Prestressed Concrete in Highway Bridges and Pavements

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BRIEF historical review. Advantages: reduction in critical materials; reduced ratio *DL/LL*, particularly for long spans; elimination of cracks. Pretensioned wires or strands for precast members. Post-tensioned multiple parallel wire cable systems. Post-tensioned bars and cables. Continuous multispan bridges. Principle of prestressing with reference to importance of high steel and concrete stresses. Analysis of critical loading stages. Magnitude and frequency of vibration for thin, prestressed slabs. Recommended steel and concrete stresses. Factors of safety. Special considerations: importance of end anchorage, bond of reinforcing, end block stresses, etc. Choice of most economical prestressing system. Comparative cost with structural steel and reinforced concrete. Need to adapt prestressing methods to suit standard American construction procedures and equipment. Material and labor costs for different systems of prestressing. Review experimental prestressed pavements. Suggest method to produce continuous prestressed pavements without joints for infinite lengths. Definitions and notations. Design criteria. Need to overcome domination of patents systems; establishment of consulting engineers in prestressed concrete design for major structures; need for simplified methods of prestressing for smaller structures.

● THE principle of prestressing was first used in bridge construction by the construction battalions of Julius Caesar. They made large barrels using curved staves around which bronze hoops were forced from opposite ends to provide adequate circumferential compression to resist nonuniformly distributed loads. These barrels were used as pontoons for floating bridges for the transport of Caesar's armies and military equipment in the conquest of Britain.

Nearly 2,000 yr. later, in the early days of reinforced concrete, it was realized that if concrete could be placed in compression by external means sufficiently to offset tensile stresses caused by load, higher reinforcing stresses could be used in combination with reduced concrete sections for members subjected to tension or bending. However, the first attempts to prestress concrete beams about 50 yr. ago failed from a lack of knowledge of the magnitude of creep in steel and concrete under sustained load. The small initial prestressing forces developed with low steel stresses were quickly dissipated.

Not until 1925 when Freyssinet and others started their investigations into the plastic strains in steel and concrete under high stress was it realized that to maintain stablity of the opposing stresses in steel and concrete in prestressed concrete it was necessary: 1) to provide means for periodically readjusting the initial stresses to compensate for creep losses over a considerable period of time or 2) to use sufficiently high initial steel stresses that these losses could be absorbed with only a small percentage drop in the initial steel and concrete stresses.

METHODS OF PRESTRESSING

The first prestressed bridge in which provision was made for readjusting the stresses was probably the ambitious 223-ft. arch span designed by Dischinger and constructed at Saale in Germany in 1928, in which the concrete arch ties were prestressed by rods tightened with turnbuckles and left exposed for periodic adjustment. While the theory was sound, the need for restressing the steel from time to time more than offset the advantages gained, and this method faded from the scene.

Freyssinet soon followed with his well-known system of posttensioning based on using 12 to 18 parallel wires contained in a

single sheath and stressed at the ends with a double-acting jack and anchored by a common cone-and-socket device. The success of the early Freyssinet bridges soon led to the development of similar systems by Magnel, Roš, and others, varying only in detail. These systems are generally classified as "posttensioned parallel-wire systems."

During the same period, Hoyer, in Germany, adapted to the construction of bridge beams the method of pouring concrete around small diameter wires pretensioned in an external frame, which were later released to transfer the prestressing force to concrete by bond alone. Many bridges were built in this way for the Autobahns in Germany.

Prior to the war these were the only two methods of linear prestressing available and consequently all the prewar prestressed bridges in Europe and all the prestressed bridges built so far in the United States follow one or the other of these original systems.

These systems were developed primarily for prestressed simply supported precast members. They cannot readily be used for continuity or for cast-in-place construction, and as they depend upon the use of numerous small wires, anchored singly or in small groups, they require from 125 to 175 man-hours of labor per ton of wire in place, stressed and grouted.

Since the war, several new materials and methods of construction have been introduced which greatly expand the range of the type of bridges for which prestressing can now compete with structural steel or reinforced concrete.

The Roebling Company of Trenton offers a fabricated prestressing strand with suitable end anchorages, which greatly reduces the field labor required for installation and stressing. These strands have been used in a number of bridges, particularly those designed by Bryan & Dozier, of Nashville, Tennessee.

Lee-McCalls, of England, developed a process for treating alloy steel bars to produce high physical properties and which, with special, threaded end anchorages, provide a robust and economical stressing unit guaranteed for an ultimate strength of 145,000 psi. with practically no creep. This special steel for prestressing is now manufactured in this country by Stressteel Corporation and is being used in the Tampa Bay bridge in Florida and several other smaller bridges throughout the country.

The Concrete Products Company of Pottstown, Pennsylvania, has found that it is possible to develop adequate bond in pretensioned members using seven-wire strands instead of single wires. This greatly reduces the number of elements handled. Slab-and-girder units up to 50 ft. long made by this method have been used in a number of bridges in Pennsylvania.

Fritz Leonhardt, of Stuttgart, Germany, realized that for economical construction of long, multispan bridges it was necessary to develop much-larger concentrations of prestressing in individual conduits and to reduce the frictional losses in curved prestressing units in order to combine the advantages of prestressing with those of continuity for multispan bridges. In his system, any desired number of seven-wire strands are placed in parallel layers in a rectangular, light-metal conduit in which special friction-reducing plates are placed at top and bottom of the conduit at each point of change of direction of the cables as required to develop continuity over supports. At their ends the strands are deployed around semicircular concrete blocks which are simultaneously jacked against the poured-in-place slab-and-girder sections of the structure to produce the required stress in the steel across the entire section of the structure in one operation. This system eliminates the multiple end anchorages and separate jacking operations required in other systems and has been successfully used on many long-span continuous bridges in Europe.

Franz Dischinger, of Berlin, has developed a method of prestressing for progressive cantilever construction over deep gorges or swift rivers to eliminate the use of falsework. This system makes use of counterweighted piers from which the cantilevers are progressively constructed and prestressed in 10-ft. increments from each end by means of a moveable steel scaffolding projecting from the completed portions of the cantilever. At the center of the completed span, a rocker joint is installed which, in conjunction with vertical prestressing, insures the transmission of shear without bending moments.

Freyssinet, of Paris, has achieved perhaps his greatest triumph in prestressed bridges in

the construction of three arch bridges in Venezuela. In one of these bridges the main arch spans 498 ft. and, at midspan, is 220 ft. above the canyon floor. In these bridges the arches themselves are prestressed to overcome tension caused by raising the neutral axis above the funicular curve to facilitate transfer of wind forces to the deck. The piers are cellular prestressed construction, and the deck consists of precast slabs set between prestressed stringers which, in turn, are carried on prestressed beams spanning across the top of precast prestressed spandrel columns.

By choosing the right combination of design and materials, prestressing has now been applied to all classic types of bridges, including the deck of a suspension bridge constructed in San Salvador by the Roebling Company.

Classification of Prestressed Concrete Bridges Constructed or Under Construction at End of 1952

Location / Type			U.S.	Foreign	Totals	
Simple Span	Precast	Number	92	269	361	No 582
		Length in Miles	4.22	5.75	9.97	
		Span Range	20'-160'	25'-243'		
	Cast in Place	Number	3	218	221	
		Length in Miles	0.03	4.65	4.68	14.65 Miles
		Span Range	40'-60'	19'-405'		
Continuous	Precast	Number	—	1	1	No 44
		Length in Miles	—	0.03	0.03	
		Span Range	—	36'-50'		
	Cast in Place	Number	—	43	43	
		Length in Miles	—	2.28	2.28	2.31 Miles
		Span Range	—	13'-515'		
Totals		Number	95	531	No 626	
		Miles	4.25	12.71		16.95 Miles

Figure 1. Classification of prestressed-concrete bridges constructed or under construction at end of 1952.

By using concrete strengths of 6,000 psi. or more for precast work and 4,000 psi. or more for cast-in-place construction and initial steel stress of 100,000 psi. or more (as possible with high-strength wires, strands, and processed-alloy bars), all types of bridges can now be built in prestressed concrete with savings of 40 to 60 percent in concrete and 60 to 80 percent in steel required in equivalent reinforced-concrete design. As there is no need to have any concrete below the neutral axis under full design load, depth-span ratios can be greatly reduced without producing cracks or increasing deflection. The resulting saving in dead weight reduces foundation dimensions or permits the use of longer spans without increasing the support reactions.

TYPES OF PRESTRESSED BRIDGES

Figure 1 is a tabulation of all the world's reported prestressed bridges, which now number 626. The author has heard rumors of other bridges not reported in the technical journals but believes this table covers all but a few small bridges. It is interesting to note that only 95 bridges have been built in the United States, with a total length of 4.25 mi., in contrast to 530 bridges built in foreign countries, with a total length of 12.7 mi. Tampa Bay bridge alone accounts for about 75 percent of the total length of United States bridges. It should also be noted that no continuous bridges have yet been built in this country, whereas 44 have been constructed abroad.

Figure 2 shows a small highway bridge designed by Bryan & Dozier and constructed in Madison County, Tennessee. The precast girders are manufactured at a central plant, using concrete blocks with grouted joints prestressed with Roebling strands. The longitudinal joints are filled with concrete, when the topping is placed after erection of the girders.

Figure 3 shows details of the Walnut Lane Memorial Bridge in Philadelphia, which received such wide publicity as the first major prestressed bridge on this continent. The main span is 160 ft., composed of 13 precast I-section girders with the top flanges abutting and transversely prestressed through periodic diaphragms. The prestressing of this bridge followed the Magnel system, in which cables of 68 wires were made up on the job and threaded through holes formed in the girders with rubber cores.

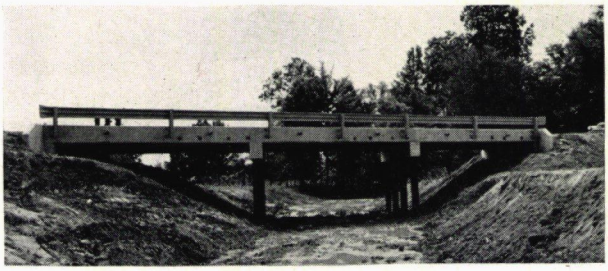
Figure 4 is a fine example of one of the well-known Freyssinet bridges over the Marne. This bridge was made up of precast-concrete sections, which were suspended in position from an overhead cable system until the prestressing could be introduced. This bridge carries a span of 243 ft., and at midspan is only 3 ft. 5 in. deep.

Figure 5 shows details of the Tampa Bay bridge in Florida, which upon completion will have 363 spans, each 48 ft. long, carried

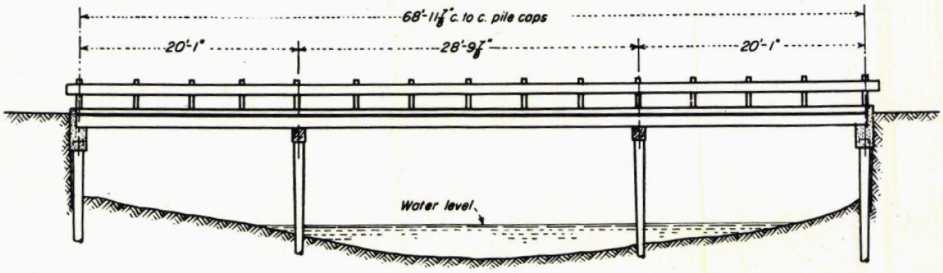
by six precast girders prestressed with three 1-in.-diameter Stressteel bars.

Figure 6 shows details of a design proposed by Donovan H. Lee, of London, for a trestle structure similar to Tampa. It is made up entirely of precast-concrete elements in which continuity for superimposed loads is provided in both directions by use of supplemental prestressing bars placed over supports after the girders are erected and by transverse bars running through the haunched precast plates resting between the top flanges of the girders. In this way the 48-ft. spans used at Tampa can be increased to 60 ft., using five girders instead of six.

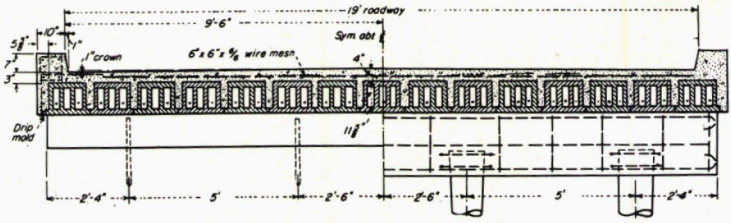
Figure 7 shows the first continuous, cast-in-place, prestressed-concrete bridge, which was designed by Gustave Magnel, of Ghent, Belgium, and constructed at Sclayn in 1948. Each span is just over 200 ft. in length, and continuity is developed by the use of a very deep haunch over the central support, enabling the prestressed cables to be carried from end to end of the bridge in a straight line.



General View



Section on ℄ of Roadway



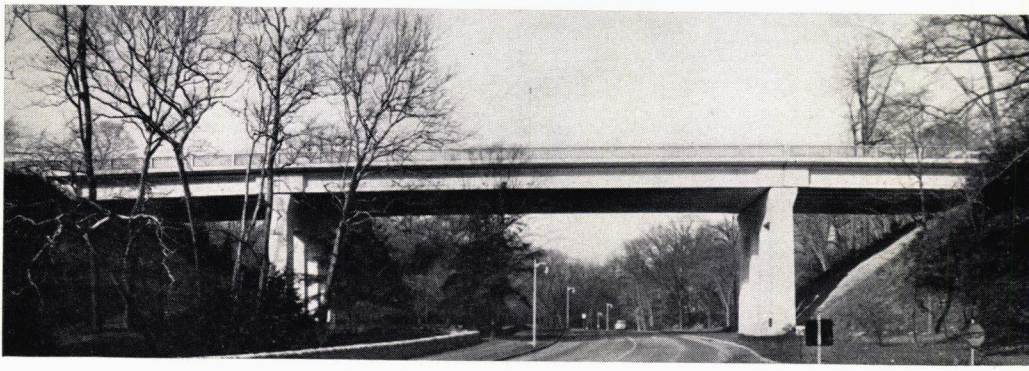
At Mid-Span At Support

Transverse Section

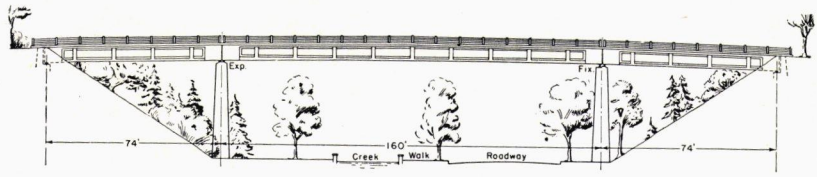
Figure 2. Highway bridge at Madison County, Tennessee: three simple spans, each of precast blocks, prestressed with anchored strands.

Figure 8 showing a railway bridge designed by Leonhardt, in Germany, is included only to show details of his methods for continuity for cast-in-place structures. The bottom left-hand corner shows the arrangement of the cable boxes rising at four points over the supports and deployed around the semicircular end blocks resting on the abutments. The bottom right-hand corner shows the seven-wire strands as they are arranged in one of the prestressing conduits. The top right-hand corner shows the bridge after the deck has been poured and immediately prior to prestressing and grouting of the cables.

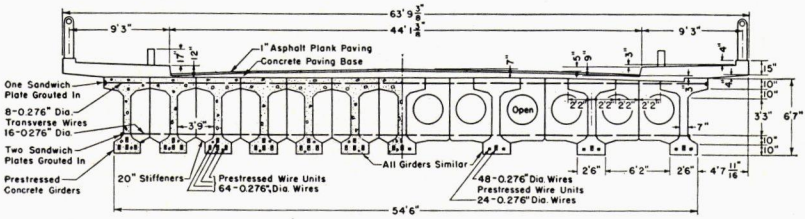
Figure 9 shows a typical example of a Leonhardt cast-in-place continuous highway bridge, built at Neckargartsach, Germany, in the American zone. This design had to be approved by the U. S. Army Engineers to carry 70-ton tanks, imposing a considerably greater loading than our H20-S16. As you will see from the cross section, only four box-girder webs are used to carry the deck, which is 39 ft. 8 in. in width. By increasing the



General View



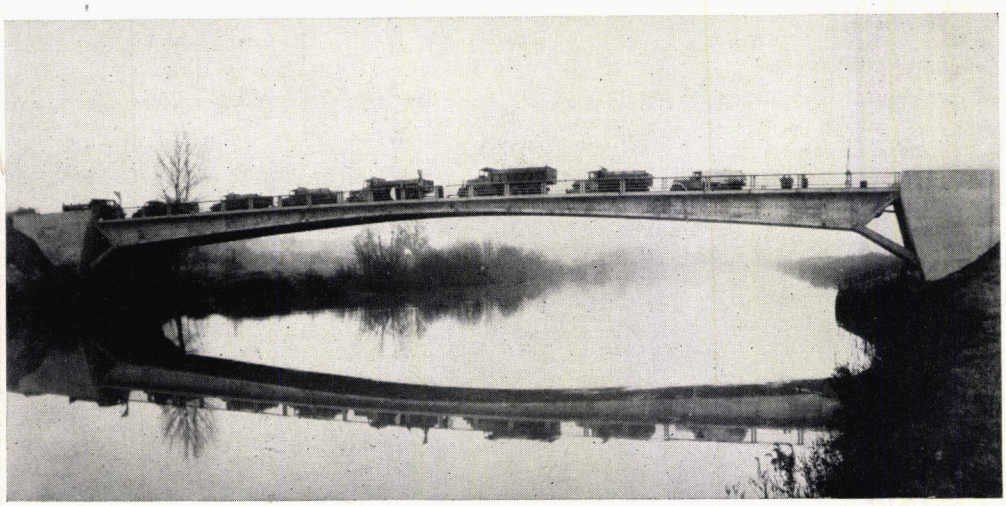
Elevation



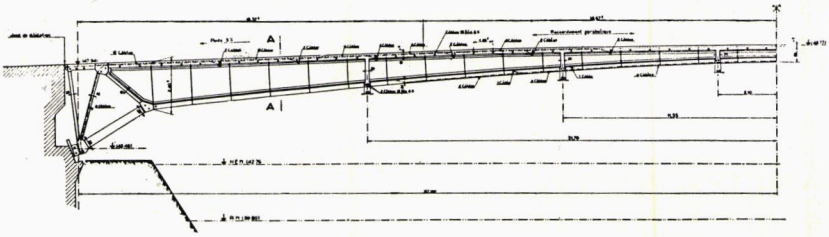
Center Span Approach Support

Transverse Sections

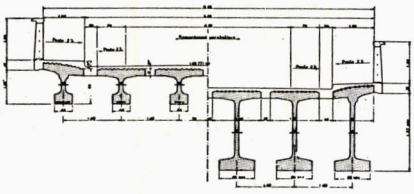
Figure 3. Walnut Lane bridge over Lincoln Drive, Philadelphia, Pennsylvania: three simple spans (74 ft., 160 ft., 74 ft.) prestressed with individual cables of parallel wires.



General View



Longitudinal Half-Section



At Mid-Span Near Abutment

Transverse Section

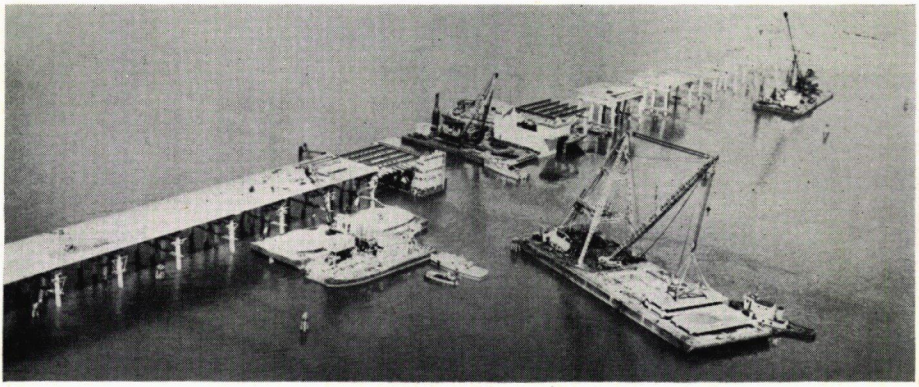
Figure 4. Highway bridge over River Marne, Esbly, France, (243 ft. span) precast elements prestressed by individual cables of parallel wires.

spacing of the girders and using high concentration of prestressing, the concrete quantities are greatly reduced, as compared with a section such as the Walnut Lane bridge. It should also be noted that the transverse cables in the deck are curved to provide continuity over the girders in the same way as the main longitudinal carrying members.

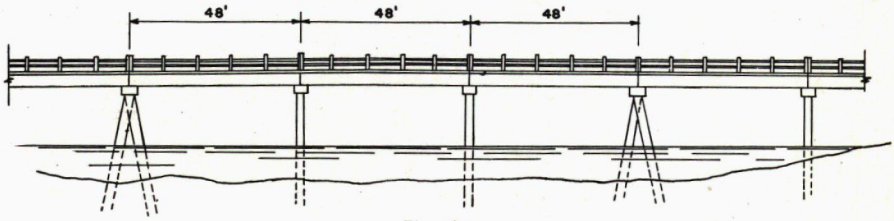
Figure 10 shows a still-better example of what can be done with the Leonhardt system

for long spans. The main span of this bridge is 315 ft. in length, flanked by two heavily counterweighted approach spans of only 62 ft. in length. This bridge uses a single box-girder section with heavy transverse prestressing in the top slab.

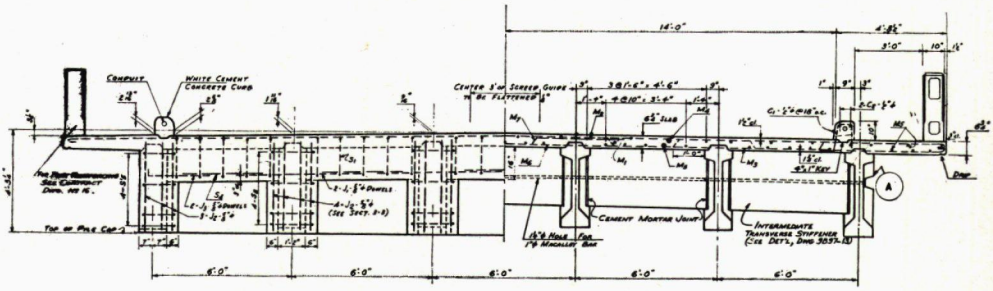
Figure 11 illustrates the use of Leonhardt's system for a typical throughway overpass bridge using a slab only 22 in. in depth to carry the two center spans of 60 ft. and two approach spans of 40 ft. By the use of transverse prestressing across the tops of the columns, the need for a cap is eliminated, as the deck forms its own cap, being prestressed in two directions. Using a depth of only 22 in. greatly reduces the amount of cut and fill needed for grade separations in level country. Cost studies show that such a bridge would cost less than structural steel or reinforced-concrete construction.



General View



Elevation



Transverse Section

Figure 5. Tampa Bay, Florida, highway bridge, simple spans (48 ft.), prestressed with Stressteel bars.

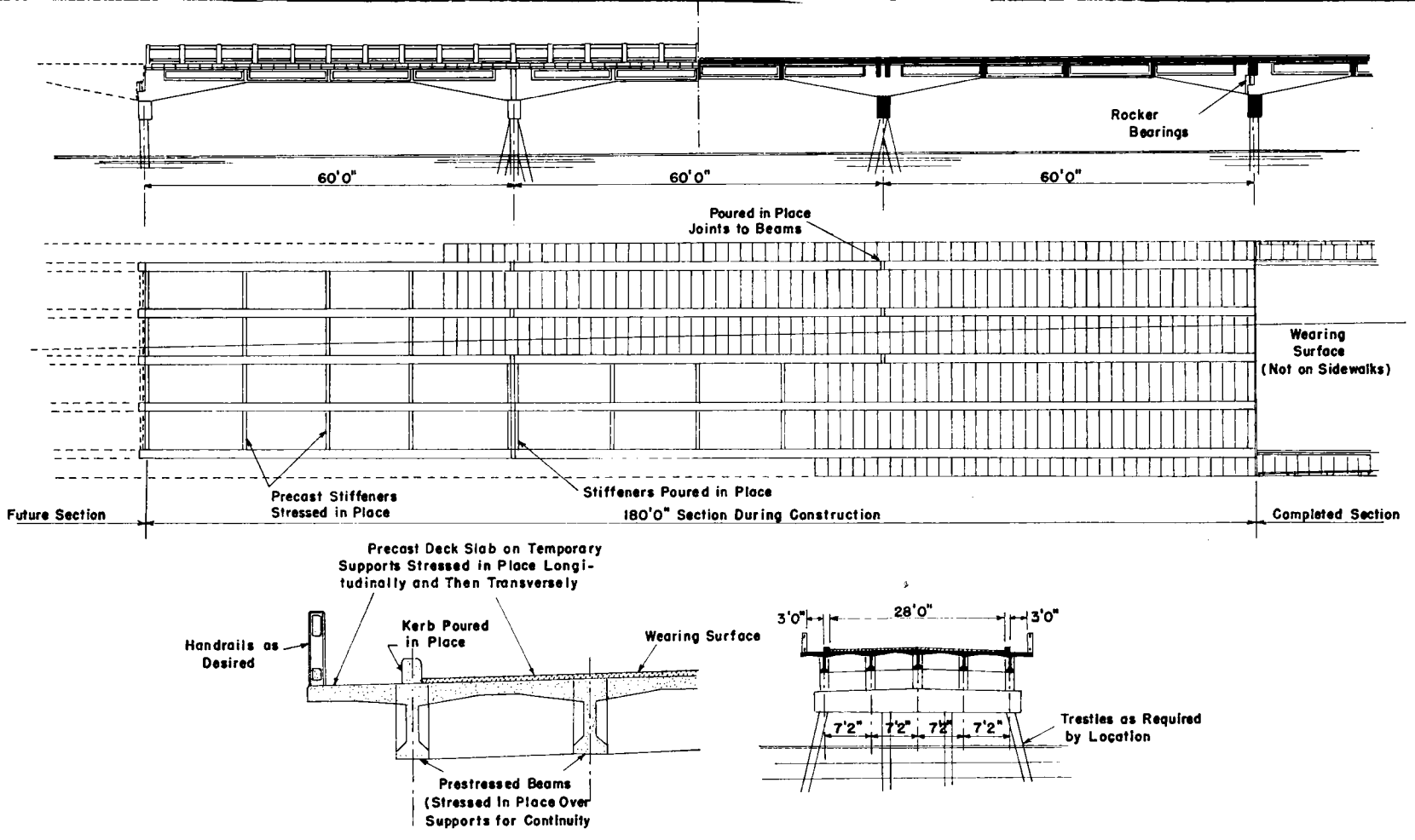
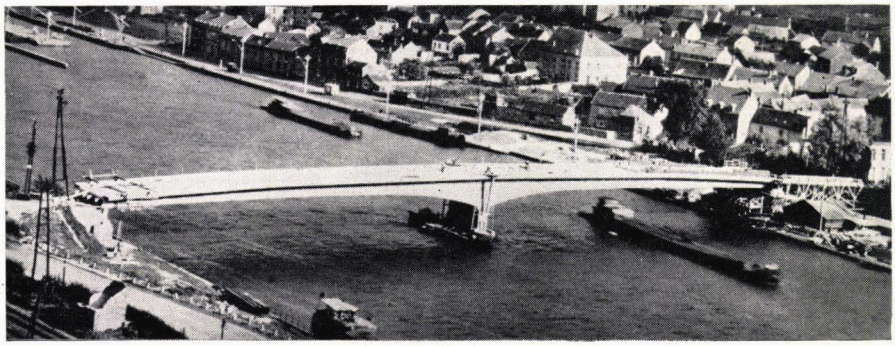
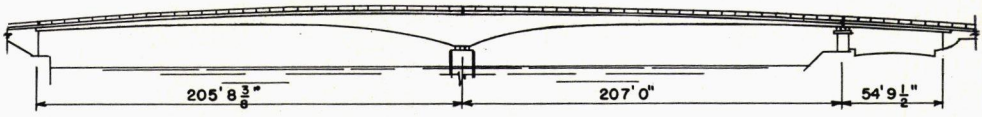


Figure 6. Multispan road bridge, general arrangement.

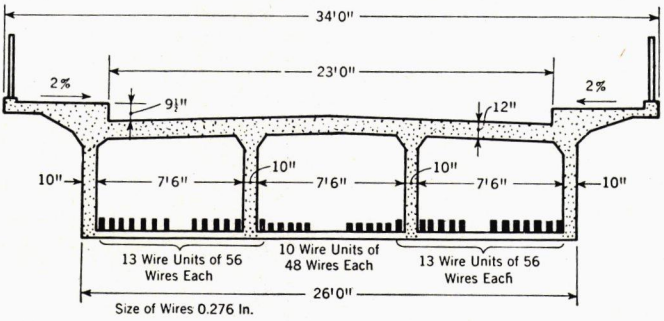
Figure 12 shows details of a typical Dischinger progressive cantilever bridge under construction. The longitudinal sections show the counterweight arrangement at the piers to carry the progressively increasing load of the main span as it is constructed. The author tacular arch bridges designed by Freyssinet now under construction in Venezuela. The top illustration shows the method of erecting the formwork for the arch span of 498 ft. Details of the extremely slender columns and deck stringers and girders are shown below.



General View



Elevation



Transverse Section

Figure 7. Sclayn, Belgium: Cast-in-place continuous two-span (205 ft., 207 ft.) highway bridge, prestressed with individual cables of parallel wires.

does not believe that such construction would be economical in this country for bridges requiring only normal falsework, but it would be fine for construction where falsework would be unduly costly or impossible.

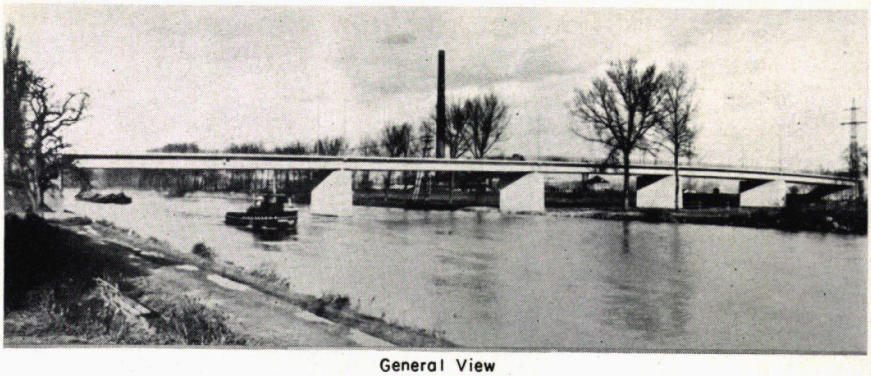
Figure 13 shows details of one of the spec-

ECONOMICS

The great savings in materials which can be achieved with prestressing combined with the more-economical materials now available, requiring only 25 to 40 man-hours per ton, are rapidly making prestressed concrete com-

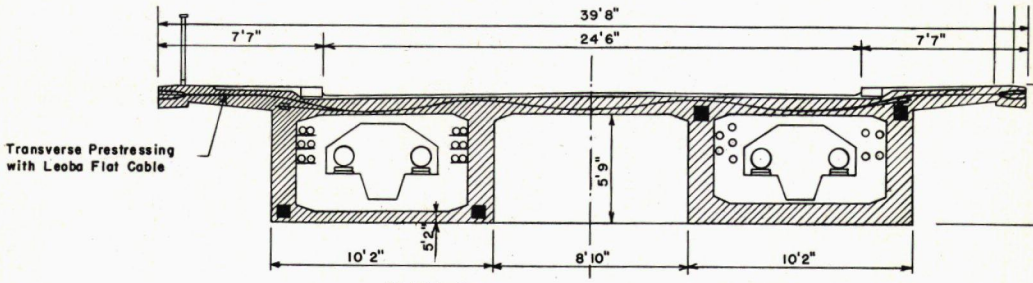
Figure 8. Five-span-continuous railroad bridge at Heilbronn, Germany: spans (upper left) are 69 ft., 60 ft., 72 ft., 72 ft., and 64 ft.; bridge (upper right) is ready for prestressing; view (lower left) shows prestressing units and end blocks; typical prestressing unit (lower right) before closing of box.

petitive in cost with structural steel and reinforced concrete for a wide variety of bridges. A few years ago it would have been unthinkable that prestressed concrete could compete with a structure such as the Tampa Bay bridge where the conventional design was saving of about $150,000 over the prices received for two alternative conventional designs in reinforced concrete, even though the prestressed price included some $70,000 for design and testing which was not required for the two conventional designs.



General View

Longitudinal Half-Section



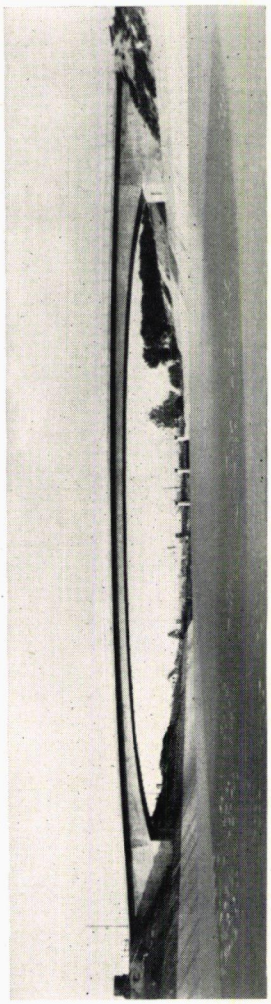
At Mid-Span Over Support

Transverse Section

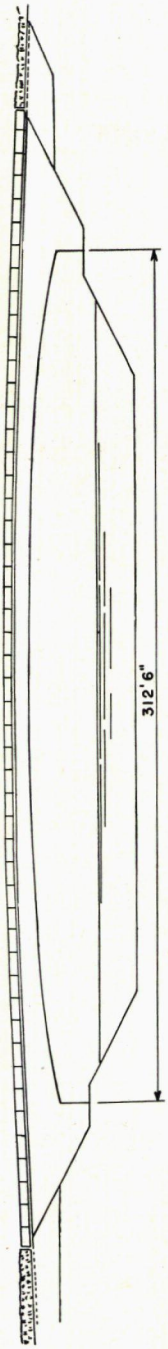
Figure 9. Neckargartach, Germany: Cast-in-place continuous five-span (137 ft., 142 ft., 142 ft., 142 ft., 137 ft.) highway bridge, prestressed with looped cables of parallel strands.

based on the use of 35 ft. spans, but this important bridge is now under construction with prestressed girders at a contract cost of only $3.30 per sq. ft. for the superstructure, which in combination with the savings in the reduced number of pile bents resulted in a

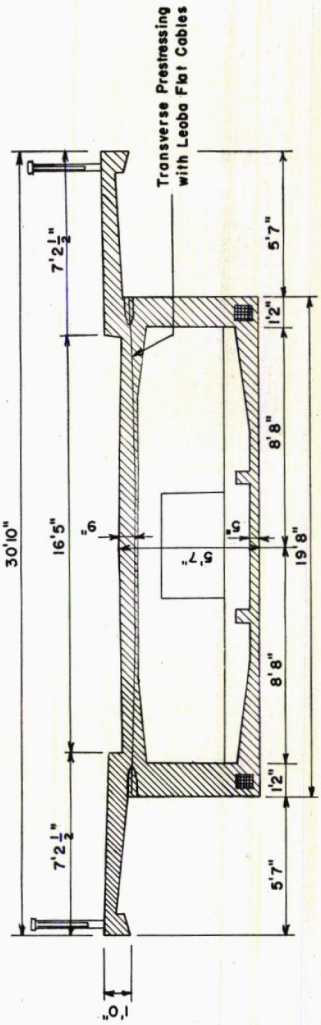
While no continuous, prestressed, cast-in-place bridges have yet been built in this country, careful cost estimates show that for multiple spans of 70 ft. or more they can compete favorably with structural steel or reinforced concrete.



General View



Longitudinal Elevation

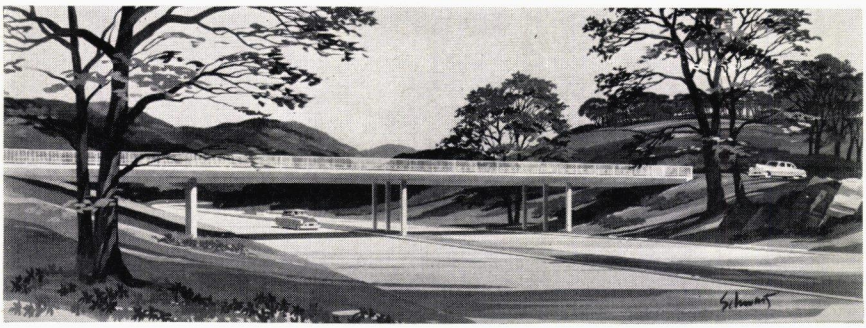


Transverse Section at Midspan

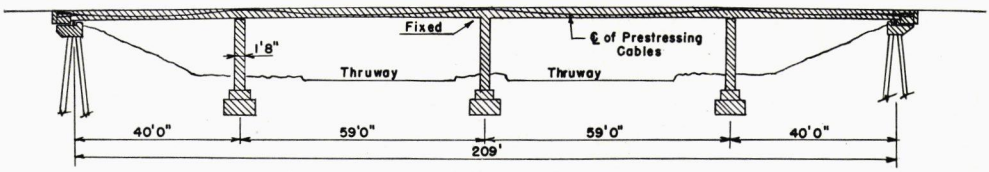
Figure 10. Heilbronn, Germany: highway bridge over Neckar Canal, prestressed with looped cables of parallel strands and cast in place.

Figure 14 shows comparative quantities of materials and costs for a typical, four-span, throughway overpass bridge using 1) steel girders and concrete deck, 2) prestressed, precast concrete girders and deck, and 3) prestressed continuous slab. Even for these short spans the two prestressed solutions show a satisfactory saving over the conve-n tional type of bridge. While the cost of the two prestressed solutions are about the same, the saving in depth with the continuous slab might afford economies in cut and fill favoring this solution. As spans increase, the cost per square foot of bridge for prestressed, cast-in-place, continuous construction usually increases at a slower rate than the other methods of prestressing.

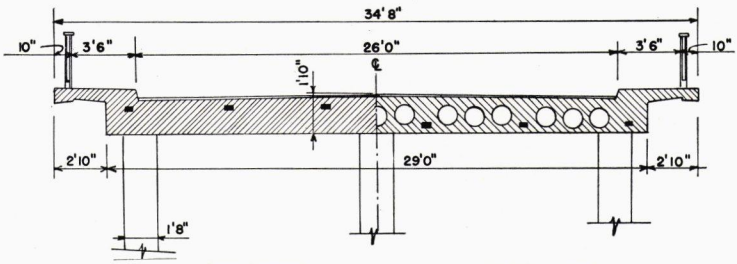
Depending on the quantity of materials and amount of repetition involved, the cost of prestressed-concrete superstructures in place will usually fall between $80 and $140 per cubic yard. This includes the cost of all mild and prestressed steel and formwork but excludes the cost of falsework. This may seem a high unit cost in terms of reinforced concrete, but when applied to the reduced material quantities needed in prestressed design, it will usually show an over-all saving in total cost.



General View



Longitudinal Section



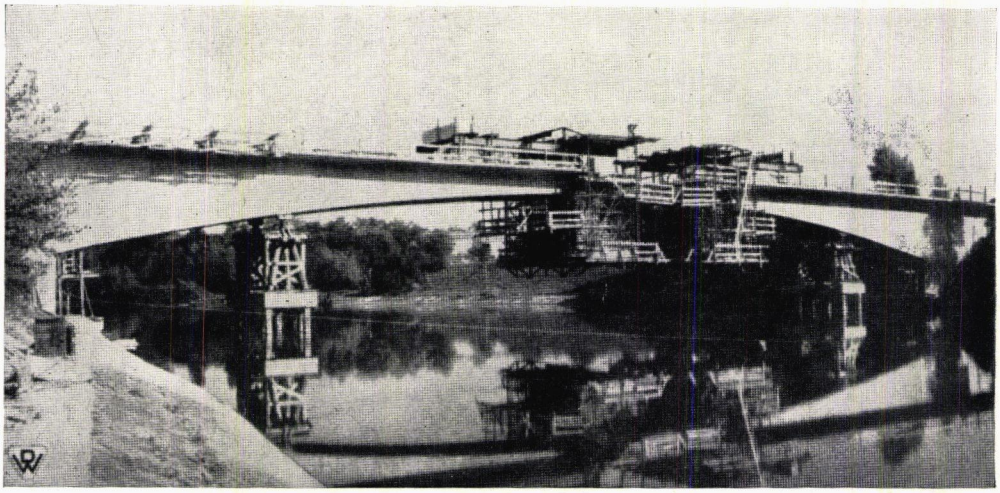
Over Support At Mid-Span

Transverse Section

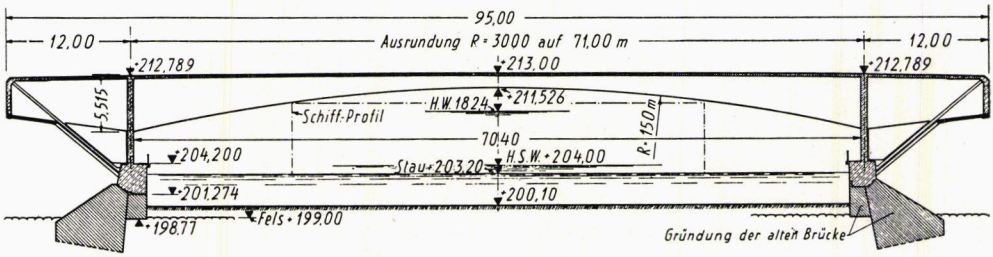
Figure 11. Project for thruway overpass: continuous four-span (40 ft., 59 ft., 59 ft., 40 ft.) hollow slab prestressed with looped cables of parallel strands.

DESIGN

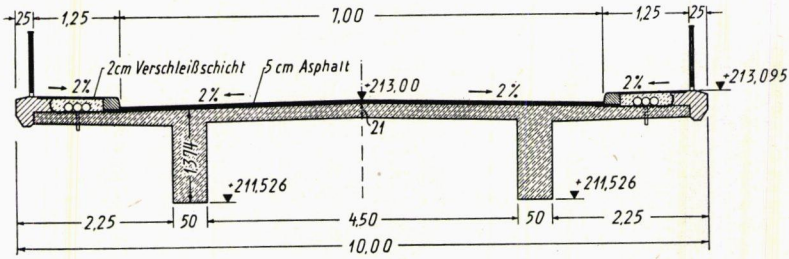
Sixty papers have been published on the design of prestressed-concrete bridges. This design is really no more difficult than the de-



General View

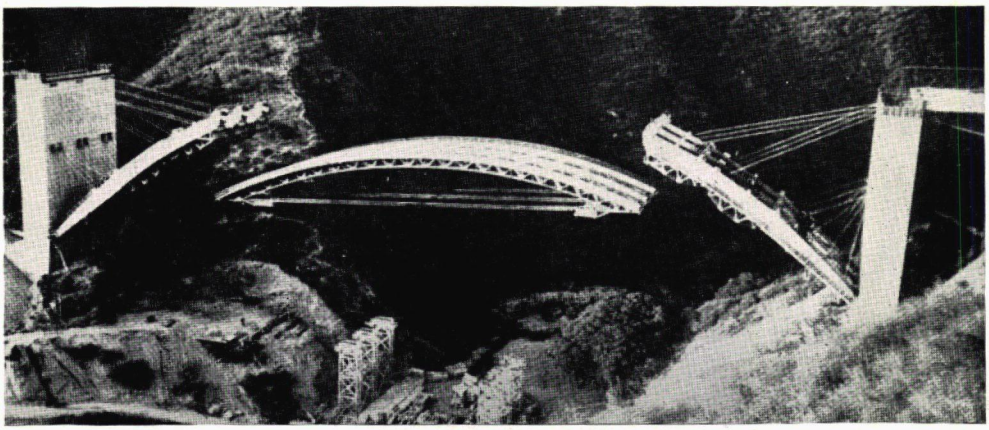


Longitudinal Section

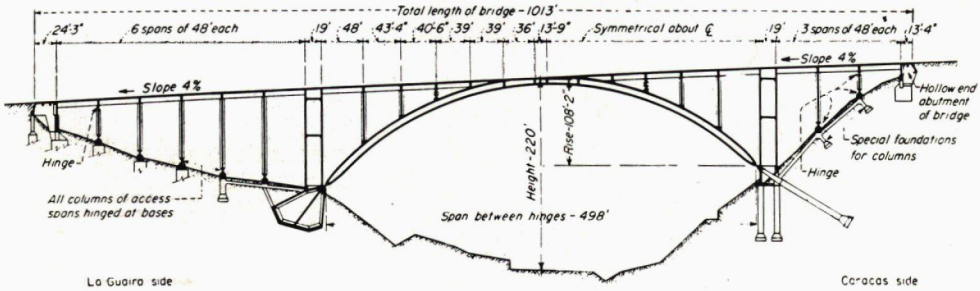


Transverse Section at Mid-Span

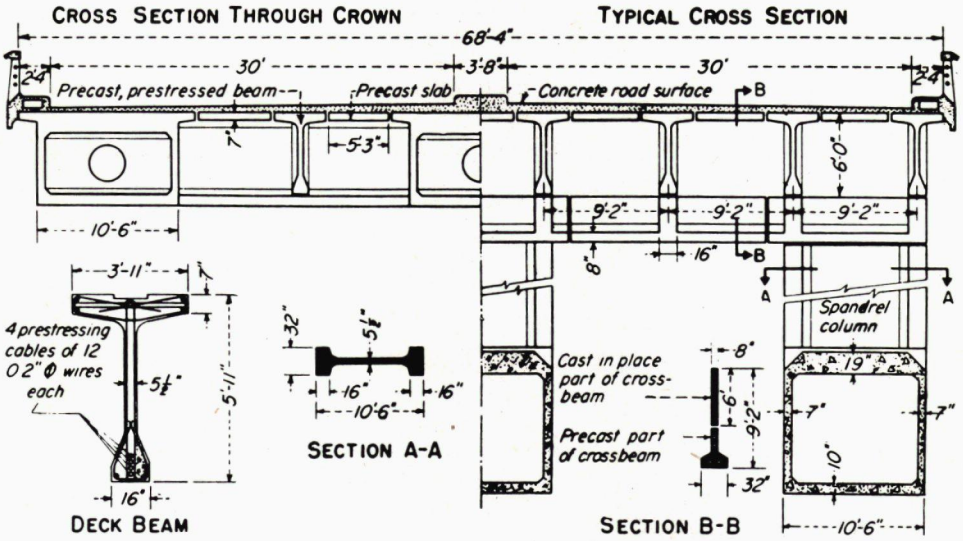
Figure 12. Highway bridge at Neckar Canal, Neckarem, Germany: progressive cantilever construction prestressed with bars.



General View



Elevation



Transverse Sections

Figure 13. A 498-ft.-span arch bridge near Caracas, Venezuela, prestressed with individual cables of parallel wires.

sign for similar conventional bridges. However, prestressed design is usually more lengthy, as it is necessary to analyze the stresses at several stages of loading in addition to those for maximum dead and live load. Analysis of statically indeterminate prestressed bridges tends to be somewhat more complicated and lengthy than for conventional construction, due to the prestressing which must be considered as an additional loading condition.

to the many practical considerations which must be explored.

Solid or cored slab sections with depth-span ratios of about 1 to 30 are usually chosen for simple spans of 30 to 60 ft. and which, with continuity and haunching, may be used up to spans of 100 ft.

Where it is desired to cut down the superstructure weight in the smaller-span range at the cost of greater structural depth, a composite section using prestressed-concrete gird-

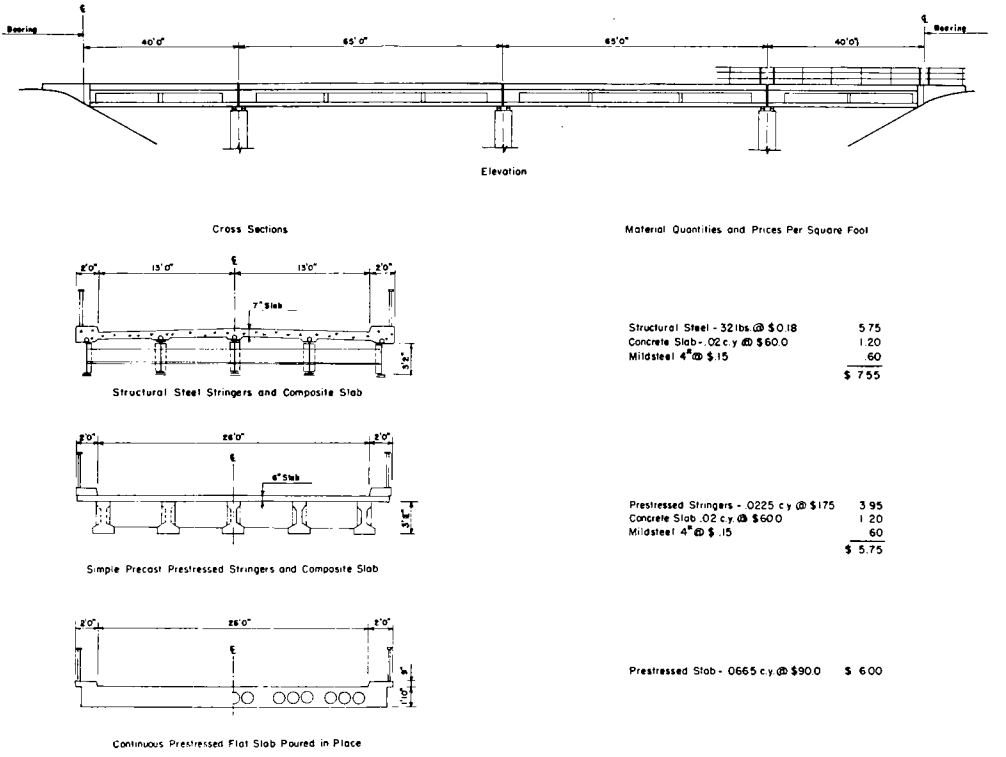


Figure 14. Material and cost comparisons for typical thruway overpass bridge.

A conventional calculation for shear has little meaning with a prestressed-concrete section if it ignores the effect of the prestressing force. It is necessary to consider principal stresses by drawing a Mohr circle. By suitable vertical inclination of the prestressing, it is possible to eliminate all diagonal tension.

Considerable experience is needed in selecting the most-economical section, which is seldom the most-theoretically efficient owing

ers keyed to a poured-in-place slab may be used. The depth-span ratio with this type of section would usually lie between 1 to 12 and 1 to 20, depending on the transverse distance between stringers.

Where depth is not the limiting factor, the transverse spacing of the stringers should be increased proportionately with the increase in span length.

Continuity can best be applied to cast-in-place construction and has been effectively used in the range of spans from 60 to 350 ft.

CONSTRUCTION

In the construction of these bridges, normal concrete methods are followed for both precast and cast-in-place construction, but greater supervision is required to insure accuracy of formwork and concrete control, due to the higher-strength concrete and thinner sections used. Unusual features of construction are mainly the placing, stressing, anchoring, and grouting of the prestressing elements, which must be done with the greatest possible care and accuracy.

In posttensioned construction, the prestressing steel is either placed in holes formed in the concrete by metal tubes or rubber mandrels of one kind or another or placed in light-metal, liquid-tight conduits, either of circular or rectangular shape, which are positioned and fixed in the formwork in much the same manner as reinforcing bars. Many types of jacks have been developed for stressing the various prestressing elements. Stresses in the steel are calculated from the hydraulic-jack pressure and cross checked by multiplying the measured strain of the steel by its modulus of elasticity. By such cross checking, it is possible to determine the degree, if any, of internal friction particularly in curved units.

Grouting of the prestressing units after stressing must be done in such a way to assure complete penetration of the grout surrounding the steel from end to end of the member. Best results are obtained by using a displacement-type pressure-grout machine and a grout mixed in the proportion of one part cement, ¼ part flyash, ¾ part fine sand, 4 to 6 gal. of water per bag of cement and 1 lb. of a lubricating admixture such as Plastiment. This grout should be injected at a pressure of approximately 50 psi. until it flows from the vent hole at the far end of the member in sufficient amount to indicate that all air has been expelled. All escape holes should then be plugged and pressure maintained on the grout for about 1 min.

RESEARCH

About 150 papers have now been published on various phases of research in prestressed concrete for bridge construction. A great deal of work has been done on the static and creep properties of various prestressing materials and anchorages and, to a lesser extent, on their fatigue properties. Many full-size girders, including one girder 160 ft. long at the Walnut Lane bridge, have been loaded to destruction, and in most cases, the deflections and loading at cracking and failure corresponded closely with the calculated conditions. A number of tests have been made to compare the behavior of prestressed girders using bonded and unbonded prestressing. These show that while cracking in each case will occur at approximately the same load and deflection, the unbonded condition will result in failure at a much-lower increase in load after cracking than for the bonded condition. Lehigh University is now conducting an interesting fatigue test on a 40-ft. girder subjected to 1 million cycles of application of live load. Creep in concrete has been investigated quite fully, and we are now able to predict with reasonable accuracy the losses which are likely to occur under most conditions.

This research has been undertaken without any centralized coördination, with the result that certain important fields have been neglected. We know far too little about the fatigue and relaxation properties of many prestressing materials and anchorages. We also need to know more about the change in the modulus of elasticity of steel and concrete under increasing, decreasing, and sustained stresses. There has not yet been sufficient research on the fire-resistance properties of prestressed structures.

PAVEMENTS

The high elastic properties of prestressed concrete should make it an ideal material for the construction of pavements built without joints over considerable lengths, but the author has been unable to deal with this subject in the same detail as bridges, as only two pavements have been built so far. This is because no satisfactory solution has yet been found to overcome the effect of friction with the subbase, which for normal coefficients of friction, rapidly neutralizes the effect of prestressing in comparatively short lengths.

Figure 15 shows various methods of prestressing pavements which have been suggested. The runway at Orly Airport, in France, designed by Freyssinet, is 1,380 ft. long by 200 ft. wide and was constructed with a triangular joint pattern, using transverse prestressing

and rollers in the joints with the longitudinal reaction resisted by heavy concrete abutments. The other example is a section of highway pavement at Crowley, England, 400 ft. long by 24 ft. wide, prestressed with the basket-weave arrangement to impart a transverse prestressing.

When concrete is placed under compression it must shorten elastically. In pavements, this shortening is resisted by friction. Suggestions have been made to place a lubricated surface over the subbase to reduce friction, but while this might permit the use of longer sections of pavement, it would only exaggerate the problems of joints between the sections capable of taking greatly increased thermal movements.

One possible solution to overcome the restraint of friction would be to pour the concrete continuously with temporary transverse construction joints provided at frequent intervals using prestressing placed in a diagonal pattern. As the prestressing proceeded along the pavement, each joint, in turn, would be jacked apart by an amount exactly equal to the elastic shortening of the concrete between the joints. While held by the jacks, the joint would be filled with mortar, which would be allowed to gain its full strength before the jacks were relaxed. In this way, the prestressing would then react against the mortar in the joints to place it under the same compression as the slab, without overall shortening of the pavement. By this means, it might be possible to construct a continuous slab without joints uniformly prestressed to prevent buckling during warm weather or tension cracking in cold weather. Such a slab would respond elastically to wheel loads to the extent that its precompression would withstand bending moments.

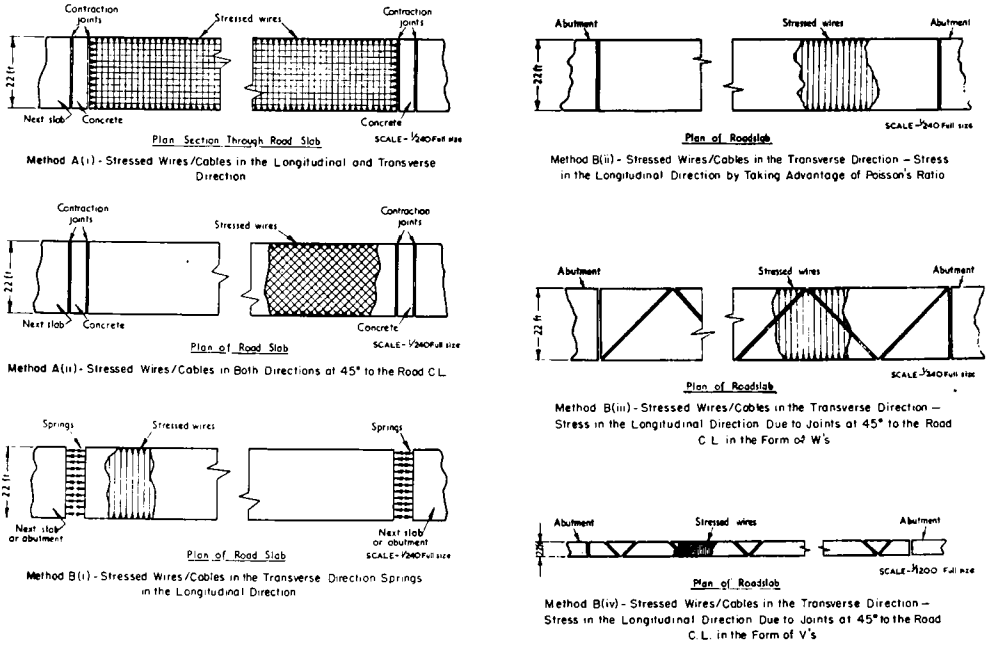


Figure 15. Methods of prestressing pavements.

A small amount of money devoted to research in this field might well produce surprising and spectacular results.

CONCLUSION

In the past few years the idea of prestressed-concrete bridges has developed from a glint in the eye of a few visionaries to a full-fledged competitor with older methods of construction. The recent introduction of new materials and methods of construction have reduced the labor required for the prestressing steel from 150 man-hours per ton to something

in the order of 30 man-hours per ton. Five years ago there was not one prestressed bridge in North America, but today they have been constructed in at least 15 states. Many of the old, patented, and proprietary systems of prestressing have been swept aside in the onrush of more-efficient materials and methods of construction available to designers and builders without restriction. Instead of opposing this healthy development, designers and builders with experience in this field should lend every assistance to those who wish to enter it and should look for their reward to the expanding market which they will thus help to create.

Just as in suspension bridges, there will always be a place for the specialist designer and contractor for the larger and more-complicated structures which are bound to develop as confidence increases as a result of the successful construction of a large number of smaller structures.

For prestressed concrete to gain its rightful placed in the large future for highway bridges which lies ahead, we must be willing to set aside the restrictive use of patents and confusing claims for competitive "systems" and direct our talents toward research, which is sadly lacking in certain areas, toward designs tailored to suit the job and not the "system," and toward continuing improvement in prestressing materials and construction methods.

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DISCUSSION

E. L. Erickson, *Chief Engineer of Bridges*, and D. P. Babcock, *Highway Bridge Engineer, Bureau of Public Roads*—This paper is interesting and useful, especially the paragraph on "Economics." Most engineers today are convinced that prestressed-concrete construction is practical in many cases, but due to the high labor costs in the United States, they believe that other systems are more economical. For some types of construction this is probably still true, but for others the author of this paper presents data to show that considerable money may be saved by recourse to prestressing. The very fact that

the prestressed method is growing so fast in popularity in this country would indicate that an increasing number of engineers believe it to be economical.

The reduction in the past few years from 150 man-hours to 30 man-hours per ton required to prestress the steel has doubtless had a lot to do with the increase in its use.

The data presented by the author in Figure 14 for a 65-ft.-span superstructure shows the cost of a steel stringer design to be $7.53 per sq. ft., $6 for a prestressed slab bridge and $5.75 for a prestressed stringer bridge. These figures are based on $60 per cu. yd. for ordinary concrete, $90 for prestressed concrete slab, and $175 for prestressed-concrete stringers. It would be interesting to know how these values were determined.

A few statements made in the paper seem to require further explanation:

"In these bridges the arches themselves are prestressed to overcome tension caused by raising the neutral axis above the funicular curve to facilitate transfer of wind forces to the deck." It is not clear how this prestress facilitates the transfer.

"As there is no need to have any concrete below the neutral axis under full design load depth span ratios can be greatly reduced. . . ." If the prestressing produces compression throughout the section under full load then the concrete below the neutral axis is effective; or shall we say that the neutral axis moves down to include the whole cross section? It would be interesting to have the description of Freyssinet's runway at Orly airport somewhat elaborated.

It would seem as though prestressing would tend to increase buckling of a pavement in warm weather, rather than preventing it, as stated in the paper.

Curzon Dobell, *Closure*—The author wishes to clarify the points brought out by Erickson and Babcock in their interesting discussion of the author's paper.

The unit costs used for purposes of comparison in Figure 14 developed from a careful analysis of costs.

The cost figures used in Figure 14 for a steel stringer type bridge were based on the average cost figures published by the New York State Park and Public Works Department for the New York State Thruway and including an allowance for the cost of cement. (Cement is furnished by the owner for these projects and therefore its cost is not reflected in bid tabulations.)

The unit prices used for the typical precast, prestressed stringer bridge are based on a preliminary design and estimate made by The Preload Company, Inc., for the Ohio Turnpike Authority. The stringer prices shown in Figure 14 reflect the unit cost experience being developed on the Tampa Bay Causeway project adjusted for changes in labor and material conditions.

The cross section and cost estimate of the typical slab bridge, as shown in Figure 14, is taken from a design made by The Preload Company, Inc., for a four-span continuous bridge for the New York State Thruway. Preload Construction Corporation prepared a detailed estimate of costs which was checked against current bid prices for cast-in-place concrete bridges.

All prices are bid prices; however, it is not likely that these costs can be realized on a single structure, particularly on the precast solution.

Evidently, the statement concerning Freyssinet's Venezuelan bridges requires amplification. For reasons of live-load distribution in the arch ribs, the arch pressure line at the crown was purposely placed high near the level of the deck slab by the use of flat jacks in a temporary joint at the crown. This pressure-line eccentricity and the resulting bottom tension called for some prestressing cables which were stressed after the crown joint had been mortar packed. Also, in order to transform the deck into a continuous horizontal stiffening diaphragm, the deck girders were connected to the arch ribs at the crown by anchoring in the arch the continuous prestressing cables at the top of the girders.

The statement that in prestressed concrete there is no need for concrete below the neutral axis perhaps requires some clarification. The intention was to draw a comparison as to section efficiency between conventional reinforced concrete and prestressed concrete. Whereas in reinforced concrete it is necessary to have a substantial part of concrete below the neutral axis for no structural purpose except to maintain the reinforcing in position, in prestressed concrete the neutral axis can

be located at will by the amount of prestressing force used, even to where it lies outside of the section under full load. In most prestressed-concrete designs, the neutral axis coincides with the bottom fiber under working load, eliminating the unnecessary concrete of conventional reinforced-concrete design and enabling the whole concrete section to resist flexural strain.

The general interest in prestressed pavements is gratifying. However, it was felt that description of all technical details of one particular project was somewhat beyond the scope of this paper. A description of Freyssinet's Orly runway is given in an article published in the September 16, 1948, issue of *Engineering News-Record.*

With reference to the author's suggestions that prestressing of pavements would, in addition to other benefits, prevent buckling failure, reference is made to a number of tests performed by Gustave Magnel, of Ghent. These tests demonstrate that where prestressing is centrically located in a prestressed member, even with an extreme slenderness ratio, it is impossible to produce buckling failure if the prestressing force is of sufficient magnitude. The explanation is that the self-centering effect of the prestressing force increases at a faster rate than the forces tending to produce buckling.

The author hopes that the foregoing explanations will answer the interesting questions raised in the discussion of his paper.

Median Study (California)

EDWARD T. TELFORD, *Traffic Engineer*, and
RUDOLPH J. ISRAEL, *Assistant Traffic Engineer*
California Division of Highways

ON the basis of both total accidents and casualty accidents, traversable divided and deterring earth medians were uniformly low in this study. Other deterring medians show lower rates than the undivided with all types of nontraversable medians exhibiting substantially the highest rates.

When the various medians were compared on a basis of traffic volume, it was found that traversable medians had the lowest total and injury accident rates for traffic volumes under 15,000 vehicles per day. Above this volume the advantage shifted to the deterring types of medians and, as indicated by a small sample, to nontraversable medians. Some 10,000 to 15,000 vehicles per day appears to represent optimum volume range for four-lane highways. Within this volume range the undivided highway virtually matched the lowest divided highway rates.

When the sample was sorted on the basis of median width, the lowest accident and injury accident rates for deterring medians were definitely in the 4-to-6-ft. range. Traversable medians showed lowest total accident rates in the 6-to-10-ft. range and lowest injury accident rates in the 20-to-30-ft. width group. Widths of nontraversable medians were not significant in this study.

A breakdown on the basis of type of accident shows that approach-type accidents are significant only for the undivided highway. Overtaking accidents increase slightly from traversable to nontraversable medians. The single-vehicle-accident rate for nontraversable medians is double that for other types.

On the basis of severity, deterring types of medians are lowest in casualty accidents per MVM, casualties per MVM, and casualties per 100 accidents. Nontraversable medians have markedly higher rates than all other types for casualty accidents and casualties per MVM, but the higher percentage of multiple-vehicle accidents occurring