STRUCTURAL DESIGNS AND CONSTRUCTION TECHNOLOGIES FOR CALIFORNIA HIGHWAY BRIDGES

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ABSTRACT: The California highway bridge construction market is the largest in the United States and still growing. It arguably represents the greatest concentration of highway bridge expenditure in the world. To gain insight into this important engineering and construction market, this paper reviews the technological context of California's bridge construction sector from three perspectives: A technological overview, current technological directions, and emerging trends. The paper describes the dominance of the California Department of Transportation in designing and administering highway bridge projects and highlights the emergence of standardized cast-in-place prestressed concrete box girder bridges as the dominant design. Contractors have responded to this standardized design with continuous incremental improvements through adaptation of construction process technologies. The paper concludes that falsework, formwork, and concrete placement technologies are particularly important in gaining and maintaining a competitive advantage for construction of these bridges. This has led to specialized differentiation through firms seeking technological-based market niches.

INTRODUCTION

The Pacific coast states of Washington, Oregon, and California are the major designers and constructors of cast-in-place (CIP) concrete bridges in the United States. The California state highway system contains approximately 15,000 bridges, and another 15,000 have been constructed on local city streets, county roads, and other "off-system" roads (Roberts 1988). (Bridges are classified as structures with spans over 6 m or 20 ft.)

The original data collection and analysis presented in this paper is based on the in-depth interviews with 20 practicing bridge constructors complemented by extensive site visits (Hampson 1993). Each initial interview lasted between two and four hours, supplemented by several shorter follow-up interviews. Interviews were recorded on audiotape and transcribed literally. Transcripts were then reviewed by each interviewee for completeness and accuracy. Professionals interviewed in each firm included the company president, a vice president, a project manager, and a structures superintendent. In this paper, we refer to this group of professionals collectively as "constructors." The firms interviewed in this research carry out approximately 30% of the total bridge contract value awarded by the California Department of Transportation (Caltrans) each year. Interviews with senior Caltrans representatives and comprehensive access to Caltrans records for all 6,500 bridge projects over the 1983–1992 decade provided a second invaluable source of information.

Caltrans is the dominant owner and designer of highway bridges in the California highway construction market and therefore plays a significant role in shaping the technical characteristics of California bridge construction. Between 1983 and 1992, Caltrans designed and administered over 95% of highway bridge projects throughout California. Typical of other public works sectors, Caltrans awards contracts to the lowest conforming bidder. Nevertheless, Caltrans is interested in creating an environment that promotes innovation in bridge construction.

Caltrans construction averaged almost $1.3 billion per year (in 1992 dollars) over the 1988–1992 period. The annual value of contracts involving some form of structural work (primarily bridge construction) averaged almost $1.0 billion per year over this five-year period with the actual value of bridge work alone averaging $450,000,000 per year. Over 250 contractors compete for a share of the $1.3 billion market annually, yet the largest 10 firms are responsible for almost 50% of all prime contracts. These companies are required to perform at least 50% of the work with their own forces, and they handle both larger contracts (over $50,000,000 and smaller ones (less than $5,000,000). Most of the remaining contractors compete for small- to medium-value projects. On average, 650 contracts were awarded each year for the 1983–1992 decade. The average duration of projects greater than $50,000,000 value is 800 workdays (or 3 years and 2 months) while the average duration of projects less than $1,000,000 value is only 80 workdays (or four months).

TECHNOLOGICAL OVERVIEW

This technological overview of bridge construction is structured in two categories: (1) evolution of bridge design, over which construction firms have traditionally had only limited control; and (2) construction process technology, where contractors are able to exert the most control.

Evolution of Bridge Design

Highway bridges can take several forms, depending on structural factors (e.g., span and design loads) and local factors

TABLE 1. Comparative Bridge Costs Used by Caltrans for Preliminary Estimates

Structural section (1)	Common span range (ft) (2)	Cost range (dollars/sq ft) (3)
RC slab	16–44	55–85
RC box	50–120	65–85
CIP PS box	100–600	60–100
PC PS slab	20–50	65–85
PC PS I-beam	50–120	70–95
PC PS Box	120–200	120–200
Str. steel I-beam	60–300	100–190
Str. steel box	60–500	100–250
Cantilever segmental	250–500	130–390

Note: Cost includes 10% mobilization and 20% contingency. Source: Caltrans office of structure design (1992).

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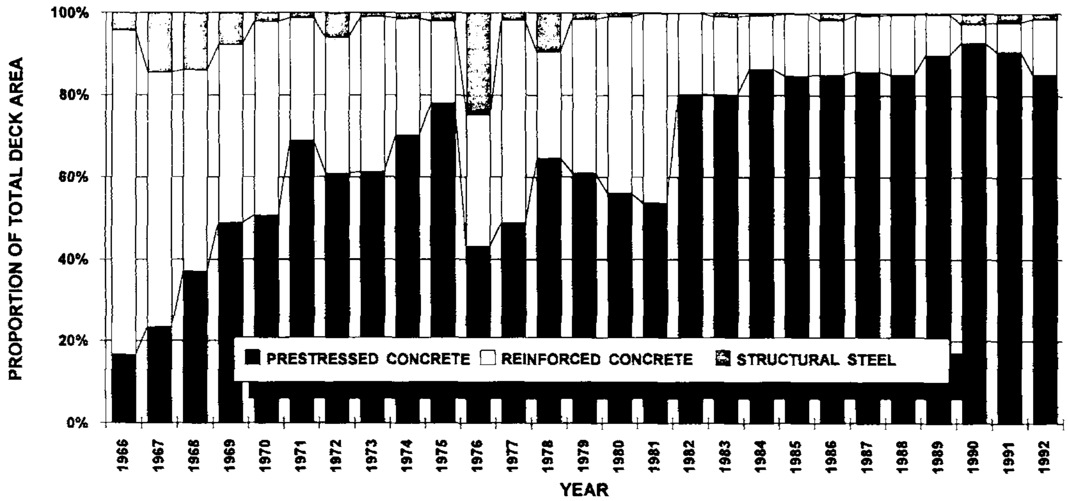

FIG. 1. Proportions of Bridge Structural Type, 1966–1992

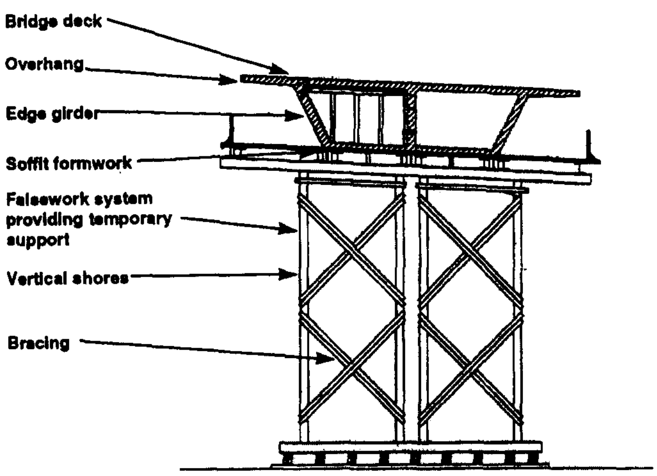

FIG. 2. Cross Section of Cast-in-Place Post-Tensioned Concrete Box Girder with Associated Framework and Falsework

(e.g., availability of raw materials, labor costs, and existing skills). Before World War II, structural steel and concrete were used about equally for California highway bridges. Shortly after World War II, the California Freeway System was born by passage of the Collier-Burns Act, which established gasoline taxes as a permanent economic base for funding major freeway and highway construction. It was also during this period that the CIP concrete box girder bridge was developed and became popular.

Because of its torsional rigidity, structural continuity, outstanding earthquake resistance, ease of construction, low initial cost, suitability for long spans, aesthetics, and low maintenance record, CIP box girder bridges increased in popularity (Roberts 1988). Accordingly, they have become the dominant bridge design form in California. Table 1 shows a section of Caltrans 1992 comparative bridge costs for preliminary estimates, highlighting the suitability for a wide range of spans and the cost advantage of CIP posttensioned box girders (referred to as CIP PS box in the table). Alternative designs are only competitive for very short spans. Roberts (1988) reports that, in California, structural steel bridges typically cost 50% more than a concrete alternative, and only in rare circumstances where optimal site conditions exist for structural steel has the cost disadvantage decreased to 30%. This cost summary represents the unique blend of natural (e.g., aggregate supply for concrete manufacture and lumber for formwork and falsework), and acquired factors of production (e.g., local labor skills and experience) that characterize the California bridge construction market.

Multicell concrete boxes can also be widened without disturbing the basic appearance. Of the 33,400,000 sq ft of new bridge deck completed in California from 1983 to 1992, 87% was posttensioned concrete and 12% reinforced concrete. Only 1% was structural steel—whereas a majority of bridges in the eastern states are supported by structural steel members. Podolny and Muller (1982) acknowledge Caltrans's success in the extensive use of CIP posttensioned box girder construction for multispan structures with spans of 300 ft and longer. Fig. 1 shows the growth of prestressed concrete bridges in California since 1966, and the principal reliance on this form of construction since 1982.

Further emphasizing the dominance of the CIP method of construction in California, the American Segmental Bridge Institute's survey of bridges throughout the United States documents only six precast concrete bridge structures constructed in California since 1964, with only two of these constructed since 1978 (ASBI 1993).

Fig. 2 illustrates the essential elements of the dominant CIP posttensioned concrete box girder form of construction and a typical formwork and falsework system. Caltrans has standardized this design. As one contractor stated during the interviews, "Caltrans bridges are really standardized now—like curb and gutter work. It's mass market stuff." From 1983 to 1992, 93% of the new prestressed concrete bridges used this CIP box girder design. Fig. 3 shows the dominance of this design (referred to as CIP/PS box girder in the figure) within the generic category of prestressed bridges since 1966.

Fig. 4 illustrates the trend in bridge deck area unit cost for Caltrans construction since 1966. Major short-duration variations in the average trend can be explained by major projects (e.g., San Joaquin River Bridge at Antioch during 1976 and Dumbarton Bridge in 1978). For comparison, we used the *Engineering News Record* (*ENR*) Building Cost Index and the Caltrans Bridge Construction Cost Index and converted them to 1992 dollars. The Bridge Construction Cost Index is an internal Caltrans index based on a set of average unit bid rates for 14 bridge construction components averaged over a period of four trimesters. Both indices show an overall increasing trend in real cost per square meter of bridge deck over this 27-year period. [Regressed average of \$8.22/m^2 (\$0.78/sq ft) per year for the *ENR* Index and \$2.74/m^2 (\$0.26 sq ft) per year for the Caltrans index over the 27-year period.] Interestingly, at the time Caltrans made a major transition to prestressed concrete construction, during the 1980–1982 period (see Fig. 1), both indices showed either a falling or an established low

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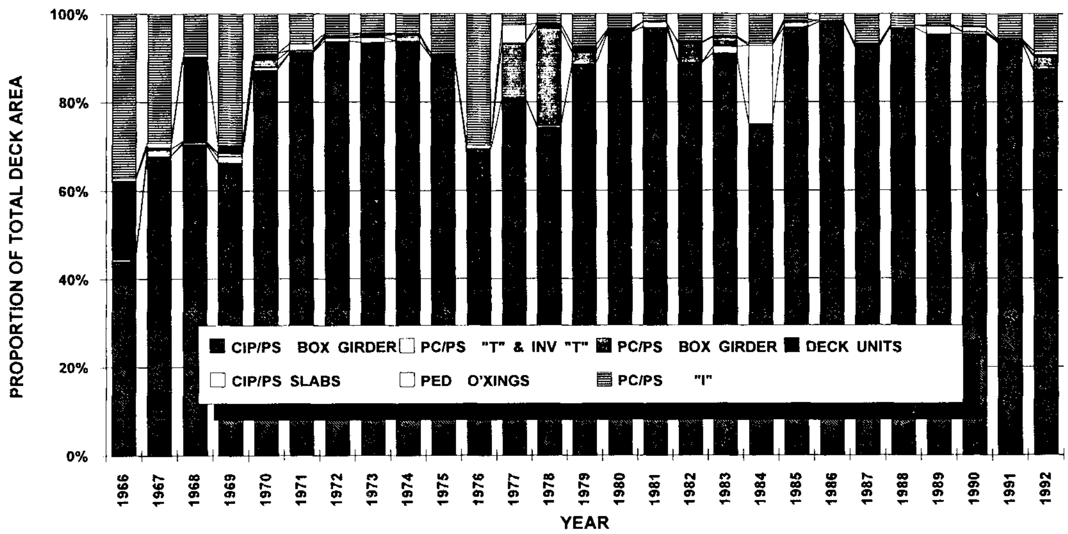

FIG. 3. Proportions of Prestressed Bridge Structural Type, 1966–1992

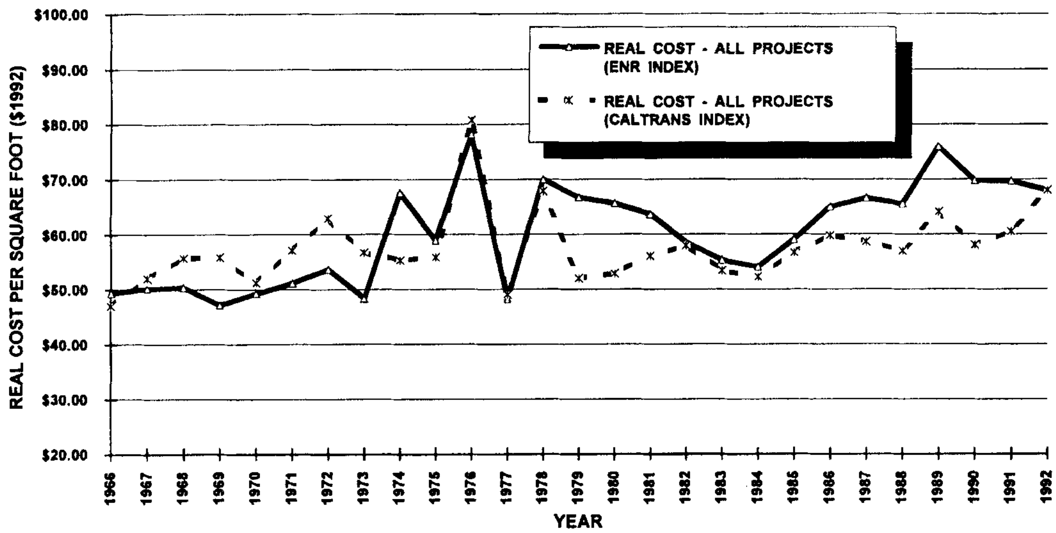

FIG. 4. Cost per Square Foot of Caltrans Bridge Deck, 1996–1992

cost per square meter of deck. However, since 1984, the trend using both indices indicates a rising unit cost. A number of factors contributed to this trend, including more rigorous standards for seismic design of bridges and increased labor costs. Though costs have risen, the CIP posttensioned box girder design maintains a cost advantage over other designs (as shown in Table 1).

Construction Process Technologies

The constructors interviewed throughout this research project consistently identified the three most important technologies in CIP concrete box girder construction as falsework, formwork, and concrete placement and finishing. They based this priority on the significant contributions of labor cost to bridge construction cost—which itself typically averages 60% of the total bridge construction cost. (The remaining costs average 30% for materials and 10% for equipment.) A typical comment from a construction manager interviewed is the following, "Our principal advantage is the falsework and the efficiency of the formwork." These managers viewed placement of reinforcing steel and posttensioning as commodities (where price and delivery terms may vary only slightly among suppliers, but the product is essentially standardized) and subcontracted these services out in virtually all cases. One company president said, "From what we can see, the competitiveness between [three California prestressing companies] is tremendous, so I just don't think the margin is there. I don't think we could realistically match their prices." Another commented, "Rebar is specialty work and there's no margin in it."

Formwork and falsework are used for the temporary support of concrete during construction. The formwork is temporarily supported with falsework from the ground, or can be cantilevered off parts of the previously built structure. Typically falsework supported from the ground is used (as shown in Fig. 2), unless the bridge is either very high (in which case series of intermediate supports are uneconomic), or it is spanning over deep water. Caltrans estimates that contractors build more than 90% of all California highway bridges using ground supported falsework.

Falsework Methods

Falsework is a very significant element of bridge construction—accounting for approximately 25% of total construction costs. Furthermore, while concrete placement and formwork methods are reasonably standard, falsework provides an important opportunity for differentiation among competitors. As one construction manager said, "Falsework is the key to the whole job." Falsework technology determines a firm's ability to bid on higher bridges and heavier loads (typically part of contracts valued over $15,000,000) which have

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become increasingly important in multilevel highway interchange projects.

In the last few decades several changes in falsework technology have taken place. Today, contractors use four primary systems: Steel scaffolding, steel towers, heavy timber posts, and steel pipe.

Proprietary steel scaffolding as shown in Fig. 5 (known throughout the industry as "tinkertoy"), typically consists of square base frames 4 ft wide × 6 ft high. Its load capacity is usually 10 kips per leg. (1 kip = 1,000 pound force = 4.45 kN.) This requires a large number of frames to support temporary bridge construction loads, and is very labor intensive during erection and dismantling. Each of the firm's constructors interviewed in this research acknowledged the passing of the era for proprietary steel scaffolding in California bridge construction. A comment typical of the constructors interviewed was, "We used to use a patented scaffold system—"tinker toy." I guess in those days labor was cheap, but the system was essentially inefficient. We now use post and timber, which is more labor efficient, and steel pipe for heavy loads and high bridges. We can cut and cap pipe and put it in place cheaper than a scaffold tower."

Steel towers typically consist of frames 3 × 3 m (10 × 10 ft) in plan, with heights of (1.5, 3, or 4.5 m (5, 10, or 15 ft). Contractors individually assemble them to match the required bridge height. Generally, each vertical corner leg has a capacity of 445 kN (100 kips). Until the early 1970s, steel frames were the dominant falsework system, with towers used only for high or heavily loaded bridges. California bridge contractors still regularly use steel towers up to heights of 30 m (100 ft). Fig. 6 illustrates a high steel tower system capable of supporting 2,670 kN (600 kips).

Heavy timber post systems consist of 300 × 300 mm (12 × 12 in.) wood posts with load transferring beams at top and bottom, and intermediate bracing. Such a system is built either as a tower, or in a panel unit or "bent" across the width of the bridge. Each post has a maximum allowable load capacity of 757 kN, 170 kips, but for safety reasons designers typically use only 579–668 kN (130–150 kips). Wood posts are today the dominant vertical shoring method for bridges up to 9 m (30 ft) high. Substantial lateral bracing is required to control buckling of these vertical wood posts under temporary construction loads. Fig. 7 shows typical 300 × 300 mm wood posts and steel beams in use for a two-span low-level overpass of an existing freeway. At heights greater than about 9 m, construction of "pony-bents" is required to allow use of wood posts. Pony-bents are a second timber frame on top of an existing frame using an intermediate platform, as shown in Fig. 8. This reduces the effective buckling length of the timber posts and increases the availability of suitable-length lumber.

Steel-pipe falsework systems use steel pipe of 450, 500, or 550 mm (18, 20, or 22 ft) diameter for temporary support (Fig. 9). A typical 550 × 7mm (22 × 0.281 in.) pipe has a maximum allowable capacity of 1,024 kN (230 kips), but approximately 757 kN (170 kips) is generally used. The pipe is nor-

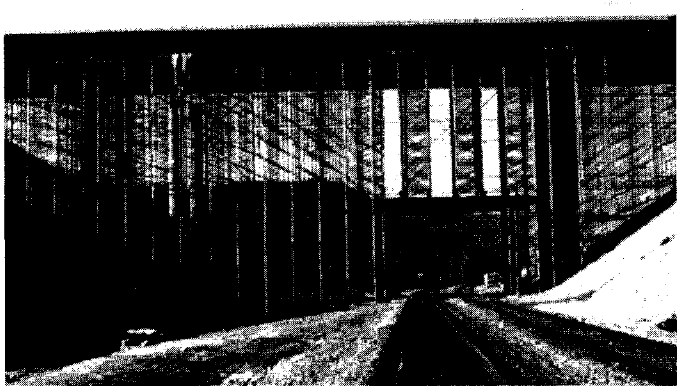

FIG. 5. Steel Scaffolding "Tinker-Toy" Falsework

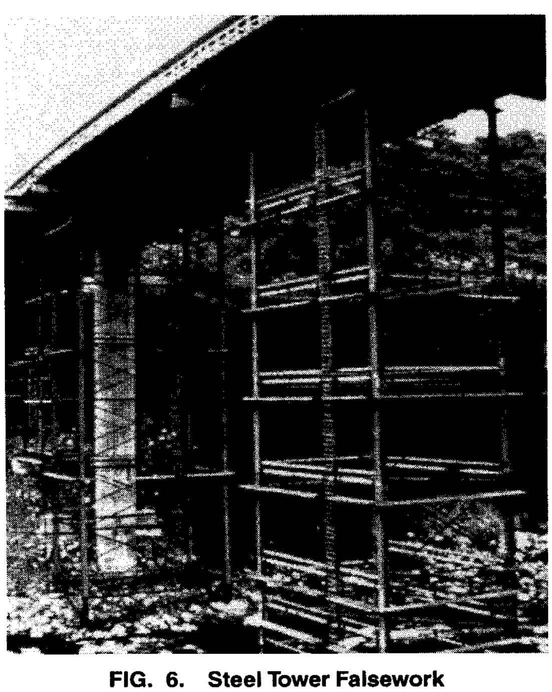

FIG. 6. Steel Tower Falsework

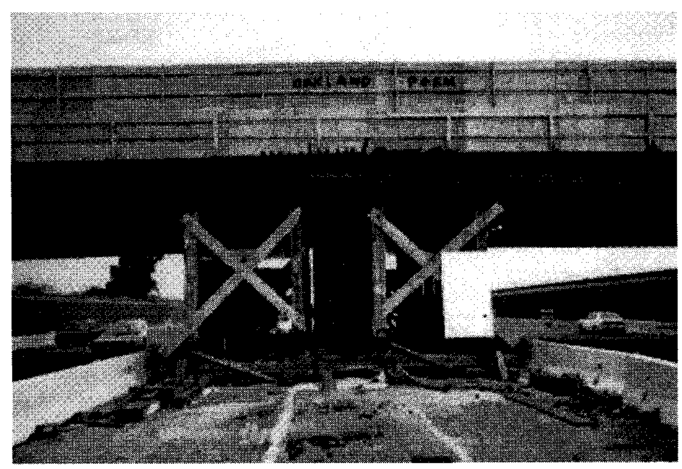

FIG. 7. Heavy Timber Post Falsework Used on Low-Level Bridge

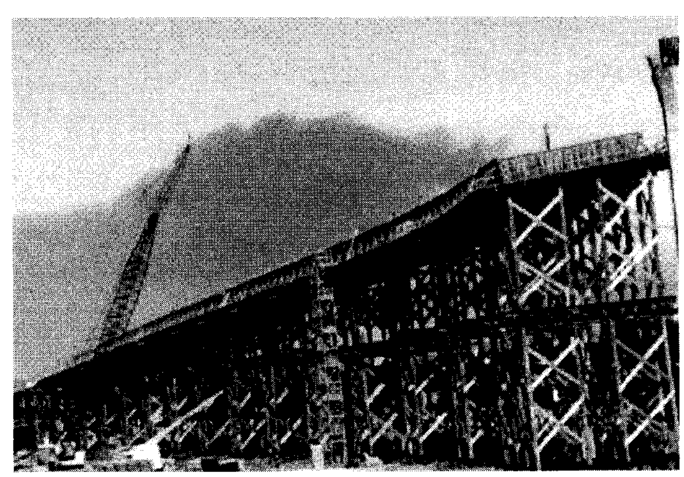

FIG. 8. Two-Tier Timber Falsework for High-Level Interchange Construction

FIG. 9. Steel Pipe Falsework

mal mild steel that can readily be cut and welded on site. The initial applications of this system used recycled oil or gas pipe, but today many firms purchase new pipe. Contractors prepare pipes on the ground to the required height, lift them into position, and place them on sandboxes or wedges, then brace to existing pipe bents using prestressing cable or steel reinforcing bars. Intermediate bracing is much reduced compared to wood posts due to the higher relative strength of steel compared to wood and the larger cross-sectional dimensions of the pipe. Following construction of the permanent bridge structure, sand is emptied from the sandboxes or the wedges removed to lower the pipe and to remove the entire falsework and formwork system. Steel pipe falsework was first used in California bridge construction in 1973. One major firm has focused its efforts on the development of this system, with about 60% of all its recent projects constructed using steel pipe falsework. Nevertheless, it was not until the last 10 years that this system gained wide acceptance in the California bridge contracting community. Labor-cost savings during erection and dismantling are its major benefits. Steel pipe falsework provides maximum benefit for heights in excess of 9 m (30 ft).

Formwork Methods

Construction managers reported that, on average, formwork accounts for approximately 20% of total bridge construction costs. Fig. 2 illustrates the major elements of the falsework and formwork system. Fig. 10 specifically shows the soffit and girder stem forms and deck forms for CIP concrete box girder construction. A concrete construction joint between the stems and deck is typical. The basic tenet of formwork in California bridge construction is to "minimize labor costs and look to efficient and safe use of materials." Progressive contractors

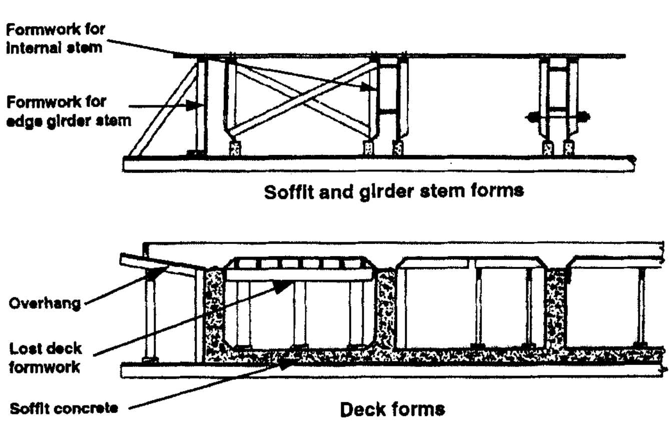

FIG. 10. Forming System for CIP Box Girder Construction

prefabricate formwork where possible to maximize reuse of materials.

Construction managers identified stem and lost deck (sacrificial) formwork as a particularly important element of the formwork system. Fig. 10 illustrates these elements in the typical box girder bridge cross section, typical in California (as shown in Fig. 3). More progressive contractors with larger contract volumes prefabricate stem and lost deck formwork units in the home office yard using specialized carpentry equipment and less costly off-site and dedicated labor. Firms often use apprentice carpenters for this repetitive task. One firm identified the lack of prefabrication as one possible reason they were not more successful. "There is potential for more high-volume prefabrication, but we haven't got to that yet—and that might be why we don't have the bigger jobs."

Stem forms can be either throwaways or gang (multiple-use) forms. The heights of the box girder bridge stems may vary from 450 to 2,400 mm (1.5 to 8 ft). Economic balance between cost of materials and labor for erection, stripping, maintenance, and reuse (for gang forms) provides a potential area for a firm to gain competitive advantage. Higher stem form requirements [above approximately 1.2 m (4 ft)] with potential for reuse on the project may favor the use of gang forms. However, gang forms require relocation via cranes, hence crane use and access are important criteria. Often internal deck forms use tilted-up stripped stem forms.

When the bridge decks are placed, there is yet no economical way to remove the deck formwork; it remains inside the internal cells forever—hence, the term "lost" deck formwork. Therefore, the challenge is for firms to optimally balance cost and safety. Too substantial of a plywood and support system and that costly material is lost forever; too flimsy the system (e.g., light-duty plywood with little support) and the contractor risks failure during placement of deck reinforcement—or worse, during concreting, with expensive repercussions. Most contractors use 3/8 in. plywood with 2 × 4 in. (50 × 100 mm) Douglas fir supports at 1 ft (300 mm) centers. "Just enough to get you by," explained one superintendent. "You use all your rubbish up in these areas."

The selection of primary support for the soffit plywood depends on the type of falsework system used (Figs. 2 and 10). Joists of 2 × 6 in. (50 × 150 mm), 4 × 4 in. (100 × 100 mm), or 2 × 8 in. (50 × 200 mm) are all used. The formwork designer must again optimize for strength, deflection, installation labor, and the much vaunted "mug factor"—the need to make systems as foolproof and safe as possible using site construction labor.

As Caltrans progresses toward more aesthetic design of freeways, designs more frequently involve curved edge girders (Fig. 10). Prefabrication of trusses in specialized carpentry workshops and subsequent transport to site has proven successful for more progressive contractors. One further step used with success on a large Century Freeway interchange in Los Angeles was the prefabrication of complete panel cells incorporating soffit, external edge girder, and overhang. This innovative approach reduced labor costs, improved safety, decreased material waste, and lessened equipment requirements.

Placing and Finishing Concrete

Construction managers identified concrete placement and finishing as the third most important area of labor costs, behind falsework and formwork.

Each firm interviewed uses concrete pumps and their own labor for placing concrete in bridge structures. A number of the larger firms own concrete pumps and rent them to other construction contractors when not using them themselves or have long-term relationships with concrete pumping firms. (No such relationships were found for the supply of ready-mix con-

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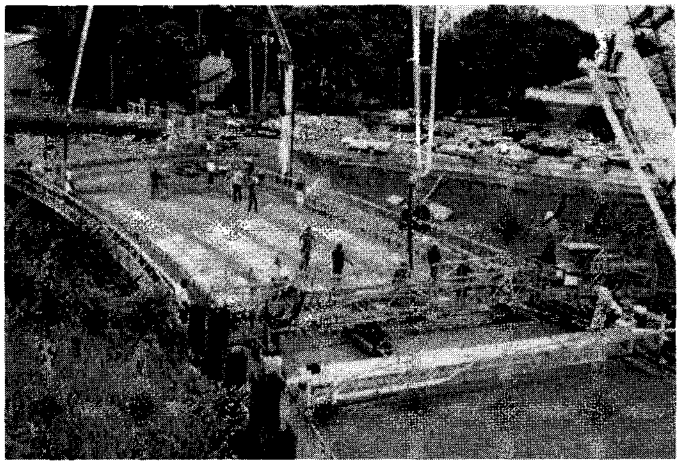

FIG. 11. Bridge Deck Pour in Operation

crete.) On a typical bridge project of six months duration, pumping equipment is used for only six to eight days—so only large contractors can economically justify the purchase of this equipment. Optimization of the size and skills of the labor crew was described as a "real win/lose situation." Too small a crew can result in not achieving the quality required (especially under adverse conditions, e.g., wind or rain). With too large a crew, labor costs quickly escalate. Most of the managers interviewed consider placement and finishing a specialized task and identify valued formen responsible for concrete placement throughout the company.

All firms interviewed handled concrete finishing in-house, "It's too important to leave to anyone else." Achieving accurate deck pours avoids the need for expensive and time-consuming concrete grinding to meet Caltrans tolerances. All firms owned rail-mounted, mechanized, vibrating concrete-finishing machines. "They're the industry standard," commented one manager, "You really do need a mechanized screed for labor saving reasons and to achieve Caltrans tolerances." He then went on to highlight the importance of setting up and operating the machine correctly. Fig. 11 shows a bridge deck pour in operation. This illustrates the use of concrete pumping equipment, a concrete finishing machine, and the high labor content of this work.

CURRENT TECHNOLOGICAL DIRECTIONS

Technological advance in California bridge construction is characterized by continuous incremental improvement. Caltrans has focused on CIP posttensioned box girder bridges, and the local construction industry has followed suit with steady advances in construction processes. For example, one construction manager referred to his company's innovative development of a mechanized falsework system, "It's not high-tech, but it's a refinement and combination of different ideas into a system that works. We took some different ideas and developed, combined, and refined them." Another quotation highlights the incremental nature of technology advance in this sector, "Innovation in this type of construction is one of refinement rather than one of major breakthroughs. It is not a high-tech industry."

The industry is mature, and technological advances are relatively minor compared with many manufacturing sectors. The actual rate of advance is difficult to quantify, but the following quotation provides some perspective, "We can now form and strip a bridge for what it used to cost us to form only, in terms of crew hours. Through a larger investment in capital equipment we've been able to get this sort of improved labor productivity." This advance is not across-the-board, however, as the vice president of one small firm indicates, "Crew hours per square foot of formwork from 20–40 years ago are generally much the same as we're working to today. Maybe what you pick up over the years in productivity improvements in equipment technology you may have lost in personal commitment and exertion."

Caltrans largely controls the direction of technical advance in bridge construction in California. For example, contractor-generated innovation in fabrication and erection of structural steel or precast bridge elements is unlikely to develop in a state where contractors' livelihood depends upon competency in CIP concrete construction.

Specific advances or trends since 1983 include increased industry adoption of steel pipe falsework, and the resultant incremental improvement of the system, including the use of posttensioning cable for bracing, handling and stripping equipment, brackets, and standardized connections. This adoption occurred in a period of relative price stability for lumber. One firm in particular has differentiated itself as the principal proponent of steel pipe falsework. It has also developed a state-of-the-art falsework stripping crane fitted with a hydraulic table and grip-like jaws, "We can level it, dump it, and it's got hydraulic pins that come up and positively clamp the beams." This stripping bracket can remove and lower wood or steel soffit support and complete steel pipe falsework bents. Contractors then cut up or reuse the steel pipe falsework as required.

Alongside the use of more steel pipe falsework, there has been a concomitant reduction in the differences in falsework inventory by competitors in the state. Most large contractors now have wood posts, steel towers, and steel pipe in their falsework inventories (to varying degrees) and are developing skills for each type. This flexibility is considered a key element of future competitiveness. For example, one construction manager said, "The option of using wood posts, steel pipe, or steel towers gives us increased flexibility to go whichever way we see an advantage." Nevertheless, simply purchasing inventory of each falsework type does not ensure its efficient use. For example, one firm's structures superintendent said, 'I have used steel pipe once and thought it went all right, but I wasn't happy with the costing results. We didn't do real well—and I want to get that money back on a similar bridge we've got coming up. I'm going back to the 12 by 12 ft wood posts. I don't know what went wrong but I know exactly what I can do with wood." Reducing uncertainty (and maintaining project safety) by relying on tried-and-true construction methods is common.

Another trend is increased prefabrication of components to reduce site labor costs, including stem and deck forms and external girder, complete girder, and soffit truss cells. This move to prefabrication is also associated with increased task specialization. One manager likened his standardized projects to the factory environment. "We try to have dedicated work crews setting up for the soffit, stems, lost deck, and stripping. For large jobs, this can almost be like assembly-line work with the one crew carrying out the same jobs."

Also since 1983 there is greater centralization of engineering capabilities at head offices; this is encouraged by the standardization of constructed facilities and advances in communication technologies, including facsimile machines and mobile radios and telephones. Distributing the cost of home office–based technical staffing over a number of projects and having production-oriented superintendents on site has allowed a number of successful California bridge construction firms to operate "lean and mean" as they describe themselves. Senior managers of these firms view this ability as a major weapon in their arsenal to retain an advantage in this market over more engineering-oriented national or international heavy construction contractors.

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Finally new technological niches have been established, with realignment of firms for specialized differentiation (e.g., earthquake retrofit, high-occupancy vehicle structures, high interchanges, and redesign capabilities).

These trends have occurred while CIP posttensioned box girder bridges remained the dominant structural form, and large value, internally repetitive structural projects increased as a proportion of total highway expenditures. Additionally, a depressed private sector allowed incumbent structural contractors to maintain or enhance their specializations and engage in increased administration of highly competitive earthwork and paving subcontractors, especially minority and women business enterprises.

EMERGING TECHNOLOGICAL TRENDS

A number of emerging technological trends are likely to affect the California bridge construction market. Some of these trends were identified from interviews with constructors, while others were distilled from a broad review of industry publications and background literature.

Emerging technological trends include the reduction in use of forest products due to lumber price increases and environmental concerns. The cost of lumber has been volatile in the past few years. For example, the cost of softwood lumber rose 38.5% in the 12 months between March 1992 and March 1993, whereas average plywood prices rose 25.0% over the same period (*ENR* 1993). Firms will likely maximize reuse of forms (e.g., more stem gang forms), minimize use of plywood (e.g., precast concrete planks instead of lost deck formwork), and increase use of steel pipe falsework instead of heavy section wood shoring. Should these price increases continue, precast concrete elements inevitably become more competitive, since they use no site formwork and minimal falsework. One caveat that Podolny and Muller (1982) placed on the use of CIP posttensioned construction was that the extensive formwork used during casting often has "undesirable effects on the environment." Should a trend away from this dominant form of construction occur, existing firms may experience difficulty in overcoming inertia of existing skills, inventory, and equipment to maintain competitiveness in this large construction sector. Large out-of-state engineering contractors have a broader base of skills and may start to provide strong competition for incumbent, technologically focused California firms.

In addition, project types are changing, requiring an enhanced multidisciplinary approach and more advanced technical capabilities. Mass-transit projects may require increased interaction with mechanical and electrical contractors or subcontractors; privatization projects require design/build capabilities; major earthquake retrofits demand high-level technical and coordination skills on site and nonstandardized shoring for heavy loadings. One construction manager commented on the value of redesign capability, "We're the leading proponents of redesign in California. Most of our larger projects have been redesigned in some form—it's an established principle that we operate on." Contractors cannot immediately acquire these new capabilities, and they may require long-term mutual alliances or joint ventures to remain competitive.

Finally, there will be further focus on specific niches to develop and maintain the technical skill levels required for success in new markets (mass-transit projects, design/build). The determination of which niche or niches to target and how to achieve the requisite capabilities for successful performance in that niche will become a strategic priority for firms.

CONCLUSIONS

This paper provided a technological overview of California highway bridge construction and identified a number of key technological trends occurring throughout the 1983–1992 period. Technological advance for this construction sector occurs in continuous incremental improvements. We identified emerging trends of potential significance to established bridge construction firms.

Technologically, California remains firmly reliant on the CIP posttensioned box girder bridge to carry its burgeoning population of motor vehicles. As the dominant owner and designer, Caltrans has adopted the CIP posttensioned bridge for 87% of all new bridges in the state. Construction contractors have focused on this form of construction and developed incremental process improvements to attack the primary cost driver of labor. Standardization of the constructed product and the associated reduction of site uncertainty has supported centralization of technical capabilities in the construction firm's home office, where contractors can distribute this cost over a number of projects.

A firm's technical capabilities are significantly affected by the evolution of broader areas of technology of which they are a part (Burgelman and Rosenbloom 1989). Porter (1983) identifies technology as one of the major factors affecting the nature of competition. Firms are differentiated in California bridge construction by their approach to technology, and constructors believe this effects their competitiveness in this sector. Construction managers identified falsework, formwork, and concrete placement as the important technologies in this sector for providing competitive differentiation. Firms have successfully increased their specialization and targeted specific niches. The emergence of new niches entailing new technological characteristics provides fresh challenges for managers of established bridge construction firms.

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APPENDIX. REFERENCES

ASBI. (1993). "Segmental bridges constructed in the United States and Canada." *Rep.*, American Segmental Bridge Institute, Phoenix, Ariz., Sept.

Burgelman, R. A., and Rosenbloom, R. S. (1989). "Technology strategy: An evolutionary process perspective." *Research on technological innovation, management and policy,* Vol. 4, R. S. Rosenbloom and R. A. Burgelman, eds., JAI Press Inc., Greenwich, Conn., 1–23.

ENR. (1993). "Construction economics—Materials prices." 230(20), (May 17), 45.

Hampson, K. (1993). "Technology strategy and competitive performance: A study of bridge construction," PhD thesis, Dept. of Civ. Engrg., Stanford Univ., Stanford, Calif.

Podolny, W. Jr., and Muller, J. M. (1982). *Construction and design of prestressed concrete segmental bridges.* Wiley & Sons, New York, N.Y.

Porter, M. E. (1983). "The technological dimension of competitive strategy." *Technological innovation, management and policy,* Vol. 1, R. S. Rosenbloom, ed., JAI Press, Greenwich, Conn., 1–33.

Roberts, J. E. (1988). "Aesthetic design philosophy utilized for California state bridges." *Proc., Visual Design Guidelines for Transp. Fac. Session, ASCE Nat. Convention,* ASCE, New York, N.Y.

J. Constr. Eng. Manage., 1997, 123(3): 269-275