Prestressed Concrete: The State of the Art in North America

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The prestressed concrete industry in North America is neglecting its research and development responsibilities. There is a need, also, to attract young people into the industry to help it flourish and grow. Despite minimal R&D efforts, the prestressed concrete industry is producing exciting developments in high strength materials and structural concepts, and excellence in building and bridge designs. The author discusses specific examples, including epoxy coated prestressing strand, the optimized bulb T-section and various box section configurations, as well as the growth in segmental and cable stay bridges. The increasing role of the computer is examined.

Although this article deals specifically with the state of the art of prestressed concrete in North America, it will be helpful to begin our discussion with a broader view of the North American construction industry and the role of research and development (R&D) in that industry.

In a nutshell, the construction industry in North America is diverse and fragmented, its financial position is cyclical, and there is little organized attention given to R&D activities.

Table 1 shows R&D expenditures for several industries in the United States, as reported in the July 8, 1985, issue of *Business Week*. Although the construction industry had the largest sales figure, the table indicates that there was no discernible pattern of organized R&D spending by construction industry firms. In a 1988 report,[1] the National Research Council estimated that not more than 0.4 percent of construction industry sales was invested in R&D. This is considerably below the investment in the future made by other major industries.

R&D data for the prestressed concrete industry is even more discouraging. R&D expenditures are also hard to determine, since research by product manufacturers is not publicly reported. However, my discussions with major post-tensioning systems manufacturers have given me some idea of their expenditures. In addition, the Precast/Prestressed Concrete Institute (PCI) estimates that R&D expenditures by pretensioners and precasters are about 0.1 percent of annual sales.

Note: This article is based on a paper presented at the Eleventh FIP Congress in Hamburg, Germany, June 7, 1990.

Table 1. R&D expenditures in the United States for 1984. (Source: *Business Week*, July 8, 1985.)

Industry	Sales $ billion	R&D $ billion	Percent
Drugs	53.6	3.8	7.1
Aerospace	61.8	2.9	4.8
Automotive	169.2	5.7	3.4
Chemical	119.3	3.6	3.1
Construction	350.0	—	—

From a wide range of respondents, I developed the data shown in Table 2. My R&D figure of 0.083 percent appears to be in good agreement with the PCI estimate of 0.1 percent. As Table 2 shows, pretensioning sales volume is greater than that of post-tensioning — a traditional pattern in North America. Sales for the prestressed concrete industry total $4.2 billion; about one third of that is for bridges.

Examining the bridge data gives a clearer picture — we know the R&D expenditures and the actual construction volume. In this most highly organized sector of prestressed concrete owners, annual research dollars amount to 0.14 percent of bridge construction volume. From this, I have concluded that, in North America, we are spending about 0.15 percent of revenues on prestressed concrete R&D. That is less than half the R&D expenditures of the overall construction industry, and less than one-thirtieth of R&D spending in the more consumer-oriented manufacturing industries.

Despite several significant innovations in the use of prestressed concrete in modern structures, one must conclude that, in North America, this industry is neglecting its R&D responsibilities.

The major sponsors of prestressed concrete research are federal and state highway departments and national research foundations. Universities undertake 45 percent of the research effort, carrying on the work in 12 universities mostly located in the traditionally strong prestressed concrete market areas of Texas, Florida, Pennsylvania, Washington and Louisiana.

The prestressed concrete industry itself provides another 35 percent of the research, mostly by manufacturers in-house; the carefully coordinated PCI research program, which provides a balance between PCI-funded research projects meeting specific industry needs and an ongoing research fellowship program to generate student interest in prestressed concrete, has been very useful. Consultants and private laboratories undertake 15 percent of the research work, and the remaining 5 percent is done by government laboratories.

New Talent Needed

There is another serious vacuum emerging in the prestressed concrete industry. In our highly technical world, young people feel that the future lies with computers. The technically qualified are opting for careers in computer science and electrical engineering, and are generally not choosing civil engineering. They see astronomical growth and development in electronics, which has moved from vacuum tubes to transistors to integrated circuits in just a few decades. We do a poor job of pointing out that our industry shows a similar potential for change.

Despite all this competition, we do see change. For example, a recently completed 58-story building in Seattle, Washington, was designed using 14 ksi (96 MPa) concrete columns where actual concrete strengths reached 18.5 ksi (130 MPa). In the laboratory, researchers have made 29 ksi (200 MPa) concretes. We need to study how best to use these exotic materials in practical applications.

On a more day-to-day level, the practical attainment of very high strength concretes with compressive stresses of 10 to 14 ksi (69 to 96 MPa) has become routine. For example, additives such as microsilica fumes and high range, water reducing admixtures have made possible the use of 10 ksi (69 MPa) columns in an 18-story precast concrete condominium in Delaware and the routine use of 9 ksi (62 MPa) long span, pretensioned girders in Texas.

Table 2. Sales volume and research expenditures in prestressed concrete in the United States and Canada (1990).

Overall sales		
Pretensioned (precast)	$2.7 x 10^9$	
Post-tensioned	$1.5 x 10^9$	
Total	$4.2 x 10^9$	
Overall research		
Known expenditures	$3.5 x 10^6$	0.083%
PCI estimate	$4.2 x 10^6$	0.1%
Bridge sales	$1.3 x 10^9$	
Bridge research	$1.85 x 10^6$	0.14%

Similar developments have taken place in steel tendons, where oversize 0.5 in. (12.7 mm) strand, 9/16 in. (14.3 mm) strand, and 0.6 in. (15.2 mm) low relaxation strands are now common. A 300 ksi (2100 MPa) strand has been introduced, and there have been experimental uses of Kevlar and fiberglass tendons for anti-corrosion and nonmagnetic applications.

The future is here today, yet we let young people think we are an old and stodgy industry. If we do not win the battle to attract bright, young men and women to our industry, we will ultimately perish.

Concern for Durability

Worldwide, there has been great concern about durability, especially in materials for structures that are subjected to harsh environments such as freezing temperatures and saltwater, and deicing salts, sulfates and pollutants.

In North America, the 1989 ACI Building Code features a new chapter devoted to the issue of durability. That ACI Code mandated the latest Post Tensioning Institute standards for improved corrosion protection of unbonded tendons. Unbonded tendons used in corrosive environments must be completely encapsulated and be further protected with high quality greases. The Canadian Standards Association has issued strict durability related guidelines for parking structures.

Considerable emphasis is still given to high quality concrete as the first line of defense against corrosion, but electrically isolated tendons, the use of plastic ducts, and improved grouting provide additional low cost insurance.

For example, an electrically isolated tendon assembly developed and patented by Schupack and Suarez completely encapsulates the tendon (including anchorages) in an electrically insulated plastic to protect it from stray currents. Schupack and Suarez report that the extra cost to incorporate their tendon

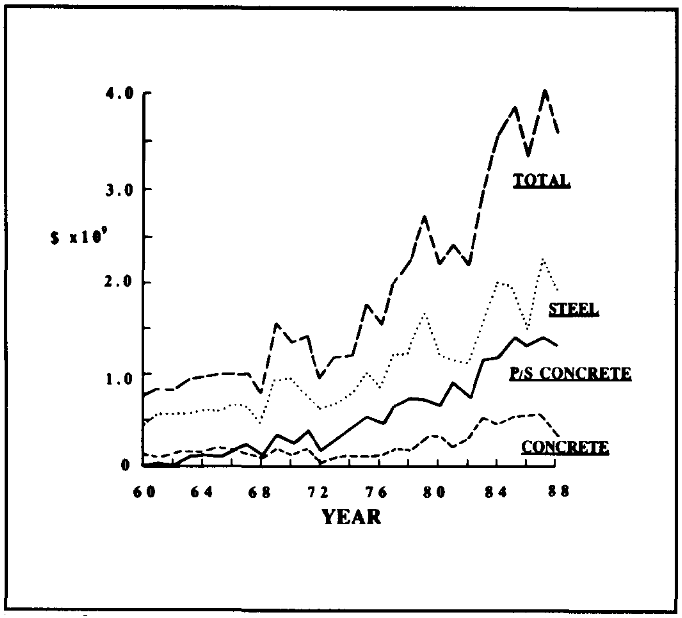

Fig. 1. Dollars spent on bridge construction in the United States.

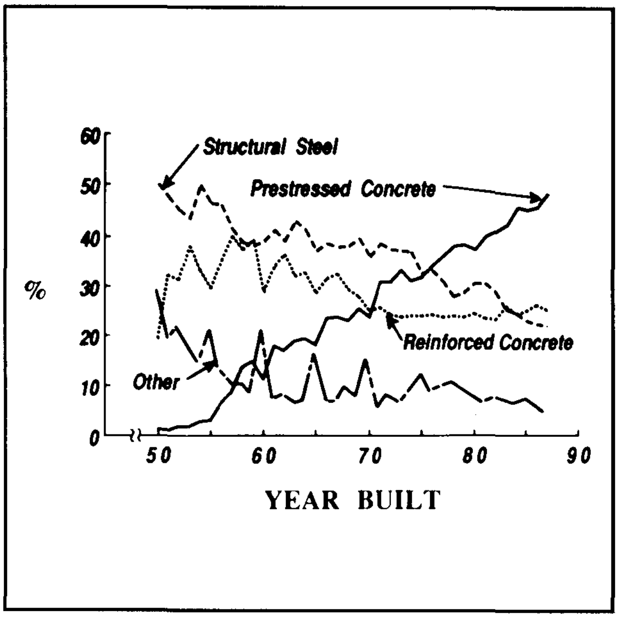

Fig. 2. Percentage of bridges built in the United States.

assembly into a large parking structure was only 1 percent of the structure's total construction cost — a modest premium to eliminate the cancer of corrosion.[2]

An exciting recent development has been the major effort by Florida Wire and Cable Company to develop and bring to commercial production an epoxy coated prestressing strand. The epoxy coating, which is extremely tough, can be used with or without an impregnated grit. The grit improves bond, giving development length and transfer length characteristics equal or superior to uncoated strand.

A recent NCHRP study[3] indicated excellent creep characteristics and found "epoxy coated prestressing strand to be remarkably tough and effective against corrosion in both pretensioned and post-tensioned applications." Although epoxy coated strand costs about twice as much as bare strand, it may be a useful alternative in highly corrosive environments. As larger scale production gets underway, the cost differential should decrease.

Because there are concerns over the behavior of the epoxy coating at high temperatures, it is not recommended for members requiring a fire rating until further fire tests have been completed. There is also evidence that epoxy coated strand requires greater edge distances than uncoated strand to prevent cracks from radiating from the strand to the concrete surface.

Advances in Bridge Construction

Overall construction spending for highways in the United States, as a percentage of gross national product, has fallen far below the golden decade from 1960 to 1970. Yet dollars spent on bridge construction have continued to grow (Fig. 1), although much of the growth reflects inflation. Fig. 2 shows the dramatic growth in prestressed concrete bridge construction compared to other types of bridge construction. The number of prestressed concrete bridges is steadily growing because of their advantageous first costs and lower maintenance costs.

Modern prestressed concrete bridges are replacing traditional steel bridges in the medium and moderately long span ranges. An excellent example is Ontario's Burlington Skyway Bridge (Fig. 3). The new prestressed concrete segmental bridge in the foreground was designed and built as a twin of an existing steel bridge.

Several new interesting structural concepts for bridges have been developed in North America. For moderate spans, the bulb-T section originally introduced by Dr. Arthur Anderson (Fig. 4) has been refined and reintroduced as an optimized PCI section with an improvement in flexural efficiency when compared to the traditional small-flange AASHTO sections. As Fig. 5 shows, the cost index of the optimized bulb-T is significantly lower than that of traditional AASHTO sections in the 82 to 148 ft (25 to 45 m) span ranges.

Probably one of the most significant current developments in prestressed concrete structural systems throughout North America has been the explosive growth of segmental and cable stay bridges. Structural concepts and erection methods for this bridge category have undergone considerable evolution. The somewhat stodgy, technologically conservative, and increasingly managerially fragmented bridge construction industry reported unfavorable experiences with some segmental and cable stay bridge projects; however, in many cases, the problems arose because their management personnel were unfamiliar with the new technology.

A new organization, The American Segmental Bridge Institute, has been founded to advance design and construction technology and to provide a resource bank of information for designers and constructors. Under the leadership of the Post Tensioning Institute, a comprehensive new design and construction guideline, "Design and Construction Specification for Segmental Concrete Bridges," was developed under a NCHRP contract and was adopted as an interim standard by AASHTO. The guideline should greatly reduce conflicts and confusion.

There has been a wide variety of applications of external tendon bridge concepts. Many current projects blend

Fig. 3. Burlington Skyway Bridge, Ontario, Canada.

Fig. 4. Early bulb-T section. (Courtesy: Dr. Arthur Anderson)

Fig. 7. Philadelphia Airport structure (Pennsylvania).

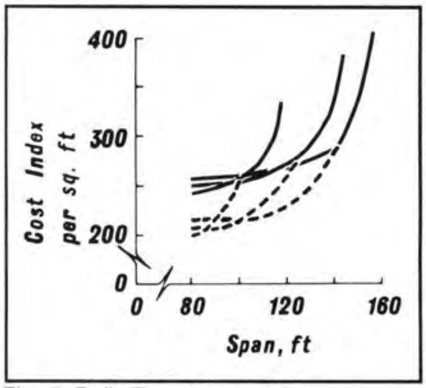

Fig. 5. Bulb-T cost comparison. (Courtesy: Portland Cement Association)

internal and external tendons to achieve improved ductility and seismic resistance. A highly original concept was used for the James River Bridge near Richmond, Virginia (Fig. 6). Here, two traditional, single cell precast concrete box girder units were erected and then joined by a precast concrete delta frame and struts to provide attachment for a single plane of cable stays. We now see concrete cable stay bridges being used in more moderate spans that had previously been the nearly exclusive province of steel girders.

Precast, pretensioned concrete curved box sections, such as those used in the Philadelphia Airport project (Fig. 7), have been introduced. Eye-catching projects for elevated transitways, such as the Atlanta MARTA (Fig. 8), use the span-by-span erected external tendon box girder system.

The Sunshine Skyway Bridge (Fig. 9) on the west coast of Florida, designed by Figg and Muller Engineers, is a stunning example of structural efficiency combined with sheer beauty. This handsome addition to one of America's major tourist areas enhances vehicular access and is, in its own right, an object of universal interest.

Building Construction

The United States and Canada have long been leaders in the use of precast, prestressed concrete products for buildings. The industry continues to flourish and, with maturity, offers quality, economy, and most importantly, aesthetically appealing products. Fig. 10 shows an example of an attractive random rib, exposed aggregate precast concrete wall panel that will contribute to an architecturally satisfying building.

Fig. 6. James River Bridge (near Richmond, Virginia).

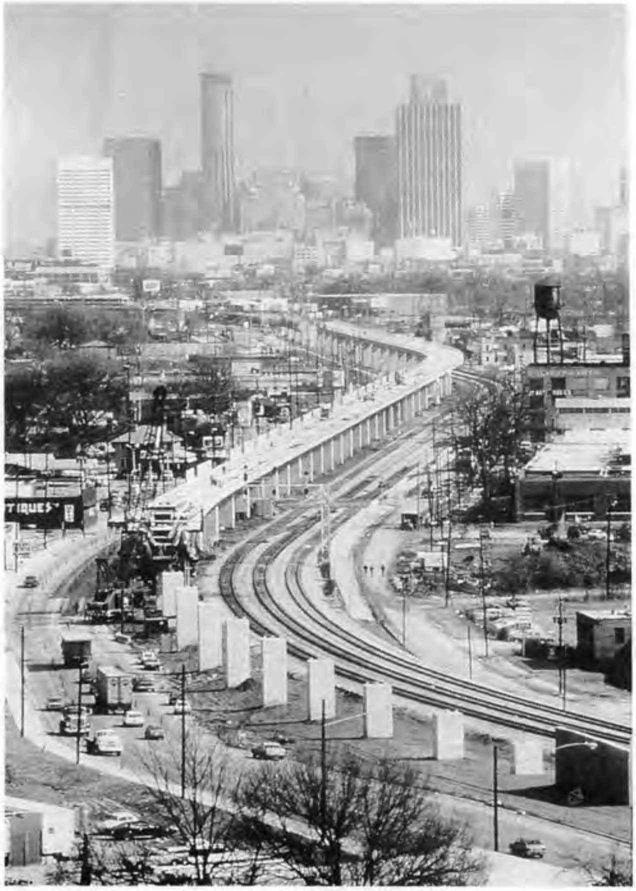

Fig. 8. Atlanta MARTA project (Georgia).

Fig. 9. Sunshine Skyway Bridge, Tampa Bay, Florida. (Figg and Muller Engineers)

Exciting precast concrete buildings such as the Park Plaza Condominium in Wilmington, Delaware (Fig. 11), incorporate the latest precast concrete technology. This handsome structure with 65.6 ft (20 m) spans was assembled from 6000 precast concrete components, including columns made with 10 ksi (69 MPa) concrete using microsilica fume additive.

The trend toward using slender precast concrete members is found in Mexico, where pretensioned long span girders are combined with pretensioned hollow-core slabs into very efficient load carrying systems (Fig. 12).

Similarly, the efficiency and versatility of post-tensioning was a key factor in a St. Paul, Minnesota, project (Fig. 13) which provides 15,150 sq ft (163,000 m^2) of usable floor space. Post-tensioning was used in the mat foundation, shoring tie-backs, beams, slabs and flat plates. These were combined with precast pretensioned hollow-core slabs and 10 ksi (69 MPa) concrete columns to create an architecturally striking project which, despite 30 different floor plans, came in below construction time and cost estimates. This is clearly a significant step forward from the ugly boxes with which concrete was sometimes associated in the past.

Computer Usage

The computer has become a common tool throughout the prestressed concrete industry. It is used by management to control production, track inventories and aid in the decision making process. Many concrete batching and mixing plants have computer-controlled automated mixing equipment that results in improved quality control.

Computer based analysis and design is now the norm for segmental bridges and standard pretensioned girders. Geometry controls for segmental bridges

Fig. 10. Exposed aggregate precast wall panel for building in Minneapolis, Minnesota. (Courtesy: Fabcon Incorporated)

Fig. 12. Long span prestressed girders combined with hollow-core slabs (Mexico).

Fig. 11. Park Plaza Condominium, Wilmington, Delaware.

Fig. 13. High rise building in St. Paul, Minnesota, utilizing precast prestressed concrete components with the aid of post-tensioning.

are generally computerized in casting yards and erection sites. Many highway departments and consulting engineers use CADD drafting stations connected to larger VAX-type computers for complete development of plan sheets. One large bridge design firm reported that 75 percent of its plan sheets and 100 percent of its specification pages are computer generated.

In other areas, such as robotics, the adoption of computerized control systems has lagged in the North American construction industry. Many precasting yards are wary of committing large expenditures to upgrading facilities and equipment. Clearly, we have much to learn from Europe and Japan in this area.

On the positive side, our traditionally strong pretensioning industry and our aggressively expanding post-tensioning industry are alive and making major contributions to the welfare of North America. Although the investment in R&D has been small, the traditional North American ingenuity, flexibility and creative capitalist spirit have maximized the benefits of the funds expended, resulting in pleasing, durable, high quality buildings and bridges from the Atlantic to the Pacific, and from the Arctic to the sub-tropics.

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