Case Study of Burlington Cable-Stayed Bridge

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Abstract: Cable-stayed bridges are becoming increasingly popular in the United States. However, the lack of experience in cable-stayed bridge construction may lead to unsuccessful projects including cost overruns and schedule delays. In light of these potential problems, a need exists to document the methods of construction used in past cable-stayed bridge projects. This paper documents the construction of the Burlington Cable-Stayed Bridge. Throughout the paper, issues regarding constructability and innovation are highlighted. Interviewed project participants agreed that this project was successful. The success is measured by the ability of contractors, subcontractors, material suppliers, and inspectors to deliver a project on time and within budget. This case study describes the general characteristics of the project, significant construction methods and techniques, and factors contributing to project success.

INTRODUCTION

Cable-stayed bridges are becoming increasingly popular in the United States. The European community has viewed cable-stayed bridges to be the the most advantageous, economical long-span bridge since the end of World War II (Rowings and Kaspar 1991). The longest span cable-stayed bridge, 2,808 ft (854 m) in length, is currently under construction in Normandy France (Reina 1993). A 1,606-ft (488-m) cable-stayed bridge is ready to open in Nepal ("Remote" 1993). Japan has constructed about 80 cable-stayed bridges, one third of the world total, since the early 1960's (Burden 1991). Meanwhile, the United States has less than 15 cable-stayed bridges.

Cable-stayed bridges are designed to support loads efficiently with all members carrying only axial forces (Rowings and Kaspar 1991). They typically require less material than conventional bridges and rely on free cantilevered construction methods such that extensive falsework is not necessary. Cable-stayed bridges appear to be more economical for spans ranging from 800 to 1,000 ft (243 to 304 m). Spans of this length are typically too long for economical use of steel girder bridges and too short for use of suspension bridges (Podolny and Scalzi 1986).

However, aside from the design advantages, the lack of experience with cable-stayed bridges in the United States has posed many challenges to both owner and contractor project participants resulting in cost overruns and schedule delays. These problems have lead to major claims, litigation, and termination of contractors and/or designers as seen on past cable-stayed bridge projects (Rowings and Kaspar 1991).

A need exists to document the methods of construction used on previously

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completed cable-stayed bridge projects. The lessons learned from one project, whether they be successes, failures or encountered difficulties, can assist in achieving success on future projects. Otherwise, failures can be repeated while not taking advantage of previous lessons that lead to a successful outcome. The purpose of this paper is to document the significant aspects of construction and management of the Burlington Cable-Stayed Bridge. Throughout the paper, issues regarding constructability and innovation are highlighted. The careful planning and consideration to these issues combined with a project environment fostering innovation, communication, and teamwork on this project are key factors to project success. The case study describes the general characteristics of the project, significant construction methods and techniques, and factors contributing to project success.

DESCRIPTION OF PROJECT

The Burlington Cable-Stayed Bridge carries U.S. 34 over the Mississippi River linking Burlington, Iowa and Gulfport, Illinois. It was built to replace a 75-year-old, two-lane steel truss bridge that suffered considerable substructure deterioration. Expensive repairs and inadequate traffic capacity justified the need for a new bridge. Fig. 1 shows the layout of the project including the four prime contracts involved.

Bridge Design

Fig. 2 presents a profile of the bridge and tower configuration. The total span length is 1,245 ft (378 m) with the two cable-stayed mainspans reaching a total of 1,065 ft (324 m) [405- and 660-ft spans (123- and 182-m)]. The bridge deck is 84 ft wide supporting five traffic lanes. The tower is approximately 316 ft (96 m) above the water surface while the deck is approximately 63 ft (19 m) above water level to allow for vertical clearance of river traffic.

The old bridge remained open during construction so that traffic could be maintained. The close proximity of the old bridge had to be accommodated in planning and design phases and represented a constraint during construction. Many cable-stayed bridges are symmetrical about the center tower such that loads on the tower are equal. However, the designers chose an asymmetrical design to prevent the towers from being located at the pier of the existing bridge. The asymmetric design was also believed to be a cheaper alternative. Siting the tower adjacent to the existing pier would have hindered construction and may have resulted in damage to the new tower when the old pier was removed. The unequal loads on the tower due to the asymmetrical design were accommodated by using eight tiedown cables fastening the shorter deck span to a pier.

The tower is comprised of two hollow concrete pylons joined at the footing and by a concrete strut 152 ft (46 m) above the deck. The pylons were constructed using 30-in. (76.2-cm) thick, 5,000-psi (34,450-kPa) concrete. The tower was configured with cables situated in a vertical plan in connection to the edge girders. This avoided compound cable angles associated with non-vertical cable arrangements. (Joehnk 1988).

The roadway consisted of A572 Grade 50 steel edge girders and floor beams and 6,000-psi (41,364-kPa) precast concrete deck panels. The concrete panels were post-tensioned to minimize deflection and avoid tension in the top of the slab thereby limiting cracking that could allow intrusion of corrosive elements. The spacing between concrete panels was filled with 6,000-psi cast-in-place concrete with a microsilica admixture. The entire span was overlaid with a 2-in. (5-cm) dense concrete riding surface.

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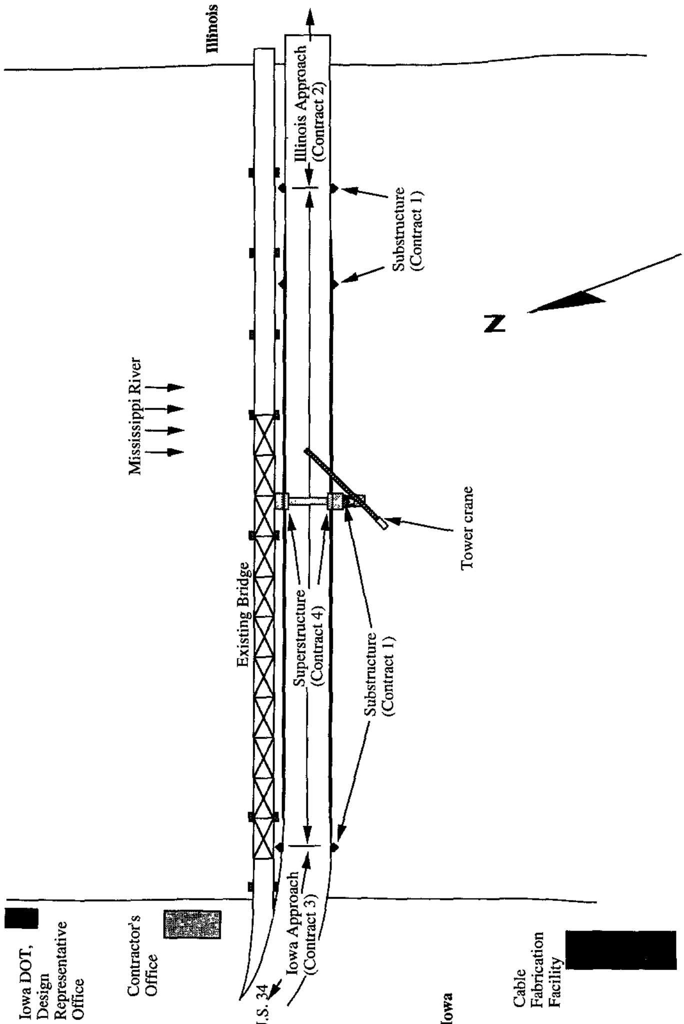

FIG. 1. Layout of Project

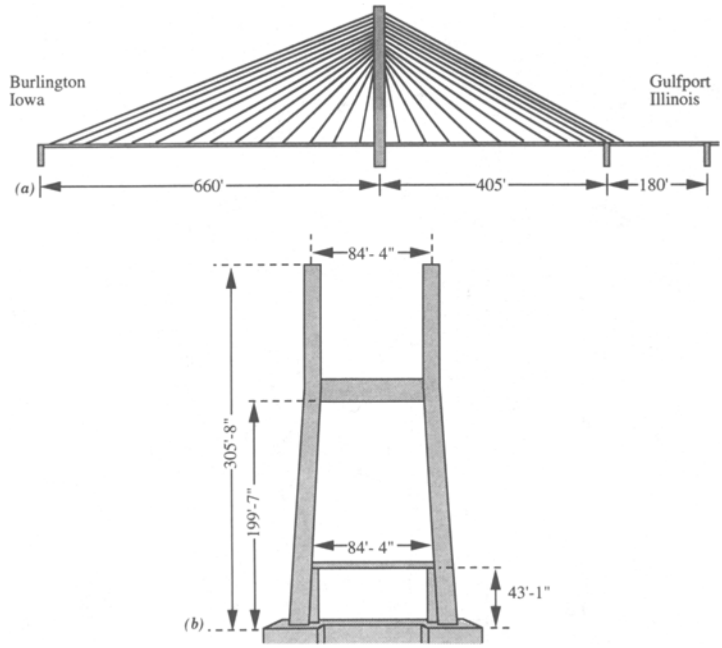

FIG. 2. Profile and Pier of Burlington Cable-Stayed Bridge: (*a*) Mainspan Profile; (*b*) Tower Configuration

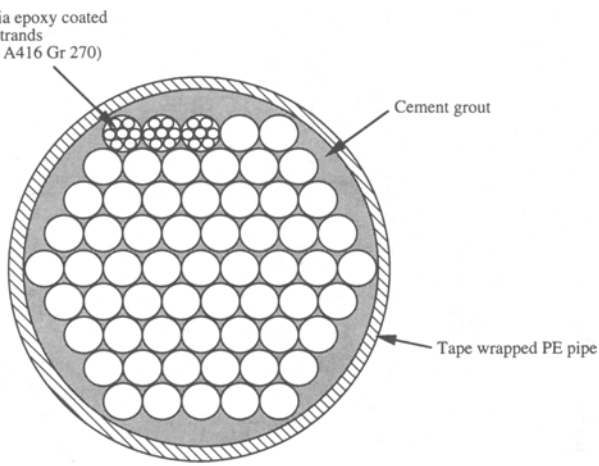

FIG. 3. Typical Cable Cross Section

The cables were fabricated using epoxy-coated seven-wire strands housed by a grout-filled polyethylene pipe. Fig. 3 shows a typical cross section of a cable. A cable consisted of between 25 and 77 strands per cable. The stays were made from alloy steel sockets bound to the cables using a mix of epoxy and steel shot. The hardened epoxy/steel-shot mix acted as a wedge in the

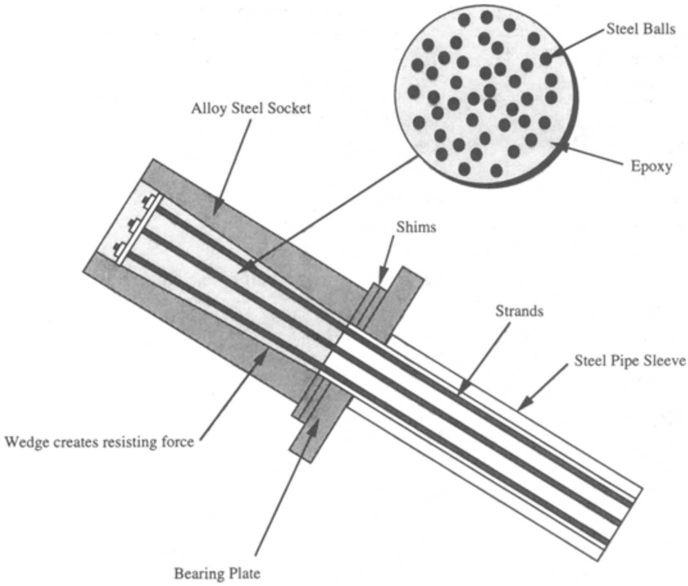

FIG. 4. Half Section of Socket Assembly (Live End)

tapered socket creating the resisting force. The stay design is illustrated in Fig. 4.

Contracts and Project Participants

The mainspan substructure and superstructure were originally bid as one contract. However, received bids were 50% higher than the engineer's estimated cost (Rowling and Kaspar 1991). Thus, all bids were rejected. A reevaluation of the project strategy and design was conducted. The Iowa Department of Transportation (DOT) and designers held a meeting with the bidding prime contractors to obtain input on how to reduce the project's cost. It was determined that a large part of the cost overage was originating from a steel housing for the cable attachments to the tower. Thus, a redesign of the tower was undertaken to decrease construction cost. The redesigned tower used posttensioned concrete instead of the steel housing for cable attachments. To minimize the schedule impact of the redesign, the mainspan was divided into the two contracts so that work could begin on the substructure while the tower was redesigned.

The final project consisted of four prime contracts administered by the Iowa DOT:

1. Mainspan substructure (contract 1)
2. Illinois approach (contract 2)
3. Iowa approach (contract 3)
4. Mainspan superstructure (contract 4)

The first two contracts were performed by one general contractor while the second two contracts were performed by another general contractor. The primary focus of this paper is on the Iowa approach and mainspan super-

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TABLE 1. Project Participants

Participant type (1)	Project activities (2)
Subcontractors	Structural steel erection
Subcontractors	Reinforcing steel erection
Subcontractors	Painting
Subcontractors	Electrical
Suppliers	Cables and stays
Suppliers	Structural steel
Suppliers	Cable anchorages, sleeves, and shims
Suppliers	Reinforcing steel
Suppliers	Bar stressing
Suppliers	Precast concrete deck panels
Suppliers	Bearings
Suppliers	Expansion joints
Suppliers	Deck drains
Suppliers	Cast-in-place concrete
Consultants	Cable-stayed bridge design
Consultants	Analysis of stresses induced during construction

structure (contracts 3 and 4). Table 1 lists project activities for these two contracts performed by various project participants.

Time Line and Schedule

Fig. 5 presents a time line showing the major events of the project. As shown, the Design Study Report began in October 1984. Three bridge alternatives analyzed were tied arch, steel truss, and cable-stayed. The suspended-arch and steel-truss alternatives may have been less expensive alternatives, but the cable-stayed option appeared to be more appropriate given the site characteristics and constraints. These constraints involved horizontal and vertical clearance requirements for river traffic, and a flared, superelevated portion of the mainspan that tied in to the existing Iowa approach of U.S. 34. Designers felt the longer span length, smaller depth of bridge deck, and ability to accommodate superelevations made the cable-stayed bridge the better choice.

The final design started in February of 1986 and focused on two design alternatives: (1) An all-concrete mainspan, or (2) a combination of steel girders and floorbeams with concrete deck panels.

The successful low bidder for the mainspan substructure (contract 1) received a contract in April of 1989. The project scope consisted of four piers including the footing for the bridge tower. The tower footing was constructed to average water elevation such that it would not conflict with the undetermined design or method of construction of the tower. The second contract, the Illinois approach (contract 2), was let two months after contract 1.

Contracts 3 and 4, the Iowa approach and mainspan superstructure, respectively, contracts were let for bidding together in June of 1990. Upon mobilization of the Iowa approach, the constructor discovered deposits of coal tar beneath the river bed. To maintain active construction, the coal tar needed to be removed, at a cost of approximately $3,000,000, from the area surrounding a pier location. To prevent construction delay, the Iowa approach span was redesigned using steel instead of concrete girders. This

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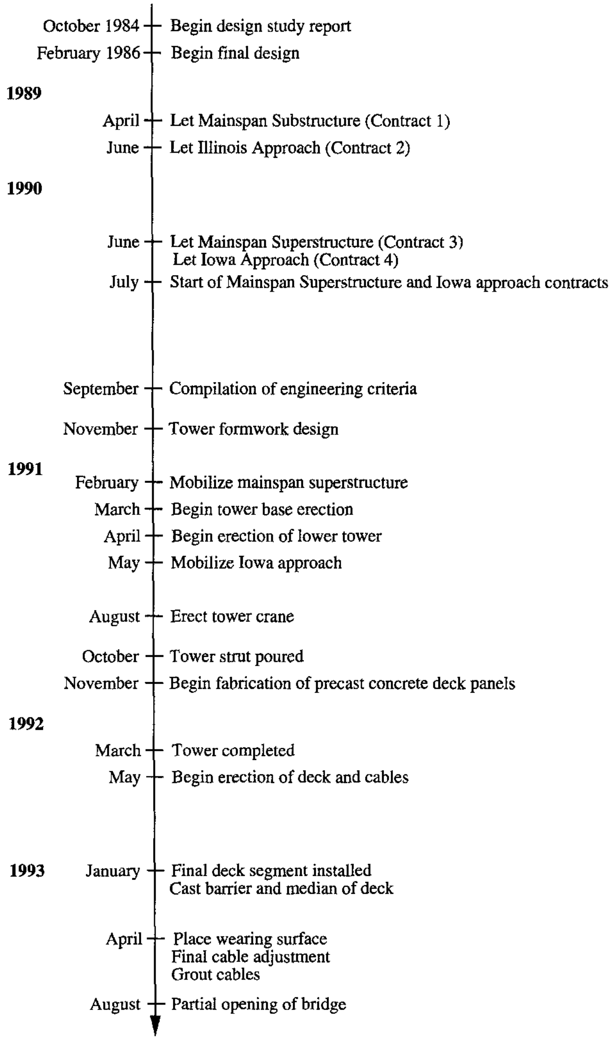

FIG. 5. Time Line of Major Project Events

allowed a two-span layout thus eliminating one of the two piers. The quick reaction by the Iowa DOT, designers, and the constructor was critical in avoiding significant project delay and additional cost damages.

The specifications stated that construction of the mainspan was to be completed within 500 work days. Work days were accumulated only during a yearly construction season from March 2 to November 14 although the constructor was not prohibited from working during the winter months. Construction began in March 15, 1991 with a scheduled completion date of June 22, 1994. The bridge was scheduled to be partially opened to traffic in May of 1993 so that disassembly of the old bridge could begin. To meet schedule, the constructor worked during winter months, which did not count towards the allocated work days. The constructor also took advantage of time-saving construction methods described later in this paper.

Cost

The combined project cost was approximately $42,000,000 based upon fixed-price contracts awarded to the lowest bid. Table 2 shows the low bids for each of the contracts as well as the bid spreads from other contractors. Note that the Iowa approach and mainspan superstructure (contracts 3 and 4) were combined and awarded to the lowest total bid.

Fig. 6 shows a pie chart representing cost for construction of the mainspan superstructure and Iowa approach (contracts 3 and 4). A large percentage of the cost was in purchasing materials. Of the $30,500,000 bid for the mainspan superstructure and Iowa approach, the cables and stays represented approximately $3,200,000, $8,000,000 for structural steel, $6,000,000 for concrete, and $1,400,000 for precast concrete panels. The material-intensive nature of the project prompted extensive consideration to materials management. This enabled efficient use of equipment, labor, and on-site storage space. Labor costs involved $8,000,000 going to subcontractors for labor and equipment. This included painting, electrical, steel-rebar erection, structural-steel erection, and cable and stay fabrication. Mobilization of the project cost $2,000,000. The remaining cost accounted for other miscellaneous items.

TABLE 2. Contract Bids

Contract index (1)	Contract name (2)	Bid amount (dollars) (3)
1	Mainspan Substructure	6,578,696.14*
1	Mainspan Substructure	7,228,901.60
1	Mainspan Substructure	8,093,042.75
1	Mainspan Substructure	8,979,632.08
1	Mainspan Substructure	9,500.431.10
1	Mainspan Substructure	9,579,501.00
1	Mainspan Substructure	10,321,086.85
1	Mainspan Substructure	10,375,162.10
2	Illinois Approach	5,046,860.30*
2	Illinois Approach	5,073,425.70
2	Illinois Approach	5,469,664.70
2	Illinois Approach	5,997,675.86
2	Illinois Approach	6,070,894.00
3	Iowa Approach[a]	7,859,050.90
3	Iowa Approach[a]	8,418,340.61*
3	Iowa Approach[a]	10,064,100.10
3	Iowa Approach[a]	12,279,307.10
4	Mainspan Superstructure[a]	22,142,860.70*
4	Mainspan Superstructure[a]	22,245,001.20
4	Mainspan Superstructure[a]	23,235,070.40
4	Mainspan Superstructure[a]	25,194,862.45

*Indicates bid that won contract award.

[a]The Iowa Approach and Mainspan Superstructure contracts were combined and awarded to the lowest total bid.

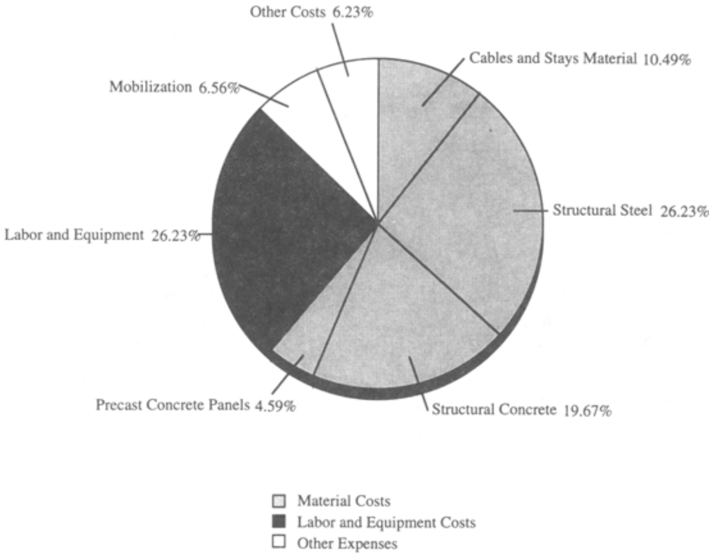

FIG. 6. Project Costs for Mainspan Superstructure and Iowa Approach

CONSTRUCTION METHODS AND TECHNIQUES

The Burlington Cable-Stayed Bridge was a new type of construction to most project participants. Lack of experience combined with the tight schedule made attention to construction planning and methods analysis essential. Careful planning and innovation used in determining construction methods are recognized as key concepts of constructability (*Constructability* 1993). This relies on construction knowledge and experience to improve the effectiveness of field operations, including construction sequencing and use of materials, equipment, and labor. Constructability also recognizes the concept of preassembly and modularization as a cost-and schedule-efficient method of construction. To be effective, issues such as location of fabrication, methods of transportation to site, equipment capabilities, and method of installation must be addressed.

Facing a schedule-driven project, the constructor, as well as the Iowa DOT, recognized these constructability issues prior to start of construction. Methods and sequences for bridge construction, focusing primarily on schedule savings, were formulated before bridge construction began. Preassembly of bridge components involving large loads and construction equipment were exploited. This enabled efficient coordination of subcontractors and equipment. This section describes the significant construction methods selected that had the most impact on the project's schedule.

Sequence of Tower Construction

The constructor faced numerous challenges in selecting the method to construct the tower. The tower construction sequence is illustrated in Fig. 7. This tower concrete placement cycle allowed pours of 80–100 cu yd (61–76 m^3) or 15–30 ft (4.5–9.1 m) in height in one week.

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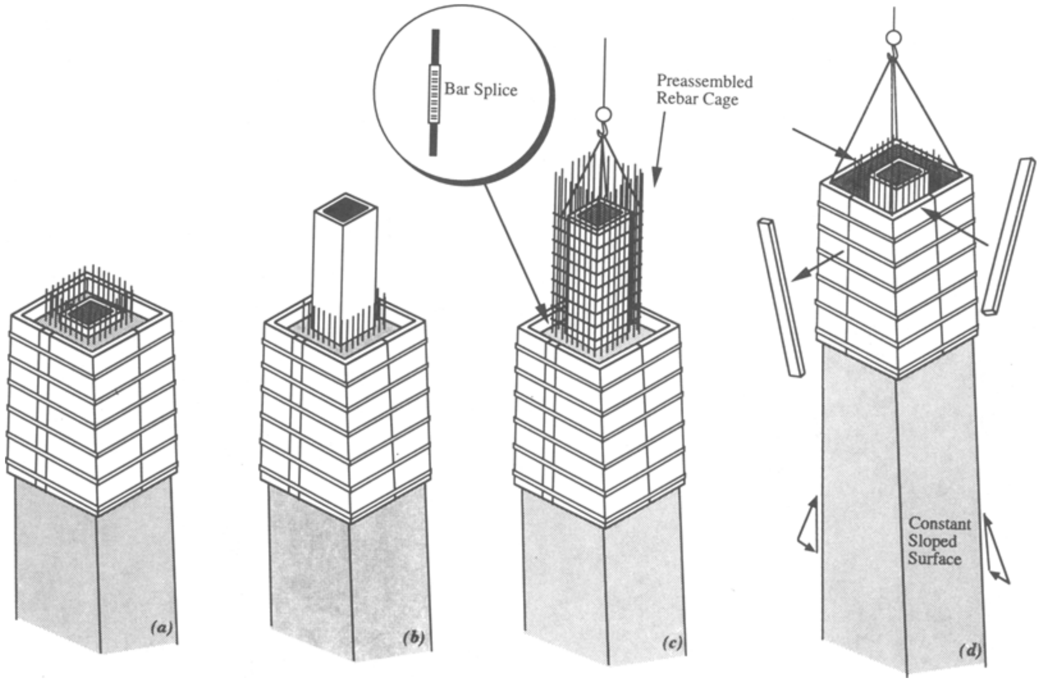

FIG. 7. Concrete Forming Sequence for Bridge-Tower Construction: (*a*) End of Previous Pour; (*b*) Place Inside Forms; (*c*) Set Rebar Cage; (*d*) Remove Vertical Strips and Jump Forms

Prefabricated Reinforcing Bar Cages

The reinforcing steel for the tower was a complex design. The original design assumed a stick-built method of steel assembly. Instead, the constructor prefabricated the reinforcing bar cages on-shore and lifted them in place by crane. This avoided the difficulties of stick-built methods such as laborers working at high elevations causing a potential safety hazard, additional time required, and potential for reduced accuracy and quality.

Barsplice Coupling

The design specified either a lap splice or a threaded mechanical splice for rebar connections. The specifications, however, stated that if a mechanical splice was to substitute for a lap splice, the contractor was required to perform testing on the mechanical splice to document its strength.

The lap splices would be labor intensive and require additional reinforcing steel while the threaded mechanical connections described in the specification would not work with the use of prefabricated cages. The constructor, prior to the start of construction, began the testing of a cold crimping method of rebar coupling using a Barsplice™ mechanical coupler. The testing process showed that the mechanical coupler exceeded the specified strength requirements. In addition, the Barsplice coupler was only 8 in. (20.3 cm) long in comparison to the 3 to 4 ft (0.9–1.2 m) required for lap-splicing.

Upon receiving the test results, the Iowa DOT and the resident engineer accepted the Barsplice coupler and issued a change order. The estimated cost savings in terms of reduced material and labor hours was calculated and divided between the Iowa DOT and the constructor. However, this calculated cost savings was exceeded by the constructor's incurred cost from Barsplice testing and the picking template for the prefabricated rebar cages. Thus, the prefabrication of the rebar cages and the Barsplice coupler cost the constructor additional money not originally in their bid. Nevertheless, the constructor believes the schedule savings resulting from this construction method justified the additional cost.

Using the Barsplice coupler was relatively simple. The cage was lifted into place fitting the coupler end onto the bars of the preassembled cage and the previously erected cage. The coupler was crimped, thereby completing the connections. Crimping was accomplished by use of a 20 lb (9 kg) forming press suspended from a comolong and guided by an ironworker. The process involved no heat or fillers, only the mechanical press. Using this method, a coupler could be fastened to a rebar in under 30 sec.

Formwork

The method of forming the concrete was also a key aspect in the tower construction. The constructor wanted to prevent lowering and raising the forms between pours due to the time required and safety concerns. At high elevations above the river, high wind gusts may cause the form to spin. If the crane lost control of a form, it may have to cut it loose resulting in lost forms and time, a potential safety hazard to workers and passerbys, and potential damage to the project and equipment.

A forming system was devised to prevent lowering the forms to grade level. The east and west sides of the tower pylons were vertical. The north and south sides were sloped in such a way that the pylon leans inward and narrows with height with the outside and inside faces deviating from vertical 4.20° and 2.42°, respectively. While the dimensions of each lift changed, the geometry remained the same. A vertical strip in the form panels was adjusted to account for the pylon's reduced dimensions. To prepare for the subsequent pour, the crane jumped the forms to the next level, and workers cut out the vertical strip of the panel [see Fig. 7(*d*)] and joined the two forms.

The weight of the formwork was also an important consideration. The constructor, therefore, used lightweight aluminum form panels to reduce its weight. The preassembled formwork system required an upfront investiment for the more expensive form panels but resulted in schedule savings as well as avoided the hazards previously described.

Pouring Concrete

Laborers placed the 5,000-psi (34,470-kPa) using a crane, 3-cu-yd (2.3-m^3) bucket, and drop pipe. The quantity of concrete to be placed and the high density of reinforcing steel necessitated a workable concrete mix. Use of superplasticizers enabled a slump of 5–6 in. (120.7–15.2 cm) with no reduction in compressive strength. Work alternated between the two pylons allowing the concrete on one pylon to cure while the other pylon was formed and poured.

The specifications stated that the difference in temperature between the inner core and outside surface of the concrete may not exceed 35°F (1.7°C). This was a concern since concrete was being poured during the winter months and the inner-core temperature exceeded 100°F (37.8°C) due to heat of hydration. Mild winter temperatures along with the use of thick insulation on the forms maintained the temperature differential under 35°F (1.7°C).

Local Off-Site Fabrication of Cables

Fabrication of the bridge cables presented several challenges. The supplier had no previous experience in this type of work. In addition, no standard method of cable fabrication existed. Thus, personnel faced many decisions in how they were to approach cable fabrication.

The specifications required that the cables be manufactured in an indoor facility. Selection of the manufacturing facility was critical in two respects: Size and location. A vacant warehouse, located adjacent to the river approximately 1 mi (1.609 km) from the project, was rented allowing work to be performed in a controlled environment. The longest cable was approximately 650 ft (198 m), necessitating a building of sufficient length to layout the tendons and prevent tangling. The close proximity to the bridge and river access allowed for efficient transport of the cables from the manufacturing facility to the bridge and thus, efficient materials management.

The cables were fabricated by first laying out a single tendon along a straight track and cutting it to its specified length. Workers used surveying equipment to ensure the track and cable were level. Each tendon was then individually pushed into the outer polyethylene (PE) pipe. This method differs from other projects where all the tendons were bundled together and encased by the PE pipe. Inserting tendons one at a time encountered several difficulties. The original design specified a helical spacer to be wrapped around the tendons to create a gap between the tendons and PE pipe. Placing the spacer in the pipe first, however, did not permit strands to be pushed through the pipe. After discussion during project meetings, it was determined that the helical spacer was not a critical component of the cable and the supplier was permitted to delete it. Another difficulty with inserting the strands individually was the increased friction between the tendons due to the epoxy coating. This difficulty increased the chances of abrasion of the epoxy coating on the tendon.

Designers were concerned about the interaction between the epoxy coating on the tendons and the bonding epoxy mix used in attaching the socket (see Fig. 4). Thus, it was determined that the tendon coating must be stripped off where the cable attached to the socket. Mechanical means of epoxy removal were chosen over chemical methods since it was thought the latter may have adverse effects on the strength of the bond in the socket. A machine was built to enclose the end of an individual tendon and strip the epoxy with internal wire brushes that rotated around the tendon. This process was performed on each tendon prior to insertion into the pipe. Once the cable was completed, workers situated the anchor socket and poured the epoxy steel-shot mix. The socket was placed in a plywood enclosure that acted as a kiln to allow the epoxy to harden. The finished cable was reeled onto a large spool by means of a motorized coiling machine custom built for this project.

Cable fabrication was a schedule-sensitive operation. The supplier employed a crew of 15 persons working six to seven days per week. Fabrication of one cable took approximately two weeks depending on its length and number of tendons. The longer cables required two work shifts, seven days per week to meet schedule demands.

Sequence for Placing Bridge Deck and Cables

Construction of the bridge deck required cooperation and communciation among the prime contractor, subcontractors, and material suppliers. The bridge deck used preassembly/modular construction techniques.

The erection sequence was divided into 45-ft (13.7-m) long sections as shown in Fig. 8. The time to assemble each section was approximately one week. The erection sequence involved the following steps:

1. Install preassembled steel girder and floor beam module.
2. Hang and partially stress two cables.
3. Place six precast concrete panels and set to correct elevation using leveling screws.
4. Place longitudinal posttensioning bars and couple to stressed bars of previously installed slab panels.
5. Fill in joints between concrete panels with cast-in-place concrete and allow to cure until 5,000-psi (34,470-kPa) compressive strength is attained.
6. Stress posttensioning bars and grout ducts.
7. Install shear studs on edge girders, grout shear-stud openings in precast panels, and infill joint above girder with 5,000-psi (34,470-kPa) concrete.

Structural Steel

In lieu of erecting the structure steel one piece at a time, the structural steel was preassembled in modules. This allowed a 45 × 84 ft (13.7 × 25.5 m) prefabricated section to be erected in one day thus contributing to schedule savings.

The structural steel was fabricated in Des Moines, Iowa. The edge girders and floor beams were shipped to Kentucky and preassembled into the modules as shown in Fig. 8(*a*). Preassembled modules were transported up the Mississippi River by barge to Burlington, Iowa. This operation required rental of six barges at a substantial cost. Once the steel sections were ready for placement, they were floated by barge underneath the bridge. A barge-mounted derrick then lifted the 110-ton (99,770-kg) section into place. The section was cantilevered off the previously installed deck until the cables

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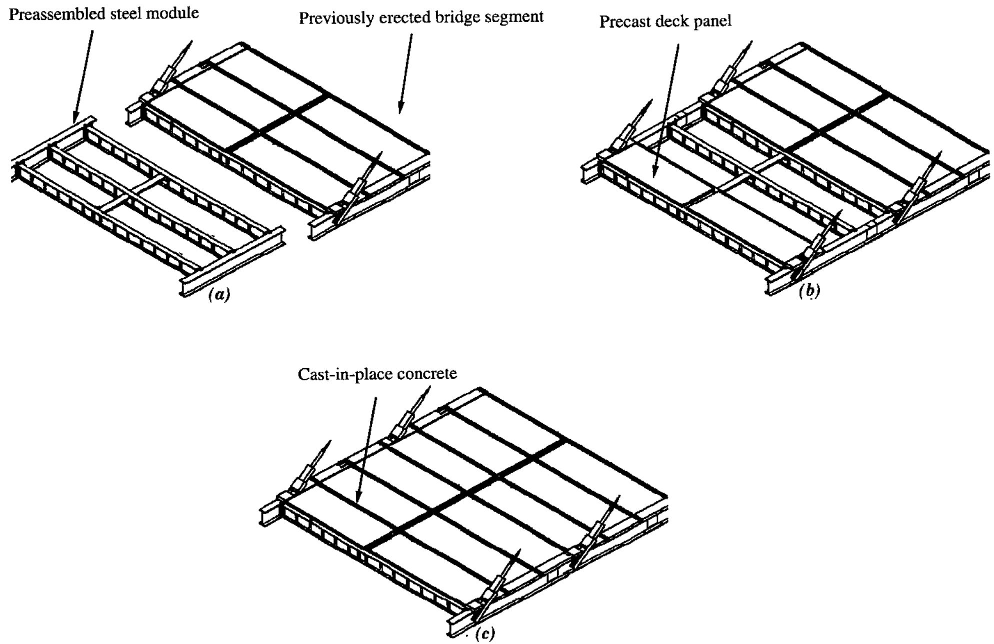

FIG. 8. Bridge-Deck Construction Sequence: (*a*) Steel Lifted into Place; (*b*) Cables Hung and Partially Stressed, Precast Panels Set, Leveling Screws Adjusted; (*c*) Tensioning Bars Coupled to Previous Segment, Joints Poured, Slabs Posttensioned

were placed and partially stressed. The steel erector used falsework to support the shorter cable-stayed span so they would not have to rely solely on balanced cantilever erection. This way, another steel section could be set on the shorter-span side in the event that the longer-span was not ready for erecting another section. The falsework also provided lateral bracing against the torsional effects of the wind.

Hanging Cables

The cables, mounted on spools, were floated to the bridge by barge and lifted onto the bridge deck. Much of the cable erection took place during cooler autumn and winter temperatures creating concerns that the PE pipe encasing the strands may crack while uncoiling the cable. To address this concern, the constructor used two movable sheds on the bridge deck. The sheds housed the cable spools and was heated during the uncoiling process.

The live end of the cable (the end to accommodate posttensioning jacks) was lifted with the tower crane and guided into its anchorage sleeve in the tower pylon. A collar was used in lifting the cable to avoid high bending stresses that could cause kinks in the cable. Once the live-cable end was connected to the tower, another crane carried the dead end to its intended position and workers attached it to the steel edge girders of the bridge deck. Tensioning of the cables was accomplished by jacking the live end from inside the hollow pylon. Workers inserted shims between the socket and bearing plate to maintain the tension once the jacks were released. Cables were partially stressed while setting each bridge deck segment and fully tensioned once the entire deck span was complete.

Precast Deck Panels

The design required precast concrete deck panels as opposed to cast-in-place concrete placement. The precast deck panels provided several advantages: Reduction in time by not requiring time to cure concrete; quick and simplified panel placement once they arrive on-site (it took about one-half day to place six panels); and a higher quality deck associated with precast concrete. The supplier set up two pouring beds at their precast facility so they could form and pour one panel while another cured. The panels were stored in the supplier's yard until they were needed on site.

To obtain access to the river, the supplier constructed a pier upriver from the project. The supplier's close proximity to the river and the newly constructed pier enabled them to bid on another cable-stayed bridge in southern Illinois. The panels were barged to the construction site as needed and lifted into place by a barge-mounted derrick. The in-place panels were adjusted to their specified elevation using leveling screws placed through the panel that were then posttensioned. Once the panels were set to elevation, the contractor filled the space between the panel and steel girders and floor-beams with a microsilica cement mix. Workers removed the leveling screws and grouted the holes after the cement gained sufficient strength.

Use of Tower Crane

During construction planning, the constructor needed to determine the equipment to be used for moving materials. They considered factors such as accessibility to points on the bridge and the needed lifting capacity. A Liebherr 450 tower crane was purchased and erected adjacent to the downstream pylon. Inserts were imbedded in pylon to accommodate connection to the tower crane thus providing the crane with lateral support.

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Although several barge-mounted cranes were also used on the site, the presence of the tower crane proved to be invaluable. The crane's lifting capacity and reach facilitated efficient materials management. Without the tower crane, material transport might have necessitated multiple handling of material and constant moving of barge-mounted cranes to accommodate lifts. The tower crane could transport material directly from a barge to the bridge in one lift. Thus, problems associated with barge-mounted cranes were avoided including limited mobility due to river ice, coordination with tug boats to move the barges, conflicts with river traffic, and high costs of barge rental. The tower crane lifted rebar cages, erected formwork, and transported concrete for the completion of the upper tower. It also lifted cables for installation in the tower, among other functions.

FACTORS CONTRIBUTING TO PROJECT SUCCESS

Interviewed project participants agreed that this project was successful. The success is shown in the ability of contractors, subcontractors, material suppliers, and inspectors, all of whom had little or no experience in cable-stayed construction, to deliver a project within the time allotted and budgeted cost. Additionally, the inspection procedures by the design engineer, the Iowa DOT, and the Federal Highway Administration (FHWA), assured quality workmanship in both the fabrication, erection, and installation of materials. Key elements of project success are highlighted in Table 3.

Elements of the project's success can be traced back to the planning and design phases. Designers paid careful attention to the location of the existing bridge and alignment of the Iowa approach. These site characteristics were evaluated for their impact on both the bridge design and possible problems during construction. For example, designers recognized the problems and risks associated with placing the new tower too close to an existing pier. Thus, attention to constructability issues up-front resulted in avoidance of potential problems during construction.

Problems occurring on the project, especially prior to or early in construction, were addressed accurately and quickly. Project participants were required to make key decisions that would minimize impact of problems on cost and/or schedule. When the first round of bids received were too high, the designers and Iowa DOT consulted with the bidding contractors on methods to decrease cost. This acquiring of construction knowledge and experience input to design is a key concept in achieving constructability. At the same time, choosing to split the project into four contracts so that substructure work could begin avoided extensive and costly delays. The same quick decision making occurred when the coal tar was discovered and redesign eliminated need of a bridge pier.

TABLE 3. Elements of Project Success

Element (1)	Contributor (2)	Success (3)
Integrated team management	Designer, DOT contractors	Constructability improvements during design
Preplanning	Contractor	Equipment selection
Modularization	Contractor	Schedule savings
Communication	All parties involved	Experience and authority to make decisions

One of the major contributions to the project's success was the constructor's five months spent planning the Iowa approach and mainspan superstructure projects prior to the start of construction. During this period of time, the constructor was able to carefully plan the construction process. Much attention was given to the tower where the constructor had to present to the Iowa DOT with both how they intended to build the tower and how they would work off the tower while building the deck. It was during this time spent preplanning that ideas about using modular rebar cages, Barsplice connectors, prefabricated formwork, and a tower crane were discussed. These were ideas not originally foreseen during project design but significantly added to the project's success. However, many of these innovative construction methods may have been less effective if not impossible to implement without a project environment that encouraged new ideas. Thus, project participants recognized that the specifications, such as the lap-splice requirement, were not necessarily the best and only way to do things. Project success depends on periodically evaluating the specifications and a willingness to change given proper assurance that quality is maintained.

The constructor also hired a consultant to analyze the stresses on the tower induced during construction. In addition, involvement of the constructor's project manager, along with other key project personnel, in this five-month planning effort gained the benefits of continuity in personnel from planning to construction.

Before and during construction of the bridge, a critical element to the project success was the frequent communication among project participants, including the two prime constructors, subcontractors, material suppliers, and inspectors. Meetings were held monthly to discuss project progress, problems, and concerns, and schedule the coordination of work crews and material delivery. Participants agreed that having representatives from involved organizations in a close proximity was advantageous in terms of facilitating communication and expediting the decision-making process. However, they also stated that the representatives needed to have both the experience and authority to make key decisions if they were to be effective members of the project team.

While the contract documents made no formal provision for partnering, project participants viewed their relationship as an informal partnering arrangement. This allowed participants to coordinate their activities and adapt to unexpected events that occurred during planning and construction with the understanding that risks and benefits were shared. Participants believed the teamwork philosophy resulted in an improved working environment and thus, a more successful project.

CONCLUSION

In comparison to other cable-stayed bridge projects, the Burlington bridge may be considered a successful project remaining on schedule and within budget as of partial opening of the bridge. This paper described the general characteristics of the project, significant construction methods and techniques, and factors contributing to project success. Industry professionals involved in constructing cable-stayed bridges may find the description of construction methods and techniques of practical value.

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APPENDIX. REFERENCES

Barsplice Products, Inc., subsidiary of FC Industries, Inc., P.O. Box 31308, 1875 Radio Rd., Dayton, Ohio 45431.

Burden, A. R. (1991). "Japanese cable-stayed bridge design." *Proc. of Instn. of Civ. Engrs., Part I, 90*, Thomas Telford, Ltd., London, England, 1021–1051.

Constructability implementation guide. (1993). *Publ. No. 34-1*, Construction Industry Institute, University of Texas at Austin, Austin, Tex.

Joehnk, G. (1988). "Burlington cable-stayed bridge." *Cable-Stayed Bridges, Proc. ASCE Struct. Div.*, Carl C. Ulstrup, ed., New York, N.Y., 13–23.

Orth, W. A. (1992). "Cable-stayed, five-lane bridge to replace old Mississippi River span." *Constr. Dig.*, Sept. 7, 12–17.

Podolny, W., and Scalzi, J. B. (1986). *Construction and design of cable-stayed bridges.* John Wiley and Sons, New York, N.Y.

Reina, P. (1993). "French readying record span." *Engrg. News Record*, 230(9), 20–21

"Remote bridge opens soon." (1993). *Engrg. New Record*, 230(9), 11.

Rowings, J. E., and Kaspar, S. L. (1991). "Constructability of cable-stayed bridges." *J. Constr. Engrg. and Mgmt.*, 117(2), 259–278.