Constructability of Cable-Stayed Bridges

By James E. Rowings,[1] Member, ASCE, and Steven L. Kaspar[2]

Abstract: The application of cable-stayed structures has increased during the last few years in North America. The implementation of these new structures has led to serious problems in the design and construction process. This paper provides an analysis of the most significant problems identified by owners, designers, and contractors. The owner-related problems include difficulties in four areas: the contract system, the bidding process, field representation, and project document reviews. Designer-related problems include incomplete design, lack of access to specification development, overly congested areas, and restrictive tolerances. Constructor-related problems include engineering requirements, inexperienced personnel, project planning, and shop-drawing specification. The paper proposes several modifications to mitigate the problems encountered. The paper includes suggested changes under the current contract environment, a modified current contract environment, and a completely new contracting approach for bridge construction. Each of the suggested changes are explained and analyzed for their potential benefits to the project outcome.

Introduction

The cable-stayed bridge has proven to be the most advantageous, economical long-span (700–2,000-ft) bridge solution throughout Western Europe since the end of World War II. A primary reason for the increased design application is that they require less material than other bridges, which should result in lower erection costs. Loads are carried efficiently because all members carry axial forces only (Robison 1986). The recent development of high-strength (with tensile capacities as great as 270 ksi) steel material has permitted cable systems to carry high axial forces without excessive elongations. Recent advances in computer technology now permit the enormous number of structural calculations required to be done quickly and cheaply. This technology has appeared in the United States in the last decade. Table 1 presents pertinent data on recent cable-stayed bridge structures in North America.

Problems will occur that were not originally anticipated with the advent and implementation of any new technique or procedure. In the United States, contractual and technical problems are more frequent and threaten to stagnate the growth of the cable-stayed bridge industry. Projects are completed over budget. Major difficulties occur, forcing significant completion delays. These projects have experienced major claims and litigation. In some cases, designers or constructors, or both, have been terminated. Solutions to these problems must be sought in order to realize the technical and economic advantages offered by cable-stayed bridge design.

Recent examples of sophisticated bridge projects illustrate the conflicts plaguing the industry. Because of differences in the interpretation of the specifications, extended delays, and a conflict over costs (Lass et al. 1989),

[1]Assoc. Prof., Civ. and Constr. Engrg. Dept., Iowa State Univ., Ames, IA 50011.
[2]Engr., Massman Constr. Co., Kansas City, MO 64114.

Note. Discussion open until November 1, 1991. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on March 10, 1990. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 117, No. 2, June, 1991. ©ASCE, ISSN 0733-9364/91/0002-0259/\$1.00 + \$.15 per page. Paper No. 25880.

J. Constr. Eng. Manage., 1991, 117(2): 259-278

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

TABLE 1. Recent Cable-Stayed Bridge Projects in North America

Bridge (1)	Owner (2)	Designer (3)	Contractor (4)	Construction engineering consultants (5)	Bridge type (6)	Contract price bid date (7)	Construction type (8)	Spans (ft) (9)	Vertical clearance (ft) (10)
Luling-Destrenan Bridge	Louisiana Department of Transportation	Franklin & Lienhard Modjeski/Masters (joint venture)	Williams Brothers Melbourne Brothers (joint venture)	HNTB	Orthotropic deck (steel tower)	$41,800,000 November 1977	A	508-1,222-508	133
East Huntington Bridge	West Virginia Department of Highways	Arvid Grant	Melbourne Brothers York Russell (joint venture)	Contech Consultants	Precast deck segments	$23,510,000 April 1981	B	608-900	84
Sunshine Skyway Bridge	Florida Department of Transportation	Figg & Muller	Paschen Construction (main span)	LoBuono Armstrong	Precast box girder	$71,100,000 1982	C	540-1,200-540	175
Weirton-Stuebenville Bridge	West Virginia Department of Highways	Michael Baker	S. J. Groves	T. Y. Lin	Composite deck	$19,990,000 September 1983	.C	820-688	69
Annacis Bridge	British Columbia Ministry of Transportation and Highways	Buckland & Taylor	PCL-Paschen-Pike (joint venture)	DRC	Composite deck	$32,900,000 January 1984	C	600-1,526-600	185
Quincy Bayview Bridge	Illinois Department of Transportation	Modjeski & Masters	McCarthy Brothers	DRC	Composite deck	$17,230,461 February 1984	E	440-900-440	63
Neches River Bridge	Texas Department of Highways	Figg & Muller	Williams Brothers	Cutler & Gallaway	Precast box girder	$22,789,000 February 1984	D	280-640-280	143
Dame Point Bridge	Jacksonville Transportation Authority	HNTB	Pensacola-Tyger (joint venture)	DRC	Cast-in-place concrete	$46,602,582 November 1984	C	650-1,300-650	175
James River Bridge	Virginia Department of Transportation	Figg & Muller	S. J. Groves Kiewit Eastern (joint venture)	T. Y. Lin	Precast box girder	$34,400,000 February 1985	D	300-630-300	145
Skytrain Bridge	British Columbia Transit	Bush, Bolman & Reid, Crowther (joint venture)	Kerkhoff Bridge Hyundai Engineering (joint venture)	DRC	Precast deck segments	$28,000,000 July 1986	C	453-1,115-453	148
Baytown Bridge	Texas Department of Highways	Greiner Engineering	Williams Brothers Traylor Brothers (joint venture)	DRC	Composite deck	$91,254,000 December 1986	D	482-1,250-482	176
Talmadge Memorial Bridge	Georgia Department of Transportation	DRC Consultants	Monterey Groves (joint venture)	Buckland & Taylor	Cast-in-place concrete	$25,700,000 July 1987	C	470-1,100-470	185

Note: Contract types: A = superstructure only; B = main span above pier foundations; C = main span substructure and superstructure; D = main span substructure/superstructure and approach spans; and E = main span above pier foundations and partial approach spans.

the Rhode Island Department of Transportation and the Alabama Highway Department terminated the original constructors and selected new ones to complete their structures. When the Iowa Department of Transportation tendered bids for the construction of the Burlington cable-stayed crossing over the Mississippi River, in October 1988, bids were more than 50% higher than the engineer's estimate. Consequently, all bids were rejected and an extensive redesign was undertaken. 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 (Soast 1986). The West Virginia Department of Highways has received $8,000,000 of claims to date on the construction of the Weirton-Stuebenville Bridge, a $24,100,000 structure. The owner claimed the constructor deviated from the accepted erection procedure, thus overstressing several segments ("State Fumes" 1989). Constructors are being forced to accept the risk involved in construction methods without the designer's guidance. The constructor's interpretation of the designer's intent is guesswork (Gee 1989). Those constructors that continue to participate will add large contingencies to cover the risk factor (McCarthy et al. 1989).

The objectives of this paper are to identify the major problems currently impairing the cable-stayed bridge industry and provide recommendations to mitigate many of these problems.

Unique Features of Cable-Stayed Bridges

The construction of cable-stayed bridges is made possible with the use of balanced cantilever construction, which permits overhead construction while maintaining traffic below. Expensive, ground-supported falsework is eliminated. Construction can proceed over deep valleys, navigable channels, and congested urban areas with little damage to areas adjacent to the construction site (Murillo 1989).

A critical element in balanced cantilever construction is the preparation and use of the erection sequence: a step-by-step analysis of the stresses and stress reduction or balancing imposed on the structure. 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 (Leonhardt 1987). The computations are updated at each stage of construction to reflect the changes in the structure's behavior.

In the United States, constructors typically do not have the engineering talent required to prepare the erection sequence. The constructor often hire a specialized construction consultant, called the construction engineer. It is the construction engineer's responsibility to calculate and prepare the erection sequence, camber curves, and deflection envelopes, according to the constructor's anticipated construction methods (Tang 1987). This reduces the constructor's concerns to those problems that he is experienced and qualified to perform—management of the labor, materials, and equipment needed to construct the cable-stayed bridge (Gee 1989).

Constructability of Cable-Stayed Bridges

Constructors have been slow to publicize the issues facing the cable-stayed or segmental bridge environment. Based on questionnaire responses from 12 highly respected constructors, deficiencies resulting from "incomplete, er-

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

roneous, or non-existent details" were ranked first or second (McCarthy et al. 1989). Other problems identified in this study included restrictive erection tolerances, incomplete field inspection, shop-drawing approval, and poor owner cooperation to resolve differences.

The Federal Highway Administration (FHWA) has studied the problems that constructors and designers say occur in the design and construction process (Nickerson 1989), and has concluded: (1) Better selection procedures should be used when choosing a designer; (2) only responsible constructors should be permitted to bid on cable-stayed structures; (3) erection schemes should be more complete with adequate detailing performed during design; (4) specifications need to be examined carefully to ensure all provisions apply and are complete; and (5) shop-drawing submission and a systematic review procedure should be explicitly stated in the specifications.

The American Segmental Bridge Institute (ASBI) has been established with its main goal "to provide a forum where designers, constructors, material interests, and owners can meet to advance the state of the art of engineering, construction, construction management, and materials involved in concrete segmental and cable-stayed bridges" (Freyermuth 1989).

Problems Afflicting Design and Construction of Cable-Stayed Bridges

Problems exist throughout the cable-stayed bridge industry. The problems revolve around the performance of the owner, designer, and constructor.

Owner Performance

Owner-related problems can be classified into four areas: the contract system, the bidding process, field representation, and project document reviews.

Contract System

In the United States, most major public works projects are developed under the design-bid-build contract system. In this contract process, the functions for design are totally separated from the functions for construction (Murillo 1989). The engineers concentrate their efforts on the design of a quality structure under final loading conditions. Their efforts are not spent on problems that will be encountered during construction. The primary objective of constructors is to build the project within schedule and budget, based on contracts with the owner and a completed design. Constructors assume that all engineering considerations are accounted for during design.

Under the realm of the cable-stayed bridge, the design-bid-build contract system is even more complicated. Fig. 1 shows a representative contractual environment that typically exists. At least 10 parties are involved in the design and construction process, creating an awkward administrative system. Because of the numerous parties required to communicate and analyze difficulties, delays result since decisions are not made in a timely manner. The (FHWA) requires an active role in the project because they often fund 80% of the project's cost (Hughes and Wheeler 1989). All decisions made during design must be justified to the owner and FHWA before design work can continue. During the construction phase, a construction engineer is required to prepare the erection sequence and other specialized engineering needs.

J. Constr. Eng. Manage., 1991, 117(2): 259-278

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

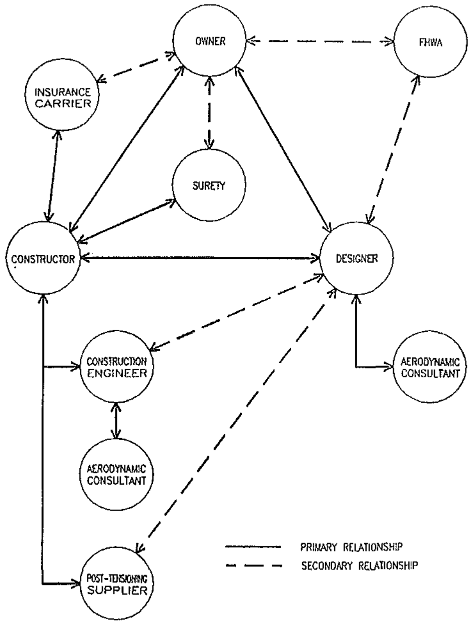

FIG. 1. Contract Environment for Cable-Stayed Bridge

Furthermore, a stay-cable and post-tensioning supplier is selected to prepare shop drawings, defining the integration of these systems into the permanent structure. All decisions made during construction must be justified to the designer, owner, and FHWA before construction can continue. This process inhibits timely decision making.

Owners are not utilizing constructors with valuable construction knowledge that would make the design and construction of the bridge more successful (H. B. McCoy and K. Jacobson, of Massman Construction, unpublished interview by the writers, April 1989). Owners advocate the position that their designer-prepared contract documents are complete. Theoretically, this tactic will prevent owners from incurring additional costs resulting from design errors or oversights. The constructor is forced into building the project without adequate information (McCarthy et al. 1989). In fact, both the owner and designer attempt to indemnify themselves from any actions made by the constructor.

Owners are not working as a construction manager to make project events happen (G. Peters, of Williams Brothers Construction, unpublished interview by the writers, July 1989). Owners are not defining the players' roles and responsibilities. Specifications are not communicating the specific requirements of each individual participant (owner, designer, constructor, FHWA, construction engineer, and inspector). Owners need to determine the separation of responsibilities, the requirements of each group, and when their specific work is performed (C. Reseigh, of Parsons Brinckerhoff Construction Services, unpublished interview by the writers, July 1989; G. Peters, unpublished interview, July 1989). These decisions need to be clearly

J. Constr. Eng. Manage., 1991, 117(2): 259-278

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

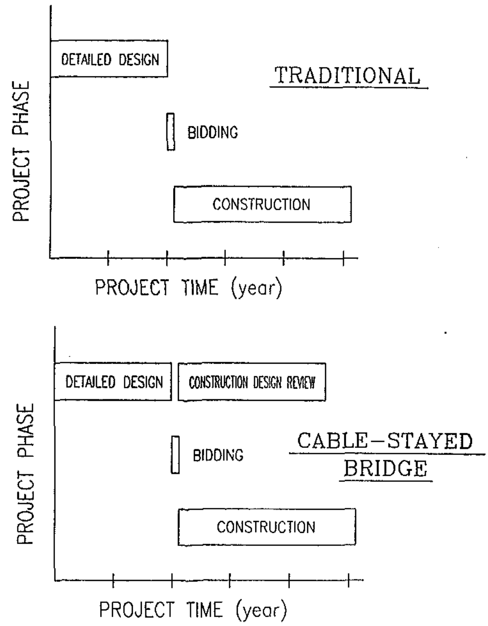

FIG. 2. Project Phase versus Project Time

and concisely stated in the contract specifications (C. Reseigh, unpublished interview, July 1989). Furthermore, the contractual obligations and the limits of professional liability attached to each responsibility are not clearly established (Moreton 1989).

A direct result of the design-bid-build contract process is the creation of adversarial roles between contract participants. Each party will spend effort proving the validity of its position during conflicts. Meanwhile, the job is delayed while compromises are reached. This type of contract system does not foster a teamwork atmosphere. It has been reported in some instances that professional jealousy occurred between the construction engineer and the designer. "The cooperative team approach is very poor" (McCarthy 1989).

Bidding Process

The design-bid-build process is separated into three distinct stages. The design stage typically requires one-and-a-half to two years. This includes concept development, preliminary design, final design, and documentation (Hughes and Wheeler 1989). The bidding stage encompasses one to three months. The construction phase requires from one to five years depending on the magnitude of the project. Fig. 2 illustrates the time required for the entire process, allowing two years for design, six weeks for bidding, and three years for construction.

One of the problems transpiring is the shortness of the bidding period. The designer is permitted adequate time to plan and work through the design and construction concepts. The designer is allowed adequate time to remedy design conflicts that arise. However, when the constructor receives the con-

J. Constr. Eng. Manage., 1991, 117(2): 259-278

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

tract documents for bidding purposes, he knows absolutely nothing about the project. It is necessary for a constructor to prepare a conceptual erection sequence, based on the contractor's preferred construction methodologies, before a detailed bid proposal can be developed. This work requires extensive additional engineering analysis and design above and beyond the scope of typical estimating requirements (H. B. McCoy and K. Jacobson, unpublished interview, April 1989).

Another problem during the bidding process is the lack of direct communication between the designer and constructor. When design errors, mistakes, construction methods, or details need clarification, the constructor directs his questions to the owner. The owner then addresses these items to the designer. After problems are corrected (this decision process involves multiple parties), the designer sends the corrected information to the owner in an addendum. Finally, the constructor will receive a reply to his remarks. This indirect method of processing questions during bid preparation creates problems and time delays. Without a direct dialogue with the designer, constructors are not receiving timely information for incorporation into a complete bid package.

Field Representation

One of the most widespread problems is the lack of experienced, qualified owner representation during construction at the job site (McCarthy et al. 1989; H. B. McCoy and K. Jacobson, unpublished interview, April 1989; W. Scharf, of Monterey-Groves, unpublished interview by the writers, March 1989; G. Peters, unpublished interview, July 1989). Owners typically assign the local resident field engineer in the project's district as their project manager. This individual and his staff usually have little or no experience or expertise in the construction of cable-stayed bridges. Consequently, when problems result, they pass the problem on to their superiors and an extensive complex, external (to the job site) organization. Fig. 3 illustrates a sample problem-decision path of a state transportation agency. This type of action has resulted in time delays and cost overruns.

Not only is it important for the owner to assign an experienced individual as a representative during construction, the owner must also delegate proper decision-making authority to this party (Nickerson 1989). Problems are funneled into a complex off-site organization and "management by committee" process. This action delays decision making for the constructor in critical situations. The job-site manager needs decision-making authority to keep the project moving. Decisions not made at the job site delay the constructor, because this is where all the new, critical information and data evolve.

The lack of project management continuity in the owner's organization is a problem. In most highway departments, projects are transferred from the planning group to the design section to the contracts section and, finally, split between the construction division and contracts section. No single individual with the proper decision-making authority is assigned to participate in the project from conception to completion. This will result in complications (G. Peters, unpublished interview, July 1989). For instance, when a problem ensues during construction, the resident engineer is not familiar with the intricacies associated with earlier phases, and the prolem is channeled through the administrative process until it reaches the proper decision-making authority. This authority may be the state transportation agency, the de-

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

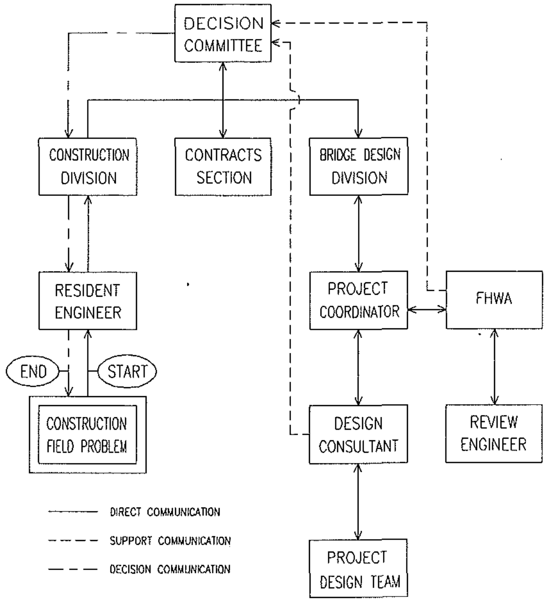

FIG. 3. Problem/Decision Organizational Structure

sign consultant, or the FHWA; typically, it is a combination of all three. In the meantime, the project is delayed while waiting for a decision.

Because the resident engineer is typically not delegated the proper decision-making authority, the change process also has stagnated the successful completion of cable-stayed bridges. Changes within fixed-price contracts (design-bid-build) significantly affect the original planned construction sequence. As projects estimated within fixed-price contracts have the most rigid pricing and timing criteria, any modifications to the original basis must be equally compensated with money and time adjustments (Davis and Ledbetter 1988). Changes should be resolved in a timely manner—not deferred until the end of the project for resolution.

Project Document Reviews

The shop-drawing-review process has caused many problems. In a federally funded project, four parties will participate in the review: (1) The resident engineer; (2) the state department of transportation; (3) the designer; and (4) the FHWA. Consequently, the turnaround time for shop drawings is critical to the limited durations of these projects. The constructor cannot legally proceed until the shop drawings are approved. Contractors have expressed the opinion that time for shop-drawing review has been excessive.

Designer Performance

During the design and construction of cable-stayed bridges, problems have resulted from the action, or lack of action, taken by the designer. Designer-related problems can be classified into four areas: incomplete design, lack of access to specification development, overly congested areas, and restrictive tolerances.

Incomplete Design

The goal of the design consultant is to prepare a design that meets the owner's requirements and permit constructors the flexibility to employ their own construction methods. Since construction input is not used in design, whether by owner restrictions placed on the designer or by the designer's personal choice, modern-day designs of cable-stayed bridges are not complete.

Since a detailed erection method is not given in the contract documents, each constructor estimates his superstructure erection costs on the schematic sequence shown in the plans or another conceptual method prepared by the constructor or a construction engineering consultant. The constructor will estimate the job assuming his construction methodology will be permitted and is complete. A significant factor affecting the constructor's bid is how comfortable he feels about the contract documents (Gee 1987). Because the designer's intent is not explicit in the contract documents, the constructor's assumed methodology may not be permitted. A major conflict can result, in the beginning of the construction process, if the construction methodology is not accepted (H. B. McCoy and K. Jacobson, unpublished interview, April 1989). The constructor's original estimate is no longer valid based on the initial assumptions. The constructor is still contractually obligated to build the bridge, and must incur all future costs based on a further defined set of designer-directed parameters. A new construction method must be prepared that is acceptable to the designer. The constructor must plan his construction activities around the new method and incur the costs associated with it. If costs are more than the original estimate, the constructor is forced to incur the additional expense. In such cases, constructors have filed a constructability claim for additional damages incurred because of changes to their original construction methods. This represents a major area of litigation today.

The failure of a designer to consider intermediate construction loads creates problems for the constructor. The constructor is forced to add additional rebar or post-tensioning, or increase the concrete strength at his personal expense. On the construction of the Talmadge Memorial Bridge in Savannah, Georgia, additional rebar and post-tensioning had to be added to the tower to resist construction bending moments. The required concrete deck strength had to be increased significantly to attain the project schedule (W. Scharf, unpublished interview, March 1989). During construction of the Dame Point Bridge, the project needed an extra 400 tons of rebar. Each strand system in the deck crossbeams were increased by one additional strand to resist construction loads (H. B. McCoy and K. Jacobson, unpublished interviews, April 1989).

Lack of Access

Lack of access can be costly in the construction of cable-stayed bridges. When the design calls for the live end of the stay cables to be stressed from the towers, sufficient space must exist within and around the tower for installation, stressing, equipment, and personnel. All post-tensioning systems require proper access at both the live and dead ends. The design must ensure that access to all areas is compatible with construction (Gee 1987).

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

Specification Development

Because a cable-stayed structure is unique, the specifications should be custom made for these projects. Typical construction standard specifications can have disastrous performance impacts on innovative design and construction projects. In certain applications, they may be out of date or inappropriate. Problems have resulted because general specifications have not addressed specific considerations on cable-stayed structures (C. Reseigh, unpublished interview, July 1989).

Overly Congested Areas

Certain intricate zones may be designed so it is nearly impossible to install all of the required components. Difficulties arise when detailing does not permit allowances for rebar sizes and bending tolerances. Interferences exist where rebar and post-tensioning systems must occupy the same space (Moreton 1989). Some forms are so congested placement of concrete is nearly impossible.

As the designer attempts to minimize the structure's material requirements, he may increase the level of effort required to build the final design. Concrete shapes that are too small increase the congestion in difficult zones, such as post-tensioning anchorages, stay-cable anchorages, and thin wall sections laced with rebar and post-tensioning steel. Ensuring proper concrete placement is difficult when no space exists for concrete chutes or vibrators. If the concrete shapes in the deck are too small, overly sophisticated form travelers may be necessary to prevent structural damage during cantilever erection. Edge girders sized with minimal concrete may be overreinforced versus underreinforced (W. Scharf, unpublished interview, March 1989).

Furthermore, designers will prepare contract documents illustrating concrete shapes and dimensions on one sheet, reinforcing details on a separate sheet, post-tensioning systems on a third, and other required embedments on a fourth. When it is time to install all components in the erected form, interferences are discovered (Kaspar 1989). Adjustments are necessary in the field, so that everything can be installed, resulting in delays.

Restrictive Tolerances

During construction of cable-stayed structures, overly restrictive tolerances are imposed on the constructors. Overly restrictive tolerances are not only difficult to obtain, but the cost incurred in attaining them may preclude reasonable construction standards. Tolerances cannot be too tight for construction work (J. Sutter, formerly of S. J. Groves and Sons, unpublished interview by the writers, July 1989). Some cases require rebar to be bent and fabricated to zero tolerance to fit in the form and provide minimal concrete cover. Tendon force and elongation tolerances require plus-or-minus five percent of theoretical values ("Design and Construction" 1988). Fig. 4 lists selected recommended tolerances for segmental box girders (often a part of cable-stayed bridges).

Constructor Performance

Constructor-related problems fall into the following categories: engineering requirements, inexperienced personnel, project planning, and shop-drawing preparation.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

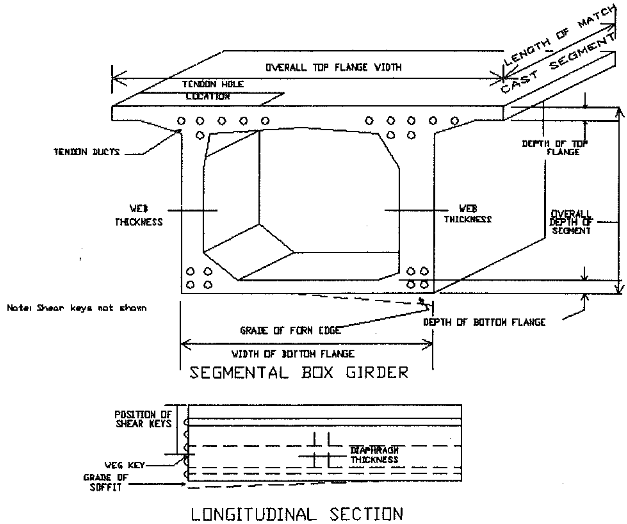

FIG. 4. Segmental Box-Girder Tolerances ("Design and Construction" 1988)

Engineering Requirements

The level of engineering effort required to build a cable-stayed bridge versus the engineering effort required to design the same structure is five-to-one ratio (G. Peters, unpublished interview, July 1989). Based on past performance, constructors are staffing their jobs with the same effort as required on other projects. They do not realize the complexities involved in cable-stayed bridges (McCarthy et al. 1989). Constructors are not aware of the engineering effort involved in these structures (M. Miller, of Howard Needles Tammen & Bergendoff, unpublished interview by the writers, April 1989). Constructors need a full appreciation of the job requirements, and they must staff the project with sufficient qualified engineering support (C. Reseigh, unpublished interview, July 1989).

For cable-stayed structures, additional engineering support responsibilities are required: development, coordination, and documentation of the erection sequence with the construction engineer; preparation of all shop drawings, including post-tensioning requirements and stay-cable systems; selection and integration of cable systems; precast yard operations and quality control (if applicable); post-tensioning and stay-cable assembly; additional materials management for post-tensioning components; stay-cable and post-tensioning stressing activities; and owner-required documentation of all the additional responsibilities. By the time constructors realize that additional engineering staff is required, valuable training and preparation time is lost, and management is forced to perform reactive planning instead of proactive planning.

Another engineering factor constructors must consider is that the superstructure design will be performed three times within the project's duration. First, the designer prepares the original design along with a schematic erection sequence. Second, working with the construction engineer, the constructor modifies this design according to his erection method. Third, this

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

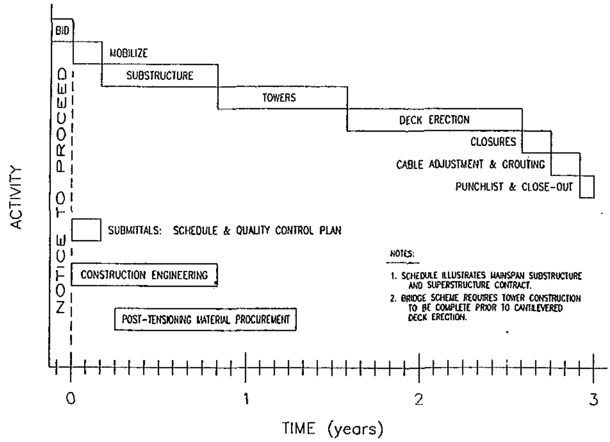

FIG. 5. Milestone Construction Schedule

modification (erection sequence) is reviewed and checked by the owner's design consultant. This three-step process requires sufficiently qualified engineering support staff. On past projects, minimal engineering support was provided, resulting in a skeletal erection sequence (Kaspar 1989).

Inexperienced Personnel

In the construction of cable-stayed bridges, one of the most frequent problems expressed was the lack of experienced personnel working for the constructor's organization (M. Sofia, of Williams Brothers Construction, unpublished interview by the writers, July 1989; N. DeLeon, of Figg & Muller Engineers, unpublished interview by the writers, July 1989; M. Miller, unpublished interview, April 1989; McCarthy 1989). Just as owners need qualified, experienced field personnel, constructors need to staff their projects likewise. Since cable-stayed bridges represent innovative construction, project personnel must have engineering-oriented attributes and the ability to work with sophisticated bridge technology.

Project Planning

Because the erection of the deck superstructure is completed according to the erection sequence, the constructor needs to plan his operations thoroughly in advance without improvisation (Grant 1987). Constructor operations need front-ended project management (M. Sofia, unpublished interview, July 1989). The importance of early project planning is shown in Fig. 5. After receiving the notice to proceed, the constructor will mobilize field personnel and equipment. Intensive planning must begin immediately to support the start of substructure construction. Early engineering work includes cofferdam designs, restrutting operations, formwork designs, and foundation design for tower cranes. In addition, the project engineer is usually required to submit a project schedule and quality control plan to the owner for review. Because of the complexity and lead times for equipment and materials, the time to begin planning the construction of the superstructure is also in the early stages of substructure construction. Problems have resulted on past

J. Constr. Eng. Manage., 1991, 117(2): 259-278

superstructure construction work because the planning activities were performed too late.

Shop-Drawing Preparation

Partial submittals of shop drawings simply do not work (N. DeLeon, unpublished interview, July 1989). The complete set of design calculations and shop drawings for a particular design need to be submitted to the reviewer. A partial submittal does not give the reviewer adequate facts about the design. The constructor cannot expect the reviewer to check and approve a partial set of drawings when they refer to details shown on other drawings. The reviewer needs all the information before a judgment can be made on the adequacy of shop drawings (Nickerson 1989).

Analysis and Considerations for Design and Construction of Cable-Stayed Bridges

Changes are needed in the design and construction of cable-stayed bridges. These changes must be encouraged and implemented by the owner. State transportation agencies and the FHWA need to take the lead to mitigate past problems and enhance cable-stayed bridge construction. Private owners realize the influence they have on the construction process. According to Robert Miller, director of project engineering for Du Pont, owners cannot afford to leave the construction industry unchanged (Miller 1988): "Owners have the clout to change the industry if they want to. However, most owners seem content to deal with construction as it is. If construction is to be changed—and this is precisely what all the best contractors want to do—owners must help." The time is ideal for owners to make significant changes to the process used for the design and construction of cable-stayed bridges. Potential improvements can be identified within the present contract environment, a modified contract environment, and an alternative contract environment.

Present Contract Environment

Working within the limitations of the design-bid-build contract system, several modifications can be made to improve project performance. These suggestions will affect the way the owner, designer, and constructor participate in the design and construction process. Recommendations are concentrated on actions each participant should take to improve cable-stayed bridge performance.

Owner

The owner can take the lead and implement changes to the cable-stayed bridge environment. The owner controls the financial resources needed to build the required product, and can place new demands on the designer and the constructor to improve the status quo. Therefore, the owner needs to take the lead and implement the following suggestions to avoid current problems on future projects.

Owner's Orientation. This is a key element in the design and construction process. For the project to be successful, the owner must assume his role (G. Peters, unpublished interview, July 1989). The owner is responsible for setting the character of the project; establishing project requirements, objectives, and policies; and communicating these guidelines to the other

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1991, 117(2): 259-278

team members. If the owner provides strong guidance and communicates a clear strategy on how the designer and constructor should perform, they will be better equipped to provide a quality product, completed on time, at or below budgeted cost.

Owner Project Manager. This is an important step to improve the cable-stayed bridge process. A project manager would provide continuity throughout the design and construction process. Responsibilities would include (G. Peters, unpublished interview, July 1989):

- Assisting in the preparation of the drawings and specifications, learning the idiosyncrasies of the design.
- Making knowledgeable decisions during construction, preventing unnecessary delays.
- Knowing all of the important project decision makers, streamlining decision time.
- Negotiating changes in all project phases.
- Acting as a liaison with the FHWA and expediting its performance.
- Possessing proper decision-making authority, making key decisions when necessary to keep the design and construction process moving.
- Ensuring the owner's project requirements (quality, safety, and cost) are not sacrificed during design and construction.

The owner should furnish him with appropriate decision-making authority. This encourages the formulation of sound decisions at the lowest practical level. The project specifications should clearly designate the limits of the project manager's authority and the ultimate responsible party or parties within the project organization. The FHWA and state transportation agency should strive to vest responsibility in a single individual.

Prequalification. Prequalification of the designer's and constructor's organizations is urgently needed. Owners should ensure that the designer and the constructor are technically qualifed before they are permitted to perform on their cable-stayed bridge projects. This will guarantee all participants are qualified in the design and construction of cable-stayed structures. Qualification guidelines need to be initiated so a fair and equal assessment of the firms' abilities is made. The ASCE has established criteria that the owner should use during the designer selection process (*Quality* 1988).

Early Project Investment. This can produce monumental gains. Because the most critical decisions affecting the project's quality, schedule, and cost are made early in the project's life cycle, owners should strive to make quality design decisions as soon as possible (Gray 1983). This requires the owner to pay the designer to analyze and design for all conditions that will reasonably develop during later project phases. Personnel responsible for work activity in later stages (i.e., construction, operation, and maintenance) should be permitted input during the conceptual and design phases. As design schemes and details are prepared, their input regarding constructability and maintainability should be carefully considered.

Presently, the alternate design process is used on all structures valued over \$10,000,000, doubling the design costs of cable-stayed structures (Hughes and Wheeler 1989). In most cases, the project participants know which of the two detailed designs will be the most economical after the conceptual design phase (McCarthy 1989). The writers believe money invested in the

J. Constr. Eng. Manage., 1991, 117(2): 259-278

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

second detailed design could be better spent by requiring a more complete first design. Eliminating the detailed alternate design and investing these funds in the first design will cost the owner no more than what is currently being spent.

At specified periods during the design phase, experienced heavy constructors need to review the design for ease of construction, quality, and safety (C. Reseigh, unpublished interview, July 1989). The designer can use constructors' experience to analyze and discuss construction concepts (H. B. McCoy and K. Jacobson, unpublished interview, April 1989). Designs can be improved and costs minimized by consideration of the construction methods ("Can Your" 1986). The final design will result in a better product that is more buildable, easier to bid, and more cost effective (H. B. McCoy and K. Jacobson, unpublished interview, April 1989). Furthermore, this process nurtures a teamwork atmosphere.

For a constructability program to be successful, the owner must require and pay the designer to utilize constructors in the design process. The designer must be receptive to construction input and evaluate it objectively. Constructability should be budgeted in the design process (C. Reseigh, unpublished interview, July 1989). Constructors who participate should be: (1) Held accountable for their recommendations; and (2) paid a fee for their services. The constructability program design costs are small compared with the reduced risk of litigation and costly settlements resulting from design errors, impractical designs, or vague specifications ("Can Your" 1986).

A complete construction method should be included in the contract plans and specifications. This would minimize problems resulting from incomplete design. The owner should pay the designer to prepare one complete, feasible erection sequence accounting for all loadings at each construction stage (Nickerson 1989; McCarthy et al. 1989; G. Peters, unpublished interview, July 1989; C. Reseigh, unpublished interview, July 1989; Gee 1989; and H. B. McCoy and K. Jacobson, unpublished interview, April 1989). Construction method details would be analyzed and reviewed by the constructors in the constructability program. All assumptions including live and dead loads, construction loads, equipment locations, traveler sizes, post-tensioning requirements, and stay-cable forces should be included with sufficient details in the contract specifications and drawings. Camber curves with allowable tolerances and deflection limits should be stated. The illustrated method "should state unequivocally that all parts of the permanent structure have been designed for the loading conditions that will arise during construction if this method is followed" (Gee 1989). Should the constructor decide to deviate from the construction method provided in the contract documents, he would be responsible to provide complete calculations for the new method.

The specifications prepared for new cable-stayed bridges should be project-specific. An entire set of new contract specifications should be developed exclusively for these projects (H. B. McCoy and K. Jacobson, unpublished interview, April 1989). "Early and complete specification development should be promoted" (Nickerson 1989). Standard specifications should be permitted as a reference only while developing the new specifications. They should be analyzed on a division-by-division basis. When sections are applicable to the project in design, they can be inserted in the new contract documents where pertinent (C. Reseigh, unpublished interview, July 1989). The sup-

J. Constr. Eng. Manage., 1991, 117(2): 259-278

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

plemental specifications, information unique to the cable-stayed bridge, would then complete the new specifications.

Integrated shop drawings are another tool the owner needs to underwrite during the design phase. These drawings, prepared by the designer in the design phase, clearly illustrate the integration of all permanent materials in congested areas. One drawing detail or section provides accurate dimensioning of a congested area and thus shows how everything "fits" in the specified concrete shape. Materials include: reinforcing steel, post-tensioning components and anchorages, stay-cable components and anchorages, blockouts, and other specified embedments. With the advances in computer-aided design, three-dimensional modeling could be used to locate possible conflicts.

Once integrated shop drawings are prepared by the designer, they can become part of the contract plans. Plans will be more complete, permitting all constructors to have the same information in the bidding phase. Where integrated shop drawings are provided, constructors will no longer need to prepare them. This will minimize the number of drawings processed during shop-drawing reviews.

The owner needs to provide sufficient time during the bidding phase to analyze construction engineering requirements. Development of the erection sequence and camber curves requires ample time. This allows the constructor to prepare a more accurate bid and minimize risk. Since considerable review and checking will be performed by the designer, the project schedule needs to reflect this important requirement.

Experienced Field Personnel. Personnel with field experience decision-making authority are needed at the field level. The owner's project manager should be assigned to the project as the resident engineer (RE) in charge of construction. Owner field personnel without previous experience in segmental or cable-stayed bridge work should be sent to training seminars. The owner should require the design consultant to staff the field team with the resident project design engineer to provide technical design assistance to the owner's field staff during construction operations.

Administrative Process. The administrative process should be streamlined, thus facilitating the design and construction process. The owners have to define which party needs to receive what documents within what time period. Fig. 6 illustrates a proposed method. Project document reviews need to designate how much time is required, the type and quality of information necessary, and people responsible for the review system. The number of personnel required to analyze, check, and review documents for project conformance should be kept to an absolute minimum. Reducing the number of people required for reviews will encourage faster document turnaround. Owners require constructors to perform promptly. As a result, they need to stay in line with the standards they impose on the construction industry (C. Reseigh, unpublished interview, July 1989).

After the owner's administrative process is defined, it should be explicitly stated in the contract specifications. Proper channels of communication and authority need to be clearly established in the project specifications for all types of project correspondence. Constructors need to know which parties will be involved in the review process. Specifications should state who will process what documents and in what order. The number of copies required for each submittal should also be designated.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

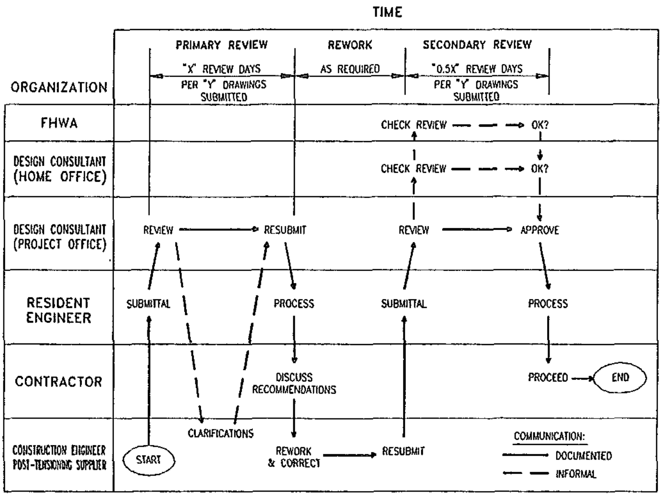

FIG. 6. Proposed Administrative Process

Designer

The designer will perform the functions the owner requests. The last section of this paper presents several design services the owner should seek in the contract with the designer. Specialized services include: constructability contribution, complete method of construction, project-specific specifications, integrated shop drawings, and adequate contract time. Likewise, the designer can supplement these ideas and improve the current design status of cable-stay bridges by the following: (1) Provide fully illustrated details; (2) ensure that the specifications promote construction efficiency; and (3) check congested areas for interferences during the design phase.

Constructor

The constructor is influenced by the owner's actions. Construction activities are also swayed by the quality of the final design. This section will concentrate on actions the constructor should take to improve the construction of cable-stayed bridges.

A constructor must staff the field project according to the needs of this distinctive type of structure. The constructor's field engineering force should include several engineers, including more than one registered professional engineer. These engineers should be assigned to the project as soon as the constructor receives the notice to proceed. Engineering-oriented superintendents should be assigned to the project as well.

Experienced personnel need to be used in staffing by constructors of cable-stayed projects. At a minimum, the project manager, general superintendent, and project engineer should have previous cable-stayed bridge experience. These individuals form a team to build the project according to the owner's project requirements and within the constructor's schedule and cost objectives.

It is especially important that the constructor plan and organize superstructure construction activities. Construction engineering work should begin as

J. Constr. Eng. Manage., 1991, 117(2): 259-278

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

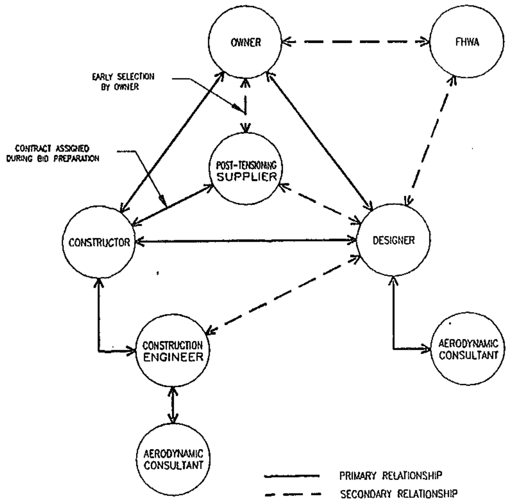

FIG. 7. Modified Project Delivery System

soon as possible. Superstructure construction will be simplified if the constructor plans these operations well beforehand.

Shop-drawing submittals must be complete before submitting them for review. A partial submittal does not give the reviewer ample information about the design. The reviewer needs all the pertinent data before a decision can be made on their adequacy. The constructor can facilitate this activity by submitting complete drawing and calculation documents. In addition, reviewers need a sufficient amount of time to review the proposed design package. The constructor should reasonably plan for a 30-day review period.

Modified Contract Environment

Fig. 7 demonstrates a proposed, modified contract alternate. If the owner and designer would select the post-tensioning supplier so that the designer knows the exact details of the systems used, the designer could resolve conflicts, fully integrate all bridge components, adequately detail reinforcing steel and post-tensioning systems, and correct cover problems. Fewer shop drawings would need to be processed. As a result, contract plans would be complete and future construction difficulties would be minimized.

Complementing early supplier selection would be a change in the contract system. Because the suppliers have been selected prior to bidding, their price quotations need to be integrated into the constructur's overall bid price. One suggested method is to include a pay item in the schedule of payments called post-tensioning suppliers. This pay item would include the supplier's price quotation proposal furnished to the owner. All constructors would have to include this price in their estimate and bid. Constructors would then be liable for the suppliers' performance during construction. If individual constructors were uncomfortable with the previously selected suppliers, they could increase their bids to reflect the additional risk incurred. This cost could either be included in the suppliers pay item or spread across other pay items.

Alternate Contract Environment

The design-build concept has found numerous applications in the European market. Owners specify the project requirements, including costs, and solicit a design-build bid. Designers join with constructors to provide a unique solution for the project. "This approach has the advantage of promoting innovation at all stages of design and construction by allowing the design engineer to consider both the type of structure most suited as well as the cost and time of construction" (Murillo 1989). Together, the project team works with the owner to provide a design meeting the project's objectives.

In the United States, success is hindered on high-tech projects because the design function is separated from the construction function. The design-bid-build constraint system forces each party to work within the definitions and limitations of this contract method. Designers are separated from constructors, preventing the implementation of construction methods into the design. Constructors are separated from designers, preventing the implementation of structural expertise into construction methods. Project participants become adversaries instead of advocates.

It is not within the scope of this paper to analyze the intricacies involved in the adoption of the design-build contract system. It is hypothesized that litigation with the owner would be minimized because the adversarial relationship between the designer and constructor would no longer exist. The designer and constructor would be on the same team. The construction engineer could be eliminated because the designer would perform these responsibilities. Shop drawings would be prepared and reviewed by the project team. The difficult review process would be streamlined, since less disinformation results. In addition to quality and safety objectives, the designer could work toward the specified construction methods (M. Miller, unpublished interview, April 1989). The constructor could have an influence on design with a greater confidence in it (H. B. McCoy and K. Jacobson, unpublished interview, April 1989). Builders would join with designers, providing an additional dimension to solve problems.

Conclusions

Building a cable-stayed structure represents state-of-the-art bridge technology. However, the North American cable-stayed bridge market has experienced continuous and ongoing problems during its development. This paper has identified serious conflicts in the design and construction process. Changes and improvements are desperately required within the present system to ensure its future and the benefits they provide.

This paper has outlined the recommendations, which have been proposed by participants on completed projects, to integrate the difficulties encountered. Further implementation studies are needed to develop an optimal process for cable-stayed bridges to be built in the future.

Appendix. References

"Can your design be built." (1986). *Civ. Engrg.*, ASCE, 56(1), 49–51.

"Contractor Planning for Fixed-Price Construction." (1987). *Publication 6-4*, Construction Industry Institute, Austin, Tex., May.

Davis, K., and Ledbetter, W. B. (1988). "Tracking system can determine costs for

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

construction quality." *Pulp Pap.*, 62(9), 130–134.
"Design and construction specifications for segmental concrete bridges." (1988). Final Report. Post-Tensioning Institute, Phoenix, Ariz., Feb.
Freyermuth, C. L. (1989). "Preliminary report to the AASHTO special task force on segmental bridges." American Segmental Bridge Institute, Phoenix, Ariz., Jan.
Gee, A. F. (1987). "Bridge winners and losers (rapid evaluation of bridge designs and construction methods." *Struct. Engr.*, 65a(4), 141–145.
Gee, A. F. (1989). "Constructability of bridges—A construction engineer's view." *Concr. Int.*, 11(5), 48–52.
Grant, A. (1987). "Design and Construction of the East Huntington Bridge." *PCI J.*, 32.6 (Nov.–Dec. 1987): 20–29.
Gray, C. (1983). "Buildability—The construction contribution." *Occasional Paper No. 29*, The Chartered Institute of Building, London, England, Feb.
Hughes, G. W., and Wheeler, W. K. (1989). "Cable-stayed bridges, report on study tour of North America, 23 Nov.–11 Dec. 88." Roads and Traffic Authority, New South Wales, Australia, Feb.
Kaspar, S. L. (1989). "Constructability and the cable-stayed bridge," thesis presented to Iowa State University, at Ames, Iowa, in partial fulfillment of the requirements for the degree of Master of Science.
Lass, H., Setzer, S., and Green, P. (1989). "Two bridge projects restart after DOTs change contractors." *Engrg. News Rec.*, 223(1), 7–8.
Leonhardt, F. (1987). "Cable-stayed bridges with prestressed concrete." *PCI J.*, 32(5), 52–80.
McCarthy, T. P. (1989). "Quality of contract documents for segmental and cable-stayed bridges." Transportation Research Board, Washington, D.C., Jan.
McCarthy, T. P., Salamie, R., and Nash, W. R. (1989). "Segmental bridge construction—A contractor's perspective." *Paper No. IBC-89*, Sixth Annual Int. Bridge Conf., Pittsburgh, Pa., Jun.
Miller, R. (1988). "Owner's not getting money's worth from today's construction industry." *Pulp Pap.*, 62(9), 160–164.
Moreton, A. J. (1989). "Segmental bridge construction in Florida—A review and perspective." *PCI J.*, 34(3), 36–77.
Murillo, J. A. (1989). "Modern bridge construction and engineering services." *TR News*, (142), 7–11, 32.
Nickerson, R. L. (1989). "Quality of contract documents for segmental bridges." Transportation Research Board, Washington, D.C., Jan.
Pankow, C. J. (1987). "The builder's function in advancing the techniques of concrete construction." *Concr. Int.*, 9(10), 23–27.
Quality in the constructed project—A guideline for owners, designers, and contractors. (1988). Vol. I, ASCE, New York, N.Y.
Robison, R. (1986). "Cable stays catch on." *Civ. Engrg.*, ASCE, 56(1), 58–61.
Soast, A. (1986). "Skyway Bridge boasts a record and innovations." *Engrg. News-Rec.*, 217(11), 23–25.
"State fumes over late bridge." (1989). *Engrg. News-Rec.*, 223(1), 8.
Tang, M.-C. (1987). "Construction of East Huntington Bridge." *PCI J.*, 32(6), 32–48.
Tappin, R. (1988). "Bridges—Design for construction." *Civ. Engrg.*, Morgan-Grampian, London, Jan.-Feb., 10–11, 13–14.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1991, 117(2): 259-278