Alternatives in the Design and Construction of Cable-Stayed Bridges

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Cable-stayed bridges have gained popularity as a design solution for long-span applications in North America. With their advent and implementation, several significant contractual, technical, and personnel-related controversies have evolved that threaten to slow the implementation of this design concept. These problems are reflected in the conflicts and claims currently plaguing the industry. A variety of constructability concepts collected from a unique blend of owners, designers, suppliers, and contractors associated with recent cable-stayed bridge projects are described. The constructability concepts relate to tower design and construction, cantilever deck design and construction, composite deck design and construction, stay-cable configuration and construction, posttensioning component operations, reinforcing steel details, prefabrication operations, stressing operations, grouting operations, closure, and general work sequencing. The concepts provide a starting point for review of designs for efficient and economical construction.

Rapid growth in the application of cable-stayed structures has occurred in North America. Since the end of World War II, the cable-stayed bridge has proven to be the most advantageous and economical long-span bridge solution. These structures represent the highly advanced, long-span bridges using currently available state-of-the-art technology.

Problems have occurred that were not originally anticipated with the advent and implementation of any new technique or procedure. Contractual-, technical-, and personnel-related controversies have evolved. Projects have been completed above budget. Major delays have occurred, forcing late completion. A high number of major claims and litigation frequency exists. In some cases, designers and constructors have been terminated, forcing severe delays and cost overruns.

Recent examples of sophisticated bridge projects illustrate the conflicts plaguing the industry. After terminating the original constructors, the Rhode Island Department of Transportation and the Alabama Highway Department selected new constructors to complete their structures because of differences in the interpretation of the specifications, extended delays, and a conflict over costs (*1*). During the construction of the Sunshine Skyway Bridge in Tampa, Florida, differences of opinion existed about the responsibilities and procedures of the owner, designer, and constructor (*2*). Contract changes and delay damages are being negotiated on the basis of these differences. The West Virginia Department of Highways has received $8 million of claims to date on the construction of the Weirton-Stuebenville Bridge, a $24.1 million structure. In addition, the owner claims the constructor deviated from the accepted erection procedure, thus overstressing several segments (*3*). An increasingly frequent complaint is the constructability of these bridges. The constructor's interpretation of the designer's intent is guesswork (*4*).

The objective is to identify constructability concepts that need to be considered during planning, design, and construction to ensure project success. The theory of constructability will be reviewed along with special considerations in the cable-stayed bridge environment. The ultimate goal is to support reduction of problems on future bridge projects.

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DESIGN AND CONSTRUCTION OF CABLE-STAYED BRIDGES

The variety of cable-stayed bridges illustrates the ingenious attempts to provide owners with unique design solutions. Modern cable-stayed bridges have used both steel and concrete towers, including single- and double-plane vertical, A-shaped, and double-plane sloping towers. Deck schemes include cast-in-place concrete, precast concrete, orthotropic steel decks, composite decks, and prefabricated steel. Cable configurations include radiating, harp, and fan. Cable systems use high-tensile bars, parallel wires, or steel bars protected by polyethylene or steel pipe (*5,6*).

The design and construction of the superstructure begins with the central towers. Today, concrete is typically used in towers because it is the most economical system (*7*). In areas of strong wind forces, A-shaped towers provide an optimal solution because of their stability (*8*). Inclined or A-shaped towers require temporary ties to prevent collapse during construction (*9*). The towers serve as an anchor for the stay cables. Once the cables are installed and stressed, the towers must provide transverse and longitudinal resistance against the applied cable forces.

Many different deck configurations are used. A fundamental advantage of concrete over steel is that construction can begin as soon as the necessary falsework, formwork, and erection equipment is ready (*10*). Construction operations are not at the mercy of the steel fabricator's delivery schedule. Precast concrete operations can begin as soon as feasible during construction. Proper planning and experienced personnel in the design and development of the precasting facilities ensure better project performance (*11*); however, precast concrete requires a large investment of resources and personnel in the early stages of the project. Cast-in-place concrete construction eliminates potential erection problems caused by improper segment fit-up (M. Miller, personal communication); thus, erection errors resulting from creep and shrink effects are prevented. On the contrary, composite deck construction offers several advantages over precast and cast-in-place concrete. Construction is simplified because difficult tolerances and match-casting requirements do not exist (*12*). The dead load of a deck configuration using structural steel is less than a similar layout using concrete. Therefore, lower dead loads are induced on the structure's foundation, minimizing substructure requirements (*13*). Each deck configuration needs to be analyzed to attain the best possible design solution.

The main structural elements transferring loads from the deck to the tower are the stay cables. Overall, they can account for 30 percent of the bridge's total cost (*7*). Closely spaced cables allow shallow, slender bridge decks with reduced bending moments. Aerodynamic stability is also increased (*12*). Closer cable spacing permits free cantilevering without the use of temporary guys (*7*). Anchoring the stay cables in the tower is simplified when the configuration permits adequate space between anchors (*8*). Harp-shaped configurations result in standardized tower connection details; in fact, a \$400,000 savings is envisaged on the Chesapeake and Delaware Canal Bridge because a harp-shaped configuration will reduce detailing and installation costs (*9*).

Constructability is defined as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (*14*). An owner can realize potentially large savings as designs are more construction oriented. For example, construction input was used in all phases during the development of a bleached market pulp mill with a savings of approximately 6 percent of construction costs—a 10-to-1 payback of the constructability program's costs. On another project, a 720,000-kW generating station, the plant went into commercial operation 4 months early and \$200 million under budget. This saving resulted from experienced construction personnel involvement in the project's development from conceptual stages to completion (*15*).

Additional benefits might be accrued if experienced construction contractors are included in the design process to analyze the construction methods implied in the designs. These constructability reviews should begin as early as the conceptual design stage. Construction personnel can provide innovative ideas about materials, equipment, and methods that will simplify design objectives. Projects designed with this input attract more bidders with lower bid prices because of minimal risk. In some cases, legal entanglements can be avoided because specifications are better defined, designs are more practical, and design errors are corrected early (*16*).

Project planning is the most important function in the life cycle of the project. Construction expertise is required to complement the planning and design functions. Seven major items benefitting project development when construction personnel are involved include (*17*) The following: estimating, scheduling, procurement, constructability, labor, contracting, and organization. Using construction expertise for these activities can improve overall project cost effectiveness.

For constructability to be successful, all members of the design or construction organization must practice this philosophy. Implementation of a constructability program is an intricate task. The most successful constructability programs provide the following (*18*):

1. Clear communication of senior management's commitment and support of constructability.
2. Single-point executive sponsorship of the program.
3. A permanent corporate program and a tailored implementing program within each project.
4. User friendly procedures and methodologies.
5. A corporate data base of lessons learned.
6. Training where necessary.
7. Easy appraisal and feedback.

CABLE-STAYED BRIDGE DEVELOPMENT

The development of a cable-stayed bridge presents its own set of special challenges during conception, design, and construction. These challenges include bridge design requirements, the alternative design process, and balanced cantilever construction.

Bridge Design Requirements

During the design of a cable-stayed bridge structure, the concept selected must meet the owner's established requirements of aesthetics, operability, economics, maintainability, and functionability. Bridge design requires experienced personnel knowledgeable in state-of-the-art techniques and methodologies. Important considerations for a cable-stayed bridge design include (*19,20*):

- A safe and technically sound concept,
- A safe and economical erection method,
- Low maintenance with a long service life,
- An aesthetically pleasing form,
- A low impact on the environment, and
- A design that permits a faster construction time compared to an alternative comprising the same material and manpower input.

Owners want their designers to provide a design scheme that minimizes material costs and exercises adaptable erection requirements. Owners desire flexibility in the final design to allow adequate competition between constructors (*21*). This flexibility will permit constructors to build the structure using methods most acceptable for them. If a project is designed that can use innovative ideas and acceptable standards of construction, the design is more buildable (*16*).

At this time, the United States has fewer than 10 engineering consultants with the capabilities required to design cable-stayed structures (*9*). When cable-stayed technology was first introduced in the United States, design consultants had to rely on European experience. Today, U.S. engineers have learned how to design cable-stayed structures independently (G. Peters, personal communication).

Alternative Design Process

In the United States, an alternate design is required for all bridge projects with an estimated cost over \$10 million (*9*). The goals behind this process are to stimulate engineering creativity and for the owner to obtain financial savings through competitive bidding. Alternate designs may be of different structural types or alternate materials. The theory behind alternate designs permits constructors to bid on the design most suitable for their construction methods and thus save the owner money.

The alternate design concept is not without its faults. First, it virtually doubles the cost of the structure design because two designs are prepared, which doubles the design cost. Second, although the alternative design process theoretically fosters innovation, it creates liability concerns presented by the openness in the contract documents, which permit constructors more flexibility (*22*). Recent trends are for designers to provide schematic erection methods only, with constructors providing structural construction details based on their proposed methods. Liability conflicts result from the changed responsibilities between designers and constructors. Third, the alternative design process can nurture the wrong type of competition. Alternates should focus on the designer's creativity versus material competition (*23*). Instead of promoting a competition regardless of material type, one alternative is typically designed by using concrete while the competing alternative uses steel or a composite scheme. Another fault in this process is that the constructor's alternative is prepared solely to reduce construction costs. It may not meet all of the owners objectives (*21*). For instance, a constructor may sacrifice aesthetics so that concrete forming operations may be simplified. Finally, an alternate design prepared at the constructor's option may not always meet the designer's intent. A constructor-proposed alternative may not satisfy code requirements as conservatively as the designer's alternative. As a result, a conflict arises between the designer and constructor early in the construction process (H. B. McCoy, personal communication).

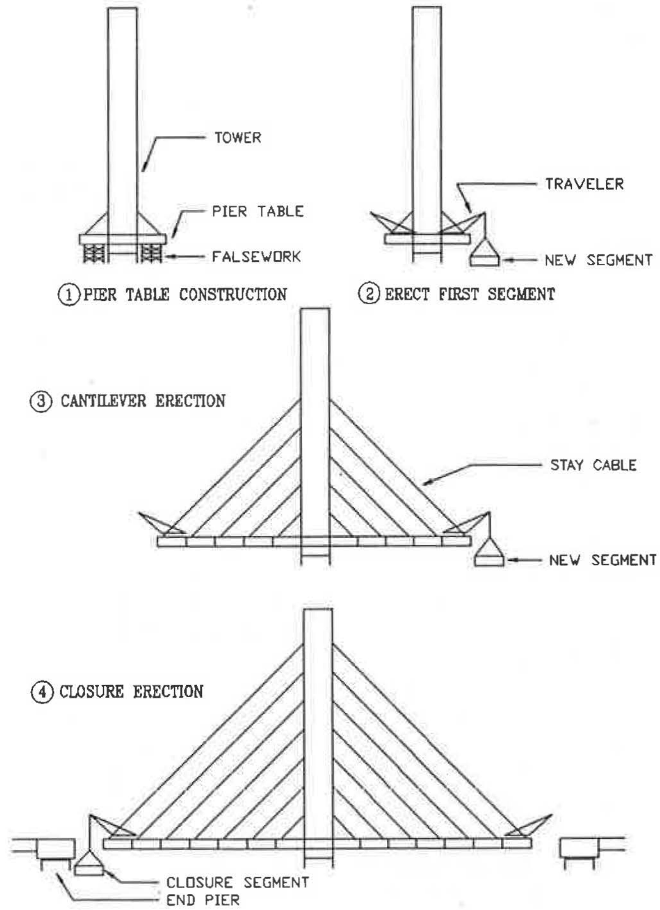

FIGURE 1 Balanced cantilever construction.

Balanced Cantilever Construction

The construction of cable-stayed bridges is made possible with the use of balanced cantilever construction. It is the most common method used in their erection. It permits overhead construction while maintaining traffic below. Expensive, ground-supported falsework is eliminated because the cantilevers are supported from previously completed segments. Construction can proceed over deep valleys, navigable channels, and congested urban areas with little damage done to areas adjacent to the construction site (*22*).

Balanced cantilever construction begins at a permanent center pier or pylon. To begin, the tower deck segments or pier table is constructed on ground-supported or pier-supported falsework. Once complete, a steel truss assembly, called an erection traveler or form traveler, is erected on the completed pier table. Next, a segment is erected on each side of the pier table. In precast or composite deck superstructures, the precast or individual structural members are erected and anchored into place. In cast-in-place construction, the segment is formed and poured in place. Once a segment is placed on each side of the center tower, the travelers are moved outward one segment to erect the next segments. Construction progresses in this way until meeting with the approach spans. Figure 1 shows the balanced cantilever process. As each span cantilevers away from the central tower, the superstructure remains balanced because an equal and opposite force exists on each span.

A critical element in balanced cantilever construction is the preparation and use of the erection sequence. The erection sequence is a step-by-step analysis of the stresses and stress reduction or balancing imposed on the structure. All forces and loads applied to the superstructure are checked against maximum permissible stresses. The final version becomes the constructor's guide to building the superstructure of the bridge. The erection sequence provides a detailed analysis accounting for alignment, applied forces, stay-cable forces, temperature and creep influences, sun contact, construction loads (cranes, forms, travelers, etc.), and erection stages (*8*). The computations are updated at each stage of construction to reflect the changes in the structure's behavior. As the cantilever progresses outward in two directions from the main tower, the entire structural system must be reanalyzed as to how the superstructure will react with the additional applied loads (*22*). Camber curves are generated from these calculations. Permissible plus and minus deviations from the theoretical camber curves are also determined in the erection sequence.

Once the deck superstructure construction begins, an erection sequence analysis helps predict for the constructor the detailed deflection and camber data for each stage. Numerous measurements are taken and compared to the theoretical camber and deflection data in the erection sequence. If measurements are within specified tolerances, the derrick is moved forward to the next segment. If the measurements exceed specified allowable tolerances, stay cable shim calculations, adjustments, and secondary measurements must be repeated until specified tolerances are attained. The erection activities are similar for segments without a cable minus the operations relating to the stay cable. Without the stage-by-stage erection sequence, the constructor would not have adequate information to safely build the deck superstructure.

During the erection of the bridge deck superstructure, the constructor should not deviate from the owner-accepted procedure (*24*). The constructor should show that the requested changes are within the tolerances allowed in the specified erection sequence if a modification is desired. When changes are outside the owner-accepted limit envelope, the constructor prepares an alternate erection sequence. This new sequence must prove to the owner that requested changes meet the intent of the previously accepted guidelines.

Constructability Concepts

Constructability concepts collected from experts in the industry should be considered during project development. With proper analysis and application, greater effectiveness might be possible in the building process. It is hoped that these concepts will provide a review list during the design and construction process and lead to improvements in future cable-stayed bridge projects.

Tower

- Towers constructed from concrete are normally the most economical system (*7*).
- Towers should be constructed from concrete because they are more economical than steel (*8*).
- Towers will normally be made from concrete because the cost of concrete compression members is approximately ⅔ of that of towers made of steel (*25*).
- Basic conditions the tower must satisfy include the following (*7*):
  —Longitudinal stiffness in regions of cable anchorages;
  —Lower tower strength to resist forces acting on it (such as cables, wind, braking forces); and
  —Use concrete strength in cross sections for maximum advantage.
- In the longitudinal direction, the tower should be slender and have a small bending stiffness to avoid large bending moments and reactions by the foundations (*8*).
- Tower bracing above the road deck should be slender and appear light between the thin cables (*8*).
- Temporary tower restraint during construction is difficult and time consuming. On the East Huntington Bridge, temporary forestays and backstays were needed to stabilize the tower during cantilever. It required cables anchored from the tower head to concrete anchorage blocks on the ground. Stressing the cables was difficult because tower head access was limited (*9*).
- Inclined tower construction requires temporary ties to prevent collapse. The towers may need to be cast with an outward chamber for dead load deflection caused by the inclination (*26*).
- Towers providing live- or dead-end cable anchorages should be readily accessible for cable installation, stressing, and grouting. This includes providing sufficient space for personnel and equipment necessary to complete these activities. If tower prestressing exists, the same access criteria is required (*26*).
- Loads induced on the tower by temporary crane tie-ins need to be checked so allowable stresses are not exceeded (*26*).

Cantilevered Deck

- Avoid pierhead segments considerably heavier than the next segments as they require additional and expensive lifting equipment (*19*).
- Pierhead segments need to be the minimum length required for the installation of one traveler (*19*).
- The pier table and cantilever need to support reactions from form travelers, erection gantries, and self-weight (*19*).
- Bottom-of-deck cable blister forming is difficult and expensive. Moreover, access needs to be provided for forming, cable stressing, and later cable adjustments (*19*).
- Details and computations of the cast-in-place concrete-forming system should be submitted to the engineer. This includes maximum loadings and stresses created because of equipment and concrete; deflections during placement, temporary supports, and tie-downs to stabilize cantilevers; and a detailed step-by-step procedure for placement, stressing, and form advancement (*24*).
- Because of applied cable forces, the longitudinal thrust in the deck increases toward the centerline of the towers. Therefore, additional prestressing is not required to resist deck tensile forces. At span ends, the cable thrust is lower and bending moments are higher, requiring deck prestress to resist applied loads (*8*).
- Deck prestress is not normally required except at the center of the main span unless it is needed for cantilevering (*9*).
- When deck prestress is needed, continuous longitudinal strands should be used from anchor to anchor versus prestress bars coupled at each segment joint (*26*).
- Camber will be monitored at each stage of construction. The constructor should submit a survey plan depicting proper erection to the final grades and cambers shown on the plans (*24*).
- Recommended erection tolerance from the predicted alignment is ± 1 in. (*24*).
- The constructor should prepare a table of elevations and alignments at each stage of construction including the following points (*24*):
  —A benchmark point from which all other measurements will be taken.
  —All four corners and center line at segment faces of top slab of pier segments to establish grade and crown.
  —Two points on longitudinal center line of each pier segment, one on each edge, to establish alignment.
  —One point on the longitudinal center line and at least one corner of each segment along every joint between cast-

in-place segments to establish elevations and alignment at every stage of erection.

—During construction, it is recommended that the engineer establish a separate, independent measuring system from the one used by the constructor.

This system of checks and balances ensures proper geometry control (*27*).

Composite Deck

- On composite structures, the concrete deck carries the compressive forces of the stay cables. The steel sections should be small to avoid creep problems (*8*).
- The overriding concern is to keep the tensile stresses in the concrete roadway slab as small as possible (*25*).
- Economy is attained through ease of construction. Long production runs of repetitive modular elements ensure erection speed and less risk for the constructor (*12*).
- Integral composite action is achieved by placing concrete strips around lapping rebar and shear connectors (*12*).
- Careful detailing is required between the composite deck and structural steel interface. Proper overlap of protruding rebar from the deck between shear studs on the steel flange is necessary for ease of construction (*12*).
- In order to minimize the effects from creep and shrinkage between the precast panels and steel deck, they should be stored for at least 60 days before erection (*28*).

Stay-Cable Configuration

- The configuration of cables and their connections to the deck and tower are significant factors in the overall costs of cable-stayed bridges (*12*).
- It is better to anchor cables at both the tower and girder ends vis-à-vis running a continuous cable from the girder through the tower to the opposite girder (*8*).
- Continuous cables over saddles are not preferred by the FHWA because they lack accessibility for inspection, they are difficult to replace, and two stays are involved in the event of an accident instead of one (*9*).
- Closely spaced cables eliminate temporary-support cables and allow free cantilevering during construction. Furthermore, they create smaller bending moments and thus smaller girder beams (*8*).
- Standardized cable configurations and geometry at the tower simplify installation and construction operations (J. Sutter, personal communication).
- A harp-shaped cable configuration results in a standardized connection detail. All cables enter the tower at the same angle (*9*).
- Harp-shaped cable configurations permit the construction of the deck before completion of the tower (*9*).
- Harp-shaped configurations require more cable steel, induce more compression forces in the deck, and produce bending moments in a longer tower section (*8*).
- In fan-shaped configurations, all cables are anchored at the top of the tower, resulting in a large force concentration at one spot. Furthermore, it is difficult to anchor all the cables in one small area (*8*).
- The semi-fan configuration moves the tower cable anchorages over a relative length of the tower head (*8*).
- Cable anchorages at the tower and deck should be recessed rather than external to simplify formwork details (*26*).

Stay Cables

- Cable-stayed bridges should be designed such that the loss of an individual cable would not result in significant structural damage to the bridge (*29*).
- Cable designs should allow replacement of any stay (*29*).
- Acceptance testing of stay cables requires sophisticated test equipment, technical expertise, and a long lead time to perform the tests. Tests are typically performed in Europe and can be expensive (*26*).
- Fatigue testing is usually required on three representative samples of the complete system. Failure of one component is cause for rejection of the complete system (*9*).
- Testing should be performed at the earliest possible time during construction to enable modifications and corrections of unforeseen complications.
- All cable items requiring testing should be clearly stated in the contract specifications.
- To simplify construction, the permanent design should use the permanent stay cable during cantilever erection. The use of temporary support cables should be avoided (J. Sutter, personal communication).
- Wrapping black polyethylene (PE) tubing with white Tedlar tape is now required by FHWA. It reduces the maximum temperature of the stay from 65°C to 38°C (*9*).
- The only problems occurring to date involving the use of PE tubes resulted from excessive pressure during cable grouting and mishandling of the stays (*9*).
- Bar stays are not accepted by the FHWA because (*9*)

  —Couplers act as stress raisers that reduce the fatigue resistance.

  —The bars have a lower ultimate tensile strength.

  —Assembly errors are possible with incomplete attachment of the bars to the couplers.

Posttensioning Components

- All posttensioning materials will be tested by the engineer (*24*).
- Contract specifications should clearly define storage requirements and corrosion protection of all posttensioning components.
- The constructor should provide a warehouse attendant during construction to ensure proper management of posttensioning materials.
- Posttensioning duct alignments should be fully dimensioned through each segment. This process is done by quoting offsets vertically and laterally from known control lines or surfaces at regular intervals of no more than 2 to 3 ft where small radii and reverse curves occur (*11*).
- In anchorage zones, allow for the largest commercially available anchorage likely to be used with the tendons con-

cerned. Then, if the constructor elects to use a smaller anchorage, it can easily be accommodated with only a minor change to the very localized detail (*11*).

- Specify a sequence for posttensioning of all tendons and bars (*11*).
- During concreting, a stiffening mandrel should be provided inside the empty duct to maintain geometry and protection of the empty duct.
- Prestressing tendons should be designed for maximum permissible eccentricities (*19*).
- Prestressing tendons should be taken full length through the structure where they can be easily stopped. Furthermore, they should not be prematurely stopped and started where the additional anchorage and stressing costs outweigh the length of tendons saved (*19*).

Reinforcing Steel

- Moreton (*11*) has made the following suggestions regarding the integration of rebar with other bridge components:
  —Ensure that all reinforcing bar cages can be assembled easily from simple bar shapes, avoiding as much as possible closed loops and multiple bends.
  —Ensure that reinforcing bar bending diagrams are shown in full in the plans adjacent to the component to which they apply or on the next sheets.
  —Ensure that reinforcing bar lengths and bends are according to normally accepted industry practice, amply allowing for bending tolerances.
  —Ensure that reinforcing bars will fit inside the concrete dimensions, recognizing that there are construction tolerances (in the specifications) on concrete thickness and covers. Do not forget that a ribbed reinforcing bar is physically larger than its nominal diameter.
  —Ensure that all reinforcing bars are bent to avoid posttensioning ducts.
  —Clearly state on the plans that if a conflict exists between the posttensioning duct and the rebar, the duct alignment takes precedence over the location of the rebar. The rebar will be relocated at the direction of the engineer.

Prefabrication

- All segments or major structural elements should be clearly marked after casting (*24*).
- A usual rejection rate for precast segments should not exceed 0.5 percent (*11*).
- Gee (*19*) has made the following comments regarding prefabrication:
  —To justify precast operations, sufficient repetition and quantity must exist for the investment of special forms and equipment.
  —If prefabricating of elements is used, cast-in-place concrete must be minimized.
  —Prefabrication or precasting can proceed while foundation or substructure work is progressing. However, the costs incurred for fabrication, transportation, and erection of large, heavy units must be cheaper than the subsequent time savings.
  —In water applications, suitable dock facilities must exist for transportation of segments.
  —Precast elements and operations must consider road transportation load requirements.
  —Delivery of precast elements should be to the most economical and accessible location.
  —Benefits from precasting cannot be suppressed while workers wait for cast-in-place concrete activities.
- Moreton (*11*) suggests the following recommendations for improvement:
  —Organize the plans for the convenience of the contractor who has to fabricate and erect the components.
  —Exhibit details in full, either on or next to the sheet showing the component, and to a large scale.
  —Exhibit the assumed ages of segments at the time of erection and all material properties assumed in the design.

Stressing

- Stressing of stays is easier when performed from the tower head (*9*).
- All strands of tendons of more than four 0.5-in.-diameter or 0.6-in.-diameter strands should be stressed simultaneously with a multistrand jack (*24*).
- Monostrand jacks are not normally permitted to stress cables because the subsequent force transfer to adjacent strands is unknown.
- Within 30 days of stressing operations, all jacks should be calibrated with a specific gauge and load calibration curves. Recalibration should be at six-month intervals. Jacks and gauges should not be interchangeable (*24*).
- Jacks should provide a means of visually examining and measuring elongation movement during stressing (*24*).
- The constructor should provide records of all stressing operations including gauge pressures and tendon elongations at each stage for review and approval. Tails should not be cut off until stressing records have been approved (*24*).
- Stay-cable force adjustments are a time-consuming task that should be minimized in any way possible (*30*).
- Final cable stressing and adjustments on the Dame Point Bridge required from 4 to 5 weeks (*9*).
- Cable adjustments are performed in the early morning such that temperature differential influences are minimized.

Grouting

- The design and subsequent testing of the grout mix may require a substantial amount of time. Allow adequate time for design, testing, and approval.
- Grouting operations are more economical if several tendons or cables are grouted simultaneously rather than a few at a time.
- It is recommended that grouting be delayed until the entire span is stressed (*24*).
- Cable grouting should be done in lifts to avoid excessive hydrostatic pressure, which can cause cracking of PE pipe (*30*).
- Within 15 days after ducts are grouted, all blockouts for anchorages should be grouted or filled with nonshrink grout, a special mortar, or another protection system (*24*).

- Cable grouting should be done in the early morning so that the grout temperature differential is minimized (*9*).

Closures

- Before construction of closures, cantilevers should be locked to prevent movement or rotation of one cantilever in relation to the other cantilever or end-pier girder (*24*).
- Before closures, stay-cable adjustments may be required to locate cantilevers in the correct position.
- Casting the end-pier girder away from the cantilever several months before connection minimizes creep and shrinkage effects (*30*).

Additional Concepts

- For steel members, a practical welding procedure or sequence of procedures should exist that enables all welds to be completed and inspected without delays (*20*).
- Design structural steel connections such that one member uses a standard-sized hole whereas the other member uses a slotted hole.
- Sufficient access should be provided for all structural steel erection and connections (*19*).
- Alternate concrete mix designs with higher strengths may permit faster turnaround for forming and stripping operations (*31*).
- Delivery times for specialized posttensioning material and equipment should be accounted for in the project schedule.
- Blockout design requirements for posttensioning and stay-cable systems include formwork, cable installation and equipment, rebar installation, stressing, grouting, pourbacks, scaffolding, and inserts for temporary work platforms (*26*).

CONCLUSIONS

The design and construction of a cable-stayed bridge have the potential for technical challenge and economical success in the 1990s. Building a cable-stayed structure represents state-of-the-art bridge technology with theoretical potential for magnificent spans. However, the North American cable-stayed bridge market has experienced continuous problems during its development. Constructability concepts have been collected and presented to focus attention on the problem areas. Constructors with losses from past projects will either increase their future bids or decide not to bid on future projects. Should this happen, more expensive alternatives, such as steel truss bridges or suspension bridges, may be built. These concepts should be examined to determine if they are appropriate on the basis of local economics and project requirements.

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