concrete is cast in the forms. Post-tensioning is tensioning that is done after the concrete has been cast and has attained the required strength. In the former, the force is transmitted by the bond between the steel and concrete. The initial prestress is immediately reduced due to the deformation and shrinkage of the concrete. Gradually, these losses are increased by further shrinkage and creep of the concrete. In post-tensioning, the elastic shortening losses are lower than in pretensioning. Like pretensioning, there is a gradual loss due to the shrinkage and creep of the concrete and the creep of the steel. Consequently, for equivalent members, the pretensioning method requires a greater initial prestressing force to compensate for the larger losses.

Pretensioning is practical only within factory or mass production facilities, since permanent anchorages are required to take the reaction of the stressed wires until the concrete attains the required strength.

Several methods of stressing and anchoring “post-tensioned” steel are in use. The methods used most commonly in the United States at present are illustrated in the *Post-Tensioning Manual.*

Design prestressed concrete members to meet the requirements of Section 5 of the AASHTO *LRFD Bridge Design Specifications*.

Expansion and contraction are important design parameters and require consideration. Bearings and joints for prestressed bridges must accommodate the movement from prestress shortening in addition to temperature changes. In framed structures, the stresses resulting from these movements must be included in the design.

The prestress shortening to be expected can be calculated by Equation 10.4(1):

$$\Delta = \frac{PL}{AE} \qquad \text{Equation 10.4(1)}$$

where:

P	=	total prestressing force, lbs [kN]
L	=	one half of the length between piers, ft [m]
A	=	cross sectional area of the superstructure, ft^2 [m^2]
E	=	elastic modulus of superstructure concrete, lbs/ft^2 (kN/m^2)

10.4.8.4 Specifications, Design Aids and Policies

The technical references listed in Section 10.2.4 will clarify and guide the usage of the AASHTO *LRFD Bridge Design Specifications*. The AASHTO *LRFD Yearly Interims* are necessary since bridge design is dynamic in nature (i.e., research and development of new technologies force changes in both design specifications as well as construction methods).

10.4.9 TIMBER

Timber bridges, properly designed and treated with modern preservatives, will give many years of minimal-maintenance service. Their use is normally limited to low-volume, secondary-road bridges and pedestrian bridges.

The following are the most common bridge components that use timber:

- Piling,
- Beams or girders,
- Decks, and
- Rails and posts.

As can be seen, it is possible to construct entire bridges of timber; however, this is rarely done. Rather, timber is combined with other elements (e.g., steel girders, concrete substructures) to produce the most economical and maintenance-free structure possible.

With the exception of temporary structures, all exposed timber should be pressure treated. The most common species of timber used are Douglas Fir and Southern Pine. Hardware is normally galvanized or stainless steel.

10.4.9.1 Substructures

Timber pilings are displacement piles that normally function as friction piles. When used as point bearing piles or when difficult driving conditions are encountered, reinforced pile tips should be considered. AASHTO *LRFD* Section 10.7.3.13.3 gives guidance on the design of timber piles as a structural member. Timber piling should not be used in soils where large boulders or cobbles exist. Timber piling is most economical when used for relatively shallow foundations. Timber-pile bents should not be used in streams that carry heavy drift and debris.

10.4.9.2 Superstructures

The most common type of timber superstructure is the longitudinal girder, simple-span bridge. Straight girders are most economical for short spans of 20 ft to 60 ft [6 m to 18 m]. Spans up to 100 ft [30 m] are possible using glue laminated girders, but may not be economical depending on location, live load and vertical clearance requirements.

A second common type of timber superstructure is the truss bridge. This may be either a bowstring truss or a parallel-chord truss. Bowstring trusses are of two general types:

1. The pony truss for spans from 50 ft to 100 ft [15 m to 30 m], and
2. The through span truss for spans longer than 100 ft [30 m].

Commonly, top and bottom chords are glue-laminated members and web members are sawn timber. Steel rods are used in tension members in the web. When water clearance allows, the parallel chord truss may be used as a deck span, thus enabling pier heights to be greatly reduced. The parallel chord truss may also be used in a through span. The practical span range for either system is 100 ft to 250 ft [30 m to 75 m].

For long, clear-span timber bridge construction, the deck-arch bridge has been used. With this type of construction, pier height is held to a minimum and yet the bridge is well above high water. The deck arch is practical for spans from 60 ft to 300 ft [18 m to 90 m], and is particularly suitable when rock canyon walls can reduce the foundation sizes for arch abutments. All present designs for timber-arch bridges should specify laminated construction.

10.4.9.3 Decks

Timber decking is the most common use of timber in current bridge construction. In the past, the most common type of deck was nail-laminated decking using nominal 2 in [50 mm] dimension lumber fastened with through-nailing of the laminations and toe-nailing of the laminations to longitudinal stringers.

Today, most decks are glue-laminated timber systems that allow longer deck spans. These glue-laminated deck systems are plant fabricated in panels and may be designed for either transverse or longitudinal decking. This has necessitated the development of improved connection systems to connect the deck panels to the superstructure. Many current systems are detailed in timber design publications and manuals. The designer should carefully select and analyze these connection systems for strength, ability to resist shrink or swell of timber members and for resistance to loosening due to vibration or deflection.

Few deck connection systems provide true lateral support to the compression flanges of supporting girders. This lateral support must be considered partial lateral support at diaphragms or cross-frames in most cases.

Most timber deck designs should include wearing planks (sometimes called running planks) to protect the primary decking from tire wear. These wearing planks are nailed to the lower deck and are replaced as required.

All timber decking should be pressure treated to extend decking life.

Timber decks may also be protected by a waterproofing membrane and an asphalt concrete overlay. Detailed mix designs for these overlays are available from the American Institute of Timber Construction.

For some designs, this overlay can be used to provide a crown section for roadway drainage. It is not practical to crown decks constructed entirely of timber.

10.4.9.4 Rails and Posts

Timber rails and posts are commonly used for railings on pedestrian bridges due to the ability of timber to produce an aesthetically pleasing appearance. These railings normally use glue-laminated timber for the rails and either glue-laminated or sawn timber for the posts. Do not use creosote treated timber for pedestrian rail systems.

Timber rail system used on FLH bridges should meet the NCHRP 350 and AASHTO *LRFD Specifications*. Timber rail systems, intended for vehicular traffic, almost always incorporate a heavy timber or concrete curbing and a steel backing plate for the timber rail elements. The rails are usually glue-laminated timber and posts may be either glue-laminated or sawn timber. As with all rail systems, timber railings must be carefully designed, with particular attention paid to connection, joints and splices.

10.4.10 BEARINGS

Bridge bearings serve several purposes, the first of which is to transmit vertical loads from the superstructure to the substructure. These bearings must also transmit lateral forces, longitudinal or transverse in direction, between the superstructure and the substructure. In addition, these bearings should take care of girder rotation.

Fixed (sometimes called pinned) bearings transmit both longitudinal and transverse forces. Expansion bearings generally transmit only friction or longitudinal shear forces from the movement of the bearing during longitudinal expansion or contraction. Expansion bearings also usually transmit transverse lateral forces from the superstructure to the substructure.

Numerous types of bearings are available. The following are the most common bearings in current use:

- Elastomeric bearing pads come in several configurations. Plain pads of 0.5 in [12 mm] thickness are used for fixed bearings in conjunction with lateral-load transfer devices such as keys in construction joints, shear lugs or anchor bolts. These 0.5 in [12 mm] pads allow rotation of girders and provide distribution of loads between slightly uneven bearing surfaces.
- Laminated pads are used for expansion bearings. These bearings may have either steel shims or fabric shims, usually spaced at 0.5 in [12 mm] increments. Laminated pad bearings usually are used with transverse lateral load transfer devices. They are usually designed for horizontal movement in one direction only. Laminated bearings must be molded as a single unit under heat and pressure to prevent bond failure between the layers.

  The durometer hardness of the elastomer should be specified on the plans. This hardness should be based on the lowest anticipated service temperatures.

  Geometric proportions (i.e., shape factors) are given in the AASHTO *LRFD Specifications* to ensure stability of the bearings. Bearing design is controlled by compressive stress, shape factor, hardness and compressive strain. Bearing thickness is controlled by movement requirements. FLH Bridge practice is to use “Method A” for the design of elastomeric bearing pads.

- Sliding bearings are a configuration normally consisting of a combination of a thin elastomeric pad (to allow rotation and to control the distribution of the bearing loads), steel bearing plates and a TFE (Teflon) surface moving against either another TFE surface, or against a stainless steel surface. These bearings have very low friction valves. They are used for moderate-span steel structures. Lugs to transfer lateral forces are often incorporated into the design of bearing.
- Alternate bearings are used in high load situations, for multi-directional movement, or where thermal movements are excessive for elastomeric bearings. They include pot bearings, disc bearings and spherical or cylindrical bearings. Pot bearings consist of a pot, a piston, an elastomeric disc, and sealing rings. The fluid type action distributes the load evenly on the base plate. These bearings may be designed with TFE sliding surfaces to allow movements. A disc bearing functions by deformation of a polyether urethane disc, which should be stiff enough to resist vertical loads without excessive deformation and yet be flexible enough to accommodate the imposed rotations without liftoff or excessive stress on other components, such as PTFE. The urethane disc should be positively located to prevent its slipping out of place. Spherical and cylindrical bearings have curved sliding surfaces consisting of two metal parts with matching curved surfaces and a low friction sliding interface.
- Roller and rocker bearings are bearings that have been used for longer-span steel bridges in the past, but are rarely used in current design. They are normally either painted or galvanized, even when used with weathering steel superstructures. Small diameter rollers do not perform satisfactorily due to corrosion and should not be used. These bearings can be designed for either fixed or expansion bearings.

All bearings should be accessible for inspection and maintenance. For bearings that are designed for longitudinal movement, the plans should include, in tabular form, the required settings throughout the probable temperature range at the time of erection or construction.

The designer should keep construction procedures in mind and carefully detail bearing seats. Difficult profile grade geometry and skew effects often will require the use of grout pads under bearings. These grout pads are cast after the abutment or pier seat is complete and allow exact bearing location to be achieved. Because it is unreinforced, the thickness of the grout pad should be limited and the grout pad should be recessed into the bearing seat.

Together with deck joints, bridge bearings are a source of major structural problems and often are the cause of serious damage to other parts of the structure. Bearings must be engineered and designed to allow free movement and to transmit superstructure loads. Careful analysis should be made of all bridge bearings. A standardized bridge bearing that fits all conditions does not exist.

10.4.11 FOUNDATIONS AND SUBSTRUCTURES

The substructure is that part of the structure that serves to transmit the forces of the superstructure and the forces on the substructure itself onto the foundation.

The foundation is that part of a structure that serves to transmit the forces of the structure onto the natural ground.

If a stratum of soil suitable for sustaining a structure is located at a relatively shallow depth, the structure may be supported directly on it by a spread foundation. If the upper strata are too weak, the loads are transferred to more suitable material at greater depth by means of piles or drilled shafts.

The design of the structural elements for foundations, substructures and retaining walls shall be in accordance with AASHTO *LRFD Bridge Design Specifications*.

Some of the items that are determined by evaluation of site investigations and/or by current practice are as follows:

- Bearing capacities of foundation soils,
- Settlement of foundation soils,
- Ability of piles to transfer load to the ground, and
- Lateral earth resistances.

In stability analyses should be performed as required in Section 10 of the AASHTO *LRFD Bridge Design Specifications*.

The following are some rough guidelines for providing for superstructure movements at abutments:

1. **Integral Abutments**. Integral abutments are constructed as a rigid connection of the deck and beams to a single row pile supported substructure. There are no expansion joints at the abutments. The length of an integral abutment structure shall be measured between the abutments centerlines. For integral abutment structure up to 325 ft [100 m] long, an expansion joint should be provided at the end of each approach slab (sleeper slab is required). The use of integral abutment should be carefully considered for structures over 325 ft [100 m] long. Consider design requirements when selecting H-pile orientation. In most configurations, H-piles will be orientated in the weak direction for longitudinal movement.

2. **Semi-Integral Abutments**. For rigid abutments, and for flexible abutments with more than 75 ft [23 m] of contributory length, allow superstructure movement to occur against the approach fill, but permit movement between superstructure and abutment with an expansion bearing. Typically semi-Integral abutments are similar to conventional abutments with the exception of the girders extending over the bridge seat and are embedded in a backwall that hangs off behind, but is not connected to, the abutment stem. Provide adequate gap between the abutment wall and end diaphragm to accommodate final movement and construction tolerance. The semi-integral abutment with the end diaphragm also can be positioned on top of abutment wall. Make sure that

the opening between the top of abutment and bottom of the end diaphragm is adequately sealed from leakage with fill material. The maximum expansion length to the nearest fixed bearing should not exceed 230 ft [70 m]. An expansion joint should be provided at the end of each approach slab (sleeper slab is required).

3. **Conventional Abutments**. Conventional abutments with an independent backwall type abutment with deck joint designed for all movements should be used when the use of jointless, integral or semi-integral abutments is not feasible.

The above guidelines should be used with careful consideration of bearing protection from contaminants as well as provision for approach fill drainage and abutment details.

10.4.11.1 Capacity of Shallow Foundations

A shallow foundation is a term applied to footings having a depth-to-base width ratio of 1 or less.

Two things control the capacity of a shallow foundation:

1. The ability of the soil to support the loads imposed upon it, known as the bearing capacity of the soil.
2. The amount of total or differential settlement that can be tolerated by the structure being considered.

10.4.11.2 Capacity of Deep Foundations

A deep foundation is a structural system of steel, concrete or masonry that transfers a load through a poor stratum onto a better one. A pile is essentially a slender pier that transfers a load either through its tip onto a firm stratum (point bearing pile) and/or through side friction onto the surrounding soil over some portion of its length (friction pile).

In general, the bearing capacity of a single pile is controlled by the structural strength of the pile and the supporting strength of the soil. The smaller of the two values is used for design.

Piles driven through soft material to point-bearing may be dependent upon the structural strength of the pile for their bearing capacity.

The supporting strength of the soil is the sum of the following two factors,

1. The bearing capacity of the area beneath the base, and
2. The frictional resistance on the contact surface area for the length of the pile.

For point-bearing piles, factor “1” is of primary significance while for friction piles, factor “2” is of primary significance.

Structural sections of piles are to be designed using the provisions for the material being used and satisfying the minimum requirements specified in the AASHTO *LRFD Specifications*. A pile load test is probably the best method available for determining the bearing capacity of an individual pile. The tests are quite expensive, however, and on small jobs, the cost of their use cannot be justified.

10.4.11.3 Substructure Analysis and Design

In the design procedure, the allowable bearing determinations are performed by the geotechnical engineer prior to completion of the approved layout for final design. Consider the following:

1. **Reinforced Concrete Columns**. Since these are the most common substructure elements for transferring superstructure loads to the foundations, discussion of other types will not be included. Reinforced concrete columns are designed according to the AASHTO LRFD specifications.

   Commonly used shapes are round, rectangular, rectangular with rounded ends and rectangular with large chamfered corners. Flares and tapers are often required. The designer should obtain help from their Team Leader and/or the senior structural engineers in determining the type and trial dimensions. The final design should provide adequate strength to cover all factored axial load plus axial or biaxial moment combinations magnified for slenderness as necessary. See Section 5 of the AASHTO *LRFD* for additional information on reinforced concrete column design.

2. **Drilled Shafts**. For design requirements, see Section 5 and Section 10 of the AASHTO *LRFD Bridge Design Specifications*.

3. **Spread Footings**. For design requirements, see Section 5 and Section 10 of the AASHTO *LRFD Bridge Design Specifications*.

4. **Pile Footings**. For design requirements, see Section 5 and Section 10 of the AASHTO *LRFD Bridge Design Specifications*.

5. **Seals**. Seals are required for cofferdam construction of foundation portions below water where the water head and soil permeability are too great to be controlled by pumping, diversion of water, etc. The need for seals is usually determined during the preparation of the preliminary bridge layout. A rough guide is that seals are required for heads of water more than 10 ft [3 m] deep. The designer calculates the depth of seals for spread footings at 0.43 times the water head at time of construction. A minimum depth of seal should be 24 in [600 mm]. The factor 0.43 is the ratio of the unit weight of water 62.4 lb/ft^3 [1000 kg/m^3] to the unit weight of plain concrete 145 lb/ft^3 [2320 kg/m^3]. The final design of the seal is ultimately the responsibility of the contractor.

   For pile footings where uplift resistance of the piles can be counted on, the seal depth may be reduced to 0.25 times the water head.

These foundation recommendations should be presented in a report along with the foundation investigation information.

10.4.12 RETAINING WALL DESIGN

Retaining walls should be designed according to Section 10 and Section 11 of the AASHTO *LRFD Bridge Design Specifications.*

10.4.12.1 Aesthetic Considerations

The type of face treatment for retaining walls is decided on a case-by-case basis according to degree of visual impact. The wall should blend in with its surroundings and complement other structures in the vicinity. Top of walls are usually on smooth flowing curves as seen in elevation.

The profile of the top wall should be designed to be as pleasing as the site conditions permit. All slope changes at the top of the wall should be rounded with vertical curves at least 20 ft [6 m] long. Small dips in the top of the wall should be eliminated. Sharp dips should be improved by using vertical curves, slopes and steps or combinations thereof. Side slopes may be flattened or other adjustments made to provide a pleasing wall profile.

Where walls are adjacent to highways, frontage roads or city streets, special surface texturing, recessed paneling or provisions for landscaping shall be considered.

10.4.12.2 Footings

For economy and ease of construction of reinforced concrete retaining walls, consider the following criteria for layout of footing steps:

- Distance between steps should be in multiples of standard plywood sizes.
- A minimum number of steps should be used even if a slightly higher wall is necessary. Small steps less than 12 in [300 mm] in height should be avoided unless the distance between steps is 95 ft [29 m] or more. The maximum height of steps should be held to 4 ft [1.2 m]. If the footing thickness changes between steps, the bottom of the footing elevation should be adjusted so that the top of the footing remains level.

10.4.12.3 Wall Joints

For cantilevered and gravity walls, joint spacing should be maximum joint spacing of 30 ft [9 m] for contraction joints and 90 ft [27 m] for expansion joints. For counterfort wall, joint spacing should be a maximum of 33 ft [10 m] on centers. For tieback walls, joint spacing should be 23 ft to 33 ft [7 m to 10 m] on centers for cast-in-place walls, but for precast units, the length of the unit would depend on the height and thereby the weight of the unit. Odd panels for all type of walls should normally be made up at the ends of the walls. For cast-in-place construction, a minimum of 1 in [25 mm] premolded filler should be specified.

No joints other than construction joints should be used in footings except at bridge abutments and where the change from a pile footing to a spread footing occurs. In these cases, a 1 in

[25 mm] premolded expansion joint through the wall and a construction joint with shear keys through the footing should be used. In addition, dowel bars should be placed across the footing joints parallel to the wall elements to guard against differential settlement or deflection of the footings.

The maximum spacing of construction joints in the retaining wall footing should be 118 ft [36 m]. The footing construction joints should not line up with the expansion joints in the wall.

10.4.12.4 Drainage

Gutters should be used behind walls in areas where there is a necessity to carry off surface water or to prevent scour. Low points in the vertical wall alignment or areas between return walls must be drained by scuppers passing through the walls.

The standard plans show typical drainage details. Special design of surface water drainage facilities may be necessary depending on the amount of surface water anticipated.

Where ground water is likely to occur in any quantity, special provisions must be made to intercept the flow to prevent buildup of hydrostatic pressures and unsightly continuous flow through weep holes.

All concrete retaining walls should have 4 in [100 mm] diameter weep holes located 8 in [200 mm] above final ground line and spaced about 13 ft [4 m] apart. In case the vertical distance between the top of the footing and final ground line in front of the wall is greater than 10 ft [3 m], additional weep holes should be provided 8 in [200 mm] above the top of the footing.

Weep holes can get clogged and the water pressure behind the wall may start to increase. In order to keep the water pressure from increasing, it is of utmost importance to have free draining gravel backfill and underdrains.

10.4.12.5 Other

Make provisions to relocate or otherwise accommodate utilities conflicting with the retaining wall. Any modifications of a standard wall to accommodate utilities should be specially designed.

Show all special wall details (e.g., sign bases, utility openings, drainage features, fences, concrete barriers, wall surface treatments) on the applicable sheet of the wall plans or on a separate plan sheet and include with the wall plans. Cross reference details between the various plan sheets on which they are shown.

10.5 APPROVALS

This section briefly discusses the steps taken by the division bridge staff to acquire client approval of proposed bridge structure type, size and location for a given project. Steps taken to obtain such approvals must be both timely and contain adequate detail to maintain assigned program schedules.

10.5.1 BRIDGE TYPE, SIZE AND LOCATION (TS&L)

The first step in acquiring partner's approval of a proposed structure is to develop one or more drawings that depict the bridge type, size and location for each site.

The highway design/location staff furnishes data required to develop a bridge site plan. A site plan includes the following:

- A plan view showing the horizontal alignment of the roadway and the ground contours of the surrounding area,
- The vertical alignment of the roadway within the limits of the bridge site, and
- The roadway typical section to be used at the site.
- Special details as required to show architectural features.

After determining approximate span lengths and superstructure depths, the bridge opening shall be checked for adequacy.

For stream crossings, a hydraulic analysis shall be made for the site.

For roadway crossings, vertical clearance above the underpass roadway shall be checked. Once the appropriate clearance checks have been made, the profile grade can be adjusted for final TS&L development.

Once developed, the TS&L drawing is then distributed to the partner agency for review and approval. Upon receipt of this approval, the structure design and contract plan development can begin.

10.5.2 DESIGN STANDARDS AND EXCEPTIONS

There are many publications available to the design engineer to aid in the development of engineering design calculations for highway structures. Deviations from specific minimum values therein are permissible only after due consideration is given to all project conditions (e.g., maximum service and safety benefits, type and purpose of improvement and compatibility with adjacent sections of unimproved roadway).

Exceptions to design standards are to be documented during the TS&L development stage. All responsible agencies should be made aware of each exception, agree to the need for the exception and be fully aware of any safety and environmental impacts resulting from the deviation. Also refer to Section 9.1.3 for documentation of exceptions to standards for structural capacity, width, horizontal clearance, and vertical clearance.

10.5.3 PLANS, SPECIFICATIONS AND ESTIMATE (PS&E)

Upon completion of the final plans, specifications and estimate (PS&E) for a structure, all documents are to be forwarded to the highway design staff for inclusion with the roadway portion of the project.

The plans and specifications should address and adequately describe the design features incorporated into the structure, the construction requirements necessary to facilitate the building of the structure and an estimate of construction costs of the project.

The estimate should reflect the anticipated cost of the project based on an analysis of previously bid items of work for structures of similar type and construction and geographic location.

Detailed plans for bridges should contain the following drawings and data:

- Site plan;
- Location and log of each foundation sounding or boring;
- Profile of the crossing;
- Typical cross section;
- Sectional drawings, as needed, to detail the structure completely;
- Quantities of materials required;
- Reinforcing bar list and bar bending diagram;
- Design loadings, working stresses, classes of concrete and grades of steel;
- Drainage area and applicable runoff of hydraulic properties;
- Design and construction details not otherwise covered in the *Specifications*; and
- References to applicable standard or industry specifications.

10.6 STANDARD FORMAT

A standard format is required in all plans and specifications. Standard formats have been established for drafting plan sheets, writing contract specifications and establishing contract unit-bid terms. Document storage and retrieval procedures for work developed on the Computer Aided Drafting and Design (CADD) System have been developed.

10.6.1 PLANS

Standard formats for plans are described in Bridge CADD Manual. A majority of this information is also stored on the CADD system for ready use and reproduction. Drafting standards are described in Bridge CADD Manual.

10.6.2 SPECIFICATIONS

There are three major types of specifications used in a contract and they are:

- *Standard Specifications*, *FP-XX*
- Supplemental Specifications, and
- Special Contract Requirements.

See the contract document hierarchy in Section 104.04 of the FP-XX.

Each Division office maintains a file of Special Contract Requirements (SCRs) that have been developed for addressing unique or specialty work that may be required due to a project's geographical location or special design features that would not be covered in the *Standard Specifications* or Supplemental Specifications. Refer to applicable Division Library of Specifications (LOS).

When it becomes necessary to develop Special Contract Requirements, they shall be written in the same format as the *Standard Specifications*.

10.6.3 ESTIMATE

An engineer's estimate is developed in the preliminary PS&E stage of plan development based on an average cost per square foot [square meter] of bridge deck. As the structural design proceeds toward the final PS&E stage, a revised cost estimate is developed based on a unit price analysis for all items of work to be accomplished under the project.

One source of data that can be used for estimating purposes is past contract unit-bid prices for similar type work within the same geographical area. Caution is urged when establishing unit prices from past records.

When estimating, the engineer must consider the current economic environment and be aware of regional cost trends and industry pricing data.

Estimates should be realistic and should be based on a reasonable cost analysis for the work to be accomplished. Unrealistic estimates (e.g., too high, too low) have a detrimental impact on future project planning and programming.