DESIGN OF PRESTRESSED CONCRETE STRUCTURES

THIRD EDITION

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PREFACE

The development of prestressed concrete can perhaps be best described by this parody, which Lin presented before the World Conference on Prestressed Concrete in San Francisco, 1957.

All the world's a stage,
And all engineering techniques merel players:
They have their exits and their entrances.
Prestressed concrete, like others, plays a part,
Its acts being seven ages. At first the infant,
Stressing and compressing in the inventor's arms.
Then the curious schoolboy, fondly created
By imaginative engineers for wealthy customers;
Successfully built but costs a lot of dough. Then the lover,
Whose course never runs smooth, embraced by some,
Shunned by others, especially building officials. Now the soldier,
Produced en masse the world over, quick to fight
Against any material, not only in strength, but in economy as well.
Soon the justice—codes and specifications set up to abide,
Formulas and tables to help you decide. No more fun to the pioneers,
But so prestressed concrete plays its part. The sixth age
Shifts to refined research and yet bolder designs,
Undreamed of by predecessors and men in ivory towers.
Last scene of all, in common use and hence in oblivion,
Ends this eventful history of prestressed concrete
As one of engineering methods and materials
Like timber, like steel, like reinforced concrete,
Like everything else.

When Lin wrote the first edition of this book, prestressed concrete in the United States had barely entered its fourth stage—the beginning of mass production. Now it has emerged from the sixth stage and into the last. This rapid advancement has made possible a rather thorough revision of the previous two editions.

This edition presents the basic theory in prestressed concrete similar to the second edition. The method of load balancing is discussed side by side with the working-load and the ultimate-load methods, forming a tripod for prestressed concrete design.

The chapters on materials, prestressing systems, and loss of prestress have been brought up to date. An important section on moment-curvature relationships has been added for flexural analysis. The problems of shear and bond, having been codified since the second edition was written, are now based on substantial experimental findings as well as theoretical interpretations. Camber and deflection are more thoroughly discussed with respect to time-dependent properties of concrete. The coverage of analysis and design of continuous beams with draped posttensioned tendons is more complete. Load-balancing with idealized tendons is covered along with the analysis using actual tendon layout in numerical example problems.

Since building codes and bridge specifications on prestressed concrete are now pretty well standardized, the ACI Code with its latest revisions is used in design examples. Bridge designers should refer to AASHTO Bridge Specifications for some minor adjustments concerning allowable stresses and load factors.

Some selected problems, which the authors have used for their undergraduate and graduate classes, are presented in Appendix E. Solutions for these are available to faculty members upon request.

We believe that this revised edition, with its up-to-date contents, will continue to be used both as a text and a reference for engineers interested in prestressed concrete.

The assistance of Martha Burns and Stephanie Burns with manuscript typing and Sow-Wen Chang and Sung L. Lam with S.I. units is gratefully acknowledged.

Berkeley, California and Austin, Texas
1981.

T. Y. Lin
Ned H. Burns

CONTENTS

1

INTRODUCTION

1-1 Development of Prestressed Concrete

The development of structural materials can be described along three different columns, as in Fig. 1-1. Column 1 shows materials resisting compression, starting with stones and bricks, then developing into concrete and more recently high-strength concrete. For materials resisting tension, people used bamboo, and ropes, then iron bars and steel, then high-strength steel. Column 3 indicates materials which resist both tension and compression, namely, bending. Timber was utilized, then structural steel, reinforced concrete and finally prestressed concrete was developed.

The main difference between reinforced and prestressed concrete is the fact that reinforced concrete combines concrete and steel bars by simply putting them together and letting them act together as they may wish. Prestressed concrete, on the other hand, combines high-strength concrete with high-strength steel in an "active" manner. This is achieved by tensioning the steel and holding it against the concrete, thus putting the concrete into compression. This active combination results in a much better behavior of the two materials. Steel is ductile and now is made to act in high tension by prestressing. Concrete is a brittle material with its tensile capacity now improved by being compressed, while its compressive capacity is not really harmed. Thus prestressed concrete is an ideal combination of two modern high strength materials.

The historical development of prestressed concrete actually started in a different manner when prestressing was only intended to create permanent compression in concrete to improve its tensile strength. Later it became clear that prestressing the steel was also essential to the efficient utilization of high-tensile steel. Prestressing means the intentional creation of permanent stresses in a structure or assembly, for the purpose of improving its behavior and strength under various service conditions.

Throughout this chapter, photographs of significant structures designed in prestressed concrete using this fundamental concept will be shown. Note that the basic idea and the high-strength materials have now become a vital part of modern structural engineering practice.

The basic principle of prestressing was applied to construction perhaps centuries ago, when ropes or metal bands were wound around wooden staves to form barrels (Fig. 1-2). When the bands were tightened, they were under tensile

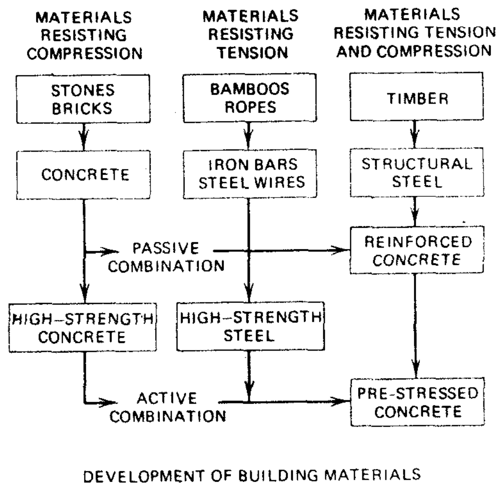

Fig. 1-1. Development of building materials.

prestress which in turn created compressive prestress between the staves and thus enabled them to resist hoop tension produced by internal liquid pressure. In other words, the bands and the staves were both prestressed before they were subjected to any service loads.

The same principle, however, was not applied to concrete until about 1886, when P. H. Jackson, an engineer of San Francisco, California, obtained patents for tightening steel tie rods in artificial stones and concrete arches to serve as floor slabs. Around 1888, C. E. W. Doehring of Germany independently secured a patent for concrete reinforced with metal that had tensile stress applied to it

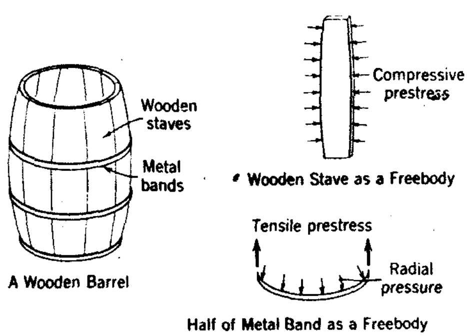

Fig. 1-2. Principle of prestressing applied to barrel construction.

before the slab was loaded. These applications were based on the conception that concrete, though strong in compression, was quite weak in tension, and prestressing the steel against the concrete would put the concrete under compressive stress which could be utilized to counterbalance any tensile stress produced by dead or live loads.

These first patented methods were not successful because the low tensile prestress then produced in the steel was soon lost as a result of the shrinkage and creep of concrete. Consider an ordinary structural steel bar prestressed to a working stress of 18,000 psi (124 N/mm^2) (Fig. 1-3). If the modulus of elasticity of steel is approximately 29,000,000 psi (200 kN/mm^2), the unit lengthening of the bar is given by

$$\begin{aligned}\delta &= \frac{f}{E}\\ &= \frac{18{,}000}{29{,}000{,}000}\\ &= 0.00062\end{aligned}$$

Since eventual shrinkage and creep often induce comparable amounts of shortening in concrete, this initial unit lengthening of steel could be entirely lost in the course of time. At best, only a small portion of the prestress could be retained, and the method cannot compete economically with conventional reinforcement of concrete.

In 1908, C. R. Steiner of the United States suggested the possibility of retightening the reinforcing rods after some shrinkage and creep of concrete had taken place, in order to recover some of the losses. In 1925, R. E. Dill of Nebraska tried high-strength steel bars coated to prevent bond with concrete. After the concrete had set, the steel rods were tensioned and anchored to the

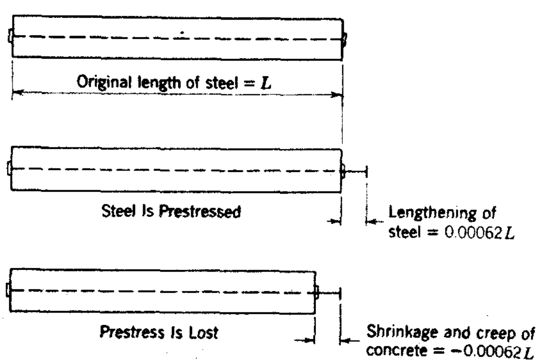

Fig. 1-3. Prestressing concrete with ordinary structural steel.

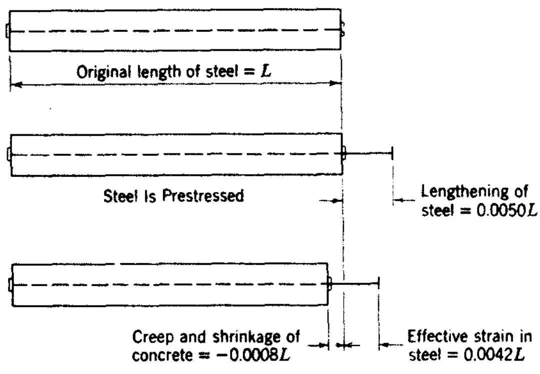

Fig. 1-4. Prestressing concrete with high-tensile steel.

concrete by means of nuts. But these methods were not applied to any appreciable extent, chiefly for economic reasons.

Modern development of prestressed concrete is credited to E. Freyssinet of France, who in 1928 started using high-strength steel wires for prestressing. Such wires, with an ultimate strength as high as 250,000 psi (1725 N/mm^2) and a yield point over 180,000 psi (1,240 N/mm^2), are prestressed to about 145,000 psi (1000 N/mm^2), creating a unit strain of (Fig. 1-4)

$$\delta = \frac{f}{E} = \frac{145,000}{29,000,000} = 0.0050$$

Assuming a total loss of 0.0008 due to shrinkage and creep of concrete and other causes, a net strain of $0.0050 - 0.0008 = 0.0042$ would still be left in the wires, which is equilvalent to a stress of

$$f = E\delta = 29,000,000 \times 0.0042 = 121,800 \text{ psi } (840\ N/mm^2)$$

Although Freyssinet also tried the scheme of pretensioning where the steel was bonded to the concrete without end anchorage, practical application of this method was first made by E. Hoyer of Germany. The Hoyer system consists of stretching wires between two buttresses several hundred feet apart, putting shutters between the units, placing the concrete, and cutting the wires after the

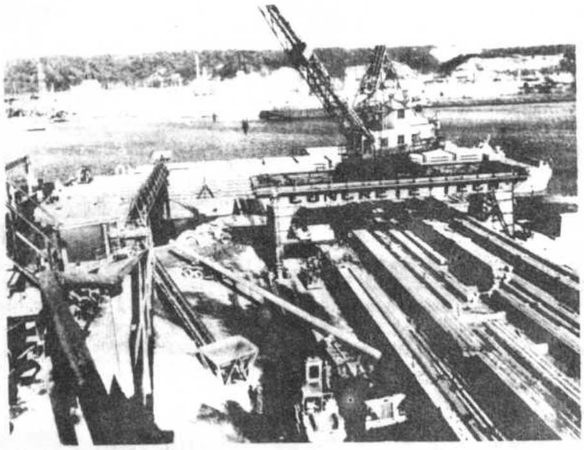

Fig. 1-5. Modern prestressing plants produce prestressed concrete products of very high quality. Shown are very long octagonal piles being shipped out of Concrete Technology Corporation's plant in Tacoma, Washington. 36,416 ft (11,100 m) of piling went to Adak, Alaska, along with 440 deck panels to construct the Naval Supply Pier (Prestressed Concrete Institute).

concrete has hardened. This method enables several units to be cast between two buttresses.

Wide application of prestressed concrete was not possible until reliable and economical methods of tensioning and of end anchorage were devised. In 1939, Freyssinet developed conical wedges for end anchorages and designed double-acting jacks which tensioned the wires and then thrust the male cones into the female cones for anchoring them. In 1940, Professor G. Magnel of Belgium developed the Magnel system, wherein two wires were stretched at a time and anchored with a simple metal wedge at each end. About that time, prestressed concrete began to acquire importance, though it did not actually come to the fore until about 1945. Perhaps the shortage of steel in Europe during the war had given it some impetus, since much less steel is required for prestressed concrete than for conventional types of construction. But it must also be realized that time was needed to prove and improve the serviceability, economy, and safety of prestressed concrete as well as to acquaint engineers and builders with a new method of design and construction.

Although France and Belgium led the development of prestressed concrete, England, Germany, Switzerland, Holland, Soviet Russia, and Italy quickly followed. Since 1965, about 47% of all bridges built in Germany were of

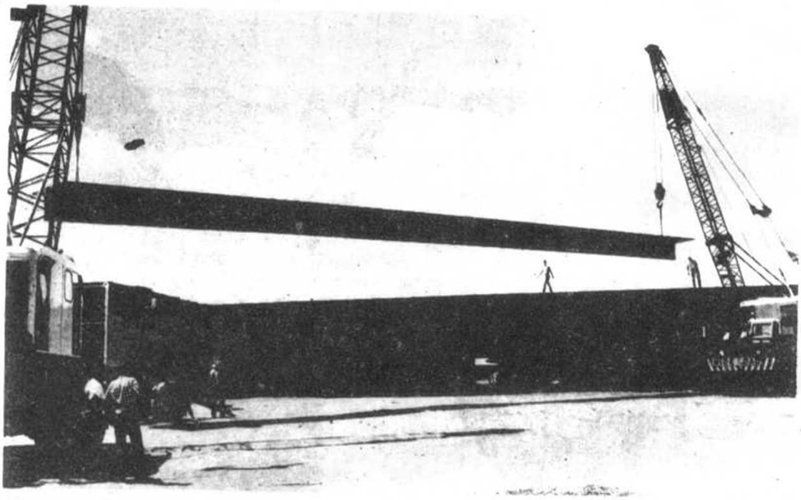

Fig. 1-6. Erection of long-span precast tee section. Shipment from plant to site for these standard cross sections is usually by truck. Beams are picked from the truck and placed in the structure.

prestressed concrete.[1] Soviet Russia annually produced 25,000,000 m^3 of prestressed concrete in 1978, most of which was pretensioned products for buildings. Since the late 1960s and 1970s most medium-span bridges (100–300 ft, 30–90 m) and many long-span bridges up to about 1000 ft (305 m) were built of prestressed concrete in all parts of the world.

Prestressed concrete in the United States followed a different course of development. Instead of linear prestressing, a name given to prestressed concrete beams and slabs, circular prestressing especially as applied to storage tanks took the early lead. This was performed almost entirely by the Preload Company, which developed special wire winding machines and which, from 1935 to 1963, built about 1000 prestress-concrete tanks throughout this country and other parts of the world.

Linear prestressing did not start in this country until 1949, when construction of the famed Philiadelphia Walnut Lane Bridge was begun. The Bureau of Public Roads survey showed that for the years 1957-1960, 2052 prestressed concrete bridges were authorized for construction, totaling a length of 68 miles, with an aggregate cost of 290 million dollars and comprising 12% of all new highway bridges both in length and in cost.

Since 1960, the use of prestressed concrete bridges has become a standard practice in the United States. In many of the states almost all bridges in the span range 60 to 120 ft (18–36 m) have been constructed with prestressed concrete.

Fig. 1-7. Precast prestressed concrete girders and columns form rigid frames for 62-ft span garage, University of California, Berkeley (Architect Anshen and Allen, Structural Engineer T. Y. Lin International, Consulting Engineers).

Since the late 1970s, posttensioned bridges of medium spans (150–650 ft, 45–200 m) have gained momentum, in the form of continuous or cantilever construction.

In the United States, while there was only one precast pretensioning plant in 1950, there were 229 in 1961. The total volume of precast prestressed products was estimated to be over 2,000,000 yd^3 (1,530,000 m^3) in 1962, of which it was roughly estimated that 50% went to bridges and the remaining to buildings and other construction projects. A survey by the Prestressed Concrete Institute in 1975 indicated that 500 precasting and prestressing plants were operating in the United States.

The growth of the prestressed concrete industry in the United States and Canada is shown by the Prestressed Concrete Institute graph on dollar sales volume of precast and prestressed concrete during the 25-year period 1950–1975, Fig. 1-9. The data on sales includes posttensioned tendon assemblies but not the value of the posttensioned structures. The breakdown of industry sales is estimated by the PCI to divide approximately 50% prestressed concrete, 30% structural precast and 20% architectural precast for 1975.

The Post-tensioning Institute (PTI) was formed in 1976 with 16 member companies participating. Most of these companies had previously been part of the Post-tensioning Division of the Prestressed Concrete Institute, and the separate organization was established to permit them to cooperate in the area of

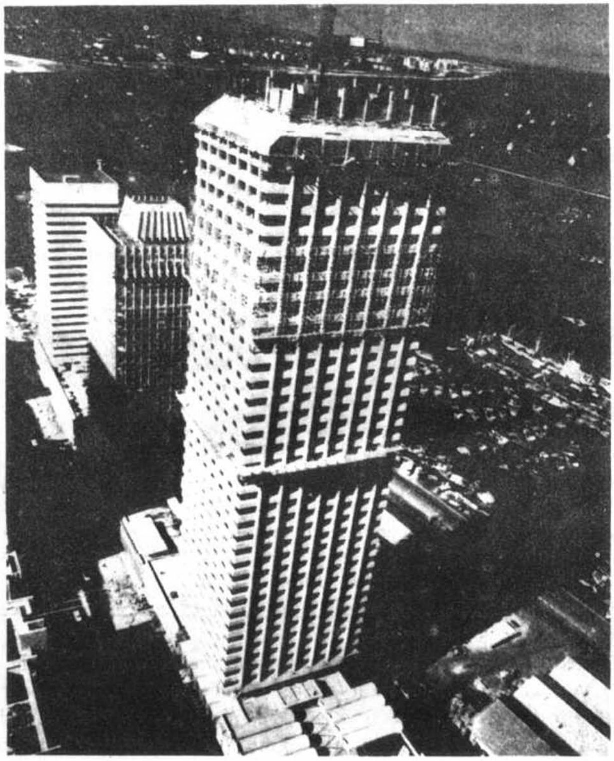

Fig. 1-8. Forty-story office building in Singapore has 8 in. posttensioned flat slabs with 30-ft spans. Reduced floor depth made possible a 40-ft reduction in the height of the building (T. Y. Lin International, Consulting Engineers).

posttensioning with clearer identity. Data shown in Table 1-1 furnished by PTI indicates that the total tonnage of prestressing steel used in the United States for posttensioning in 1974 increased to almost three times the sales in 1965. Use of posttensioning for nuclear containment structures for power plants increased to a peak in 1972 before dropping back. Note also in Table 1-1 the increasing use of posttensioning for soil and rock anchors in connection with earthwork since 1972. For 1974, the posttensioning sales were distributed as follows: buildings—59%, bridges—25%, nuclear—7%, earthwork—8%. It was estimated that 20 million square feet of flat slabs for building construction was posttensioned in the year 1974, indicating that it is a very competitive structural system. Since the

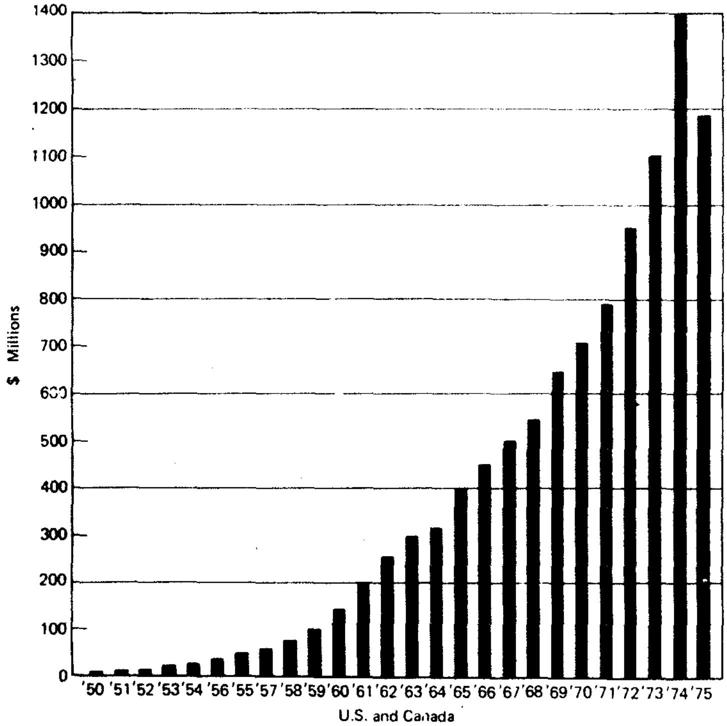

Fig. 1-9. Estimates of dollar sales volume of precast and prestressed concrete for the United States and Canada, 1950 through 1975. No breakdown, U. S.-Canada available (Prestressed Concrete Institute).

1970's, both precast, prestressed members and posttensioned, cast-in-place concrete are being utilized. Innovative designs using combinations of both are not uncommon.

The progress of prestressed concrete, both in research and in development, is perhaps best indicated by the growth of its technical societies and their publications. In the United States, the Prestressed Concrete Institute, formed in 1954, had a membership of 2150 by 1975. This institute publishes the *PCItems* and the *PCI Journal* and has very active technical committees. Introduction of the Prestressed Concrete Institute's *Prestressed Concrete Handbook*[8] in 1971 perhaps marked the acceptance of prestressed concrete as a structural system which engineers could use more easily and with confidence of acceptance as a viable system. The Post-Tensioning Institute published the *Post-Tensioning Manual*[9],

Table 1-1 U. S. Posttensioning Steel Tonnage—1965 Through 1975* (Equivalent Tonnage of ½ in. Diameter 270 ksi Strand)

Year	Buildings	Bridges	Nuclear	Earthwork	Miscellaneous	Total
1965	10,979	2,400				13,379
1966	11,310	2,736				14,046
1967	10,335	5,148	83			15,566
1968	12,204	7,159	208			19,571
1969	17,611	7,537	718			25,866
1970	19,136	8,920	2,420			30,476
1971	22,145	8,682	4,181			35,008
1972	23,721	7,182	6,118	939	166	38,126
1973	21,809	9,228	3,244	785	422	35,488
1974	23,560	10,056	2,769	3,111	236	39,732
1975	11,994	7,954	2,134	1,942	1,893	25,917*

*1975 tonnage reports incomplete. Estimated total 1975 tonnage 29,000 tons. Information from Post-Tensioning Institute.

which was initiated by the PCI Post-Tensioning Division prior to organization of the PTI.

Proceedings of the World Conference on Prestressed Concrete in San Francisco, 1957, and Proceedings of Western Conferences on Prestressed Concrete Buildings held in California in 1960, included valuable papers on all phases of the subject. The International Federation for Prestressing (FIP) with its headquarters in London has member groups in 44 countries and FIP observers in some 25 other countries. It has published hundreds of papers of their congresses held all over the world since 1963.[11] In 1975, joint sessions were sponsored by ACI, PCI, and FIP in Philadelphia tracing the development of prestressed concrete throughout the world. These sessions indicated the extent to which prestressed concrete has been utilized in large offshore structures for storage of oil, massive containment structures for nuclear power plants, and even oceangoing barges. An excellent issue of the *PCI Journal* (September–October 1976)[10] presents papers given at the T. Y. Lin Symposium on "Prestressed Concrete, Past, Present and Future", University of California, Berkeley, June 1976.

While bridges are more easily standardized by federal and state agencies, thus helping to develop prestressed concrete construction, it took more time to develop standardized building products and designs for the individual architects and engineers. However, with the incorporation of prestressed concrete into building codes since the 1960's, and a general understanding of prestressed design and construction, a rapid rate of growth was also experienced for buildings.

Thus the development of prestressed concrete in the United States has occurred in the application of posttensioning to buildings, bridges, and pressure

Fig. 1-10. Thirteen-story apartment building with all slabs posttensioned on the ground being lifted into position; 8-in. lightweight concrete spans 28-ft; San Francisco (Owner George Belchĕr, Engineer August Waegeman, Consultant T. Y. Lin and Associates).

containers, including the combination of pretensioning, posttensioning, and conventional reinforcing to structures and structural components.

Outside the field of tanks, bridges, and buildings, prestressed concrete has been occasionally applied to dams, by anchoring prestressed steel bars to the foundation, or by jacking the dam against it.[2] Piles, posts, and pipes all have been constructed of prestressed concrete. In certain structures, it is possible to prestress the concrete without using prestressing tendons. For example, the Freyssinet method of arch compensation introduces compensating stresses in the arch rib by a system of hydraulic jacks inserted in the arch. Such stresses are intended to neutralize the effects of shrinkage, rib shortening, and temperature drop in the arch. The Plougastel Bridge near Brest, with three spans of 612 ft (186.5 m) each, is an example of such application.[3]