Construction of Post-Tensioned Bridges in Germany

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ABSTRACT

A system for producing crack-free prestressed concrete by avoiding the temperature differentials due to escaping heat of hydration and sunshine is discussed. A description of girder production is followed by a report on slab production. The requirement of the strictest possible homogeneity of girders and slab is covered, and the structural, organizational, and economic advantages of the system are enumerated. If applied according to specifications, this system produces crackless prestressed concrete of such density and appearance that almost no maintenance is required. The system also yields considerable savings in material, labor, and overhead.

Concrete, an artificial conglomerate, has been in existence for more than 4,000 years. Until about two centuries ago the high compressive strength of its main ingredient, the aggregate, could not be taken advantage of because of the low compressive strength of its other ingredient, the binding agent.

The development of modern cement was a great improvement. It increased the compressive strength of the binding agent to approximately half that of the average aggregate, which meets most requirements. Unfortunately, concrete cannot withstand tension and therefore cannot endure bending. Wherever particular tensile stresses occur they result in cracks.

A century and a half ago Sir Marc I. Brunel thought of taking up the tensile share of a concrete section by iron rods and thus became the first person to apply the idea of reinforced concrete. It is now known that reinforced concrete does not fulfill its original purpose: reinforcement does not prevent cracking of concrete.

A further attempt to eliminate cracks was made about 50 years later by P.H. Jackson of San Francisco. Because the tensile strength of rebars is scarcely used unless the concrete has cracked, Jackson tried to prestress them, but the attempt failed because the prestress was reduced to almost nothing by shrinking and creeping of the concrete. Jackson's idea was finally realized by E. Freyssinet who introduced the first useful stressing system and built the first prestressed concrete bridge in 1939 near Oelde in Westphalia. This was made possible by the development of high-grade steel.

Modern reinforcing steel has such high tensile strength that not one-tenth of its allowable tension is used if the concrete is not cracked--and cracked concrete is precisely what reinforcement was intended to prevent.

After World War II, when many bridges in Germany had been destroyed and the price of steel rose enormously, prestressed concrete experienced a veritable boom. At the same time statically indeterminate systems became popular. Impressed with the possibilities of the latter, (e.g., continuous steel girders, or rigid frames, or boxes) most engineers tried to combine the two by developing methods for building continuous prestressed concrete structures.

Unfortunately, none of the methods yielded crack-free concrete. Because nobody knew what caused cracks they were considered inevitable. One might as well accept cracks and enjoy the fringe benefits of prestressing, such as larger spans or more slender beams. The idea of crack-free prestressed concrete was gradually forgotten.

A similar fate befell an article by Philipp Schreck (1) wherein he exposed the causes of cracks: the temperature differentials due to escaping heat of hydration and to sunshine. In a later supplement he proved that crackless continuous prestressed concrete structures cannot be built economically. This article too went unheeded by the profession.

Schreck was undaunted and finally realized Jackson's idea. Schreck developed a construction system that, by avoiding the detrimental effects of temperature differentials, produces crack-free prestressed concrete in the field and eliminates most problems associated with concrete bridges. Although cracks in reinforced concrete tend to be somewhat evenly distributed, rather numerous, and therefore narrow, theory tells us that with prestressed concrete just the opposite is true. Cracks occur in prestressed concrete in small numbers, are comparatively wide, and appear close to the supports. Such cracks are an effect of the two temperature differentials mentioned previously.

The notion of evenly distributed cracks in a continuous prestressed concrete structure is a pipe dream. Four conditions would have to be fulfilled:

1. The tension at the underside of the member would have to be constant;
2. The critical tension that induces cracking of the concrete would have to be constant;
3. The shear between grout and tendon and between rebars and concrete would have to be constant; and
4. The sectional area of reinforcement and of prestressing steel would have to be constant.

Note that none of these conditions is fulfilled in current practice.

Another point must be considered: A steel bridge announces its failure far in advance by visible alterations that allow its remaining service life to be determined fairly correctly. In contrast, prediction of the time of rupture of a tendon in a prestressed concrete bridge is virtually impossible. This implies that, if such a bridge has cracks, there is a constant danger of imminent collapse.

During the development of his system Schreck found, by theoretical deduction as well as by trial and error, that to avoid cracks each member of a prestressed concrete structure must be designed and treated as homogeneously as possible in all respects. This most important and peremptory condition explains the simplicity of the system (G. Pluemer, The Viaduct System, presented at annual meeting of TRB Committee on Construction of Bridges and Structures, Washington, D.C., January 20, 1982).

GIRDER PRODUCTION

The temperature differentials due to escaping heat of hydration and to sunshine affect structurally indeterminate systems of considerable height, such as box girders and continuous structures. This led

to using only simple T-beams. Although the construction height of the girders may amount to 1/16, 1/15, or even 1/14 of the span, the thickness of the slab may vary only from 24 to 28 cm, with negligible temperature difference between top and bottom. And although the girders span lengthwise from pier to pier, the slab spans crosswise from girder to girder. This distinction between the two components of a T-beam is clearly reflected in the separate production of girders and slab.

The use of a structurally determinate system all but eliminates the effect of the temperature differential due to sunshine. This leaves the problem of the escaping heat of hydration. Common sense as well as experience indicate that forced changes in the temperature of a concrete member, such as cooling its outside with cold water or heating it with steam, do not prevent a detrimentally large temperature difference between the outside and the core.

The safest and most practicable way to avoid temperature differentials is to heat the outside of the concrete member with warm air that, thanks to the development of unit heaters that use all kinds of fuel, is very economical and easy to do. A hollow steel form is required to serve as a warm air duct, and thermostats must be imbedded in the concrete section to monitor the unit heaters. The walls pointing away from the future girder must be insulated; this is most readily achieved by spraying their inside with plastic foam.

No falsework is needed because the double-walled form is self-supporting. To give it even more strength and the necessary camber, the form is prestressable. Inside the wall facing the future girder are extra-heavy-duty vibrators that can be activated individually for external compaction. The bottom plate, rigidly connecting the two side parts, is also double walled and foam insulated. The top of either side part is secured by removable railings. The gap between the two can be closed by insulated flaps and the ends can be closed by special plates designed to support the anchorage bearings.

The whole apparatus thus serves as

1. A form for the girders,
2. Its own falsework,
3. A compacting tool,
4. A heating device,
5. A curing container,
6. Shuttering gear,
7. An adjusting utensil,
8. A working space, and
9. A footbridge.

The girders have a cross section like an inverted T. They consist of a web and a bottom flange. The latter stands out 45 cm on either side of the web. The flange slopes outward with a pitch of 8 degrees and has an average thickness of 25 cm. The web has a thickness of 30 or 35 cm, making the flange 1.20 or 1.25 m wide. The height of the web depends, of course, on the span length. The top of the web ends, temporarily, at about the level of the underside of the future deck. For subsequent connection of the web and deck two parallel rows of stirrups shaped like inverted U's stick out of the web. With the exception of a slight widening at both ends, to accommodate the anchor plates, the cross section of the girder is constant throughout its entire length.

The girders are cast in place onto the bearings. These are of three kinds: (a) laminated steel-elastomer deformable in all directions, (b) laminated steel-elastomer that slide lengthwise, and (c) laminated steel-elastomer that are adjustable lengthwise. The adjustment of (c) is done by turning bolts and can be done under full load. To facilitate removal of the form its bottom part is slotted at the bearings, and the slot is closed with adjustable plates on high-speed bolts.

Two transportation trusses, 1.5 spans long, move the equipment forward into the next field where it serves as a gangway from pier to pier and as a working platform for the assembly of the reinforcing cage. Because the latter is too wobbly to be picked up at the ends, it is hooked onto the reinforcement carrier, a prestressed lightweight truss. A pair of hoisting frames affords vertical and lateral movement of the equipment, which is completed by an air compressor and a group of unit heaters with flexible ducts.

First the bearings are set on their concrete pads and the bottom part of the form is installed around them. Then one side part is connected to the bottom and the form is oiled very lightly. In the meantime the reinforcing cage including conduits has been assembled at the working platform on top of the transportation trusses; it is now lifted into place by the reinforcement carrier. Then the other side part of the form is moved over and connected to the bottom. After setting of the end plates and connection of the anchors thereto, the form is linked up with heater and compressor and is ready to be prestressed.

The concrete should at least be B 35 with a 28-day compressive strength of 5,000 psi. Usually B 45 with 6,500 psi is used, but an intermediate value of B 42 with 6,000 psi will suffice in most cases. The aggregate should be of constant mix, quality, and low cement demand. The water-to-cement ratio should be around 0.38; additives should be avoided.

The concrete is pumped into the form in the afternoon. The depositing starts at the far, or front, end and proceeds without interruption to the near end of the girder, so that there is no working joint whatsoever. Vibrators are individually activated as required to compact the concrete without segregation.

After the top has been covered by the flaps the new girder is completely enclosed and insulated so that curing is not influenced by the weather. When the concrete temperature rises, due to hydration of the cement, the unit heaters are automatically switched on and warm air is circulated through the hollow form parts so that the temperature of the core and the outer layers rises simultaneously. In this way a temperature differential due to escaping heat of hydration is avoided because the heat cannot escape. In fact, there is a heat gain that accelerates the hydration and thus the curing. This in turn speeds up the hardening of the concrete so that it reaches a rather high strength much earlier than under normal circumstances. Note that the major purpose of the warm air is to cause an even increase in temperature over the whole cross section. Faster curing is merely an additional bonus.

Shortly before midnight, when the girder has reached its peak temperature, the unit heaters are turned off automatically. After that the temperature starts to fall very slowly. Although it took about 6 hours for the temperature to rise to maximum, it takes at least 6 days or longer for it to come down to ambient level. However, 14 hours after pouring, the concrete has attained 55 to 65 percent of its 28-day strength. Not only can the form be removed, the girder can be partially prestressed; and it is now strong enough to be exposed to the air without damage.

This is the most important moment in the life of the girder. Remember that the form itself was prestressed, giving it a camber to make up for the added weight of the girder, the slab, and part of the traffic load. Now, before removal, the form is

slowly relieved of that stress while the girder is just as slowly and simultaneously partly prestressed. This avoids all vertical and lateral movement that would be detrimental to the young concrete. The new girder has been minutely shortened and the form has been considerably extended. Thus they come apart by themselves without application of external force. This explains why the system can afford wide bottom flanges with a slight slope.

One side and the bottom part of the form are now shoved into position for the next girder, and the other side part is lifted up and over the finished girder and placed next to the first side and bottom part. The inside is swept clean and oiled lightly, the new reinforcing cage is dropped in, the form is closed and prestressed, and so forth. By afternoon the next girder can be cast. One girder is produced per day.

When all girders of a span are finished, the transportation trusses are shoved over the front pier into the next field. They are then lined up with two adjacent new girders to form a two-span rail on which all the other equipment is rolled forward by casters and trucks. For this purpose the crossrails of the hoisting frames are lowered to lower their center of gravity.

The whole move takes about 1 working day, but to stay on the safe side 2 days are usually allocated. The handling of all the equipment for girder production normally requires four trained men and one helper.

SLAB PRODUCTION

About a week later, as soon as the girders are fully prestressed and the equipment for their production has cleared the span, the driveway slab is built in daily increments. Within any span the number of these segments equals the number of girders plus two, so that the speed of deck production coincides with that of girder production. On a bridge 15 m wide, for example, 3 girders and therefore 3 days are required; 2 days are scheduled for the move into the next field. This makes 5 days per span, so there will be 5 daily segments.

The major part of the equipment for slab production is the movable platform. Its front part is a little longer than a daily segment and made of rough boards. It serves as a stage for the reinforcing of the deck. Its hind part is exactly one segment long and lined with either sheet metal or Duraply. It serves as a form for the slab. The whole movable platform is divided lengthwise into strips. Those in the center are located between the girders; the outer two for the overhanging parts of the slab are supported by suspension trusses, which are lightweight steel space frames. The front ends of the trusses hang from the crossboom, a king post steel truss running on the webs of the girders between the stirrups; and their rear ends hang from cantilever carts that roll on the finished slab. The platform is built on wooden joists and blocking and is supported by steel form carts that run on casters on the bottom flanges of the girders and are adjustable in height by jacks.

When the slab section of the previous day has attained the necessary strength and when the reinforcement for the new segment has been prepared and temporarily suspended, the whole movable platform is lowered and rolled forward two increments so that it is in front of the reinforcement and fully accessible. The front part, the working stage, is swept while the rear part, the form, is cleaned and oiled. Then the platform is rolled back one increment, so that the form is now underneath the reinforcement, and raised into position. Thereafter the temporary suspension of the reinforcement is removed, the new working joint is set with a slotted board, and the form is adjusted to the girders. The next segment can now be cast.

Pumping of the concrete takes place in the early afternoon. The segment is divided into several subsections the size of the vacuum equipment. First the concrete is distributed by spade and shuffle; therefore it has a water-to-cement ratio of 0.42. Then it is compacted by bottle vibrators until it is of normal density, rather even, and about 0.25 inch too thick. Now a motor screed is passed slowly over the concrete. The screed runs on adjustable steel straightedges and gives the slab the specified slope and an evenness unobtainable manually. It condenses the concrete a second time to 0.125 inch above design thickness.

The third compaction is achieved by the vacuum technique. The concrete is covered with a two-ply mat, the bottom layer of which is perforated so finely that air or water can seep through it but cement cannot. The top layer is airtight, and its rim is carefully pressed down. A transparent hose connects the vacuum mat to a suction pump with a water meter. Within 20 to 25 minutes between 10 and 15 percent of the water is extracted from the concrete that thus loses around 1.5 percent in volume and attains the specified thickness.

While the first subsection is vacuum treated, the second section is poured, distributed, vibrated, and screeded. In this manner one subsection after the other is cast. Subsequently each subsection is finished with a skim floater, a rotating power trowel, to get a specially dense and smooth surface. Finally the new segment is covered with burlap and a tarpaulin to protect it from the weather and to prevent cooling of the surface. The whole procedure takes about 2 hours. Around noon the next day the concrete has attained the necessary strength and the process begins again. Another 24 hours later the segment can be post-tensioned and driven over by heavy equipment. The handling of the complete outfit for slab production normally requires five trained men and one helper.

HOMOGENEITY

This system offers a number of advantages in design, calculation, estimation, implementation, organization, logistics, handling of equipment, and comprehensibility for all persons involved because of its amazing simplicity and--in the broadest sense of the word--its homogeneity. Homogeneity of material is important. The concrete of the girders is treated differently than that of the slab. The former has a water-to-cement (w/c) ratio of 0.38 and is compacted once externally, and the latter has a w/c ratio of 0.42 and is compacted three times: first internally by hand vibrators, then externally by motor screed, and finally by water extraction. But the result is the same: the loss of 10 percent of the water gets the w/c ratio down from 0.42 to 0.38, and the density of both girder and slab is about 3 percent greater than that of concrete that was merely hand vibrated.

Research on vacuum dewatering has been done at the U.S. Bureau of Reclamation; the Chalmers Institute of Technology at Göteborg, Sweden; and at the Technical University of Hannover, Germany. The findings were impressive.

1. In a customary concrete slab the w/c ratio increases from bottom to top and the strength decreases; therefore the surface is less dense than the underside. In a vacuum treated slab the w/c ratio decreases from bottom to top and the strength

increases; therefore the surface is denser than the underside. Skim floating can only be done with vacuum treated concrete; customary green concrete is much too soft before setting, and after setting it is too hard.

2. Permeability is cut 60 percent with each percent of increase in density. If a concrete is made 3 percent denser, its permeability is cut to 0.4 x 0.4 0.4 = 0.064 or 6.4 percent. The additional skim floating reduces it further to about 5 percent. This was corroborated by numerous tests in which customary concrete showed a water penetration of 20 mm but vacuum treated concrete was permeated less than 1 mm.

3. The vacuum does not remove air from the concrete, but it expands the individual bubbles due to loss of pressure. When the voids are enlarged the air therein gets thinner. Frost resistance of the concrete thereby is increased considerably without raising the air demand.

4. As a result of the triple treatment (screeding, dewatering, and skim floating) the surface not only gets stronger, denser, and less permeable but also more wear resistant. This is a rather important feature to the traffic engineer if it causes a deck to last three, four, or even five times longer.

5. Carbonization of the cement by reaction with the carbon monoxide of the surrounding air is retarded by the cube of the lowering of the w/c ratio. If the latter is cut in half, the edifice lasts 8 times longer; if it is reduced by two-thirds, the duration increases 27-fold. Obviously, even a slight reduction is significant.

6. The strength attained by customary concrete after 28 days is reached after 1 week by dewatered concrete, and after 28 days is surpassed from 20 to 30 percent.

More tests have been made with similar results: shrinking and creeping are reduced considerably, there is no edge rising of slabs, the method is applicable to vertical or curved surfaces, and so forth.

The resistance of dewatered concrete to extreme changes in ambient temperature and tremendous pressure is demonstrated by the fact that it was used to line the fire chamber and exhaust tunnels of the space shuttle launching pad at Vandenberg, Calif., where the temperature reaches 6,000° F.

Just as important as homogeneity in material is constancy in all other respects. It has already been mentioned that, with the exception of a slight widening at the ends of the webs to accommodate the anchor plates, there is no enlargement or reduction of the girders; there are no cutouts; there are no crossbeams; there are no diaphragms.

Constancy in statics means a structurally determinate system; an elastic cross section, not a rigid one; and no constraints. That is why this system uses simple beams, a T-beam section, and direct, three-dimensionally elastic bearings.

Constancy in function means clear differentiation of the carrying direction of the members. The girders are prestressed longitudinally, but the slab is prestressed transversely. Continuous structures, both T-beam and box girder, under average loading conditions have positive moments in the field and negative ones over the supports. Ideally, the superstructure should be upside down. But because such a structurally correct solution is rather impractical, it is replaced by heavy reinforcing over the supports. The concrete is thicker and proportionately more mild steel is used. This system is utterly heterogeneous.

Homogeneity in treatment during construction means steady and even pouring, condensing, heating, and cooling of the concrete until it has attained the strength necessary to withstand any deviation. It means no movement, neither vertical nor lateral, during removal of forms. Transfer of carrying function from form to girder should be compensated by temporary shoring or by partial prestressing. Homogeneity means no transport of the member because that requires measures (such as a makeshift upper flange or special reinforcement) that later on, under service conditions, have no function whatsoever. The transport itself is expensive and constitutes a stress to which young concrete should not be subjected. Homogeneity also means gradual loading, with a safe time lag between increasing strength and corresponding stress. All these requirements are met by the system discussed herein.

Homogeneity in behavior under service load means constancy of structural conditions. This requirement automatically excludes use of the continuous beam because of the reversal of moments and consequent wrong position of tendons as well as because of considerations of inversion and continuity.

STRUCTURAL ADVANTAGES

Forty-eight hours after production the slab is fully integrated into the T-beam section. Creeping of the girder causes the daily working joints to be pressed together. There is also a transfer of stresses from the web to the deck that takes over its share of the compressive zone. The effective width of this upper flange is 12 times its thickness plus the width of the web, namely 3.60 m or three times as wide as the lower flange. Because the latter is situated within the precompressed tensile zone its area is adequate to withstand that precompression. It is built rather shallow and 1.20 m wide for three reasons: First it raises the moment of inertia (I) of the concrete section. Second it allows the lower two tendons to spread apart 1.00 m center to center so that the next pair may come down all the way; this increases the value of both I_x and I_y. Third it affords a track for the form carts and other equipment.

Another way to considerably raise the I_x is an increase in construction height because height enters the formula by the third power. For aesthetic reasons the height should not surpass 1/12 of the span and not fall short of 1/18. The mean value of 1/15 of the span length turned out to be the most effective and economic. The result is a wide flange section, with a high moment of inertia, made of a material with a high modulus of elasticity.

Naturally such a beam has a rather low deflection and consequently an equally small end rotation, less than half that of a standard precast girder. This in turn sharply reduces the negative moments within the slab that is continuous over the piers. The gap between the girders is 50 cm or 1 ft 8 in. The bond between girder and slab is broken on either side for another 50 cm. Thus the slab is given 1.50 m or 5 ft 0 in. for slight negative bending. Within this stretch it is reinforced a little more with mild steel in both directions, and the transverse prestressing tendons are closer than along the major part of the span where they usually are installed at 1.00 m center to center. A thickening of the slab is unnecessary, so it too is constant throughout the length of the bridge. The only heterogeneities are the expansion joints that occur at intervals of approximately 300 meters or 1,000 feet.

The goal of the system is to construct crackless concrete. One more way to avoid cracks is full prestressing. This means that each member is under constant compression in its particular carrying direction and that tensile stresses in other direc-

tions within the concrete, if they occur at all, are limited in origin, time, location, and intensity, never surpassing the allowable tensile strength of the concrete diminished by a substantial safety factor.

In prestressed crack-free concrete the slack reinforcement contributes less than 5 percent to the tensile strength of the member, and prestressing steel is more than five times more effective than slack reinforcement. It therefore makes neither structural nor economic sense to replace part of the prestressing steel by slack reinforcement or to partially stress reinforced concrete. There is no continuous transition from reinforced concrete, via restricted prestressing, to fully prestressed concrete. One cannot mix cracked concrete with crackless concrete.

Furthermore, the system uses full bond. Prestressing steel without bond "does not participate in transfer of stresses, nor contribute to the limitation of the width of cracks" (2), and it contributes not at all to their avoidance. The system also uses subsequent bond, or post-tensioning, because immediate bond, or pretensioning, is suited only for the precasting of parts that are limited in size and purpose.

The continuity of concreting ensures homogeneous material. Each girder is cast in a single operation, and the slab is built in successive portions small enough to be easily and quickly handled by the crew. While the girders are still relatively warm the deck is built at a considerably lower temperature level that, by transfer of heat from slab to web, averts the danger of cracks due to temperature differential.

ORGANIZATIONAL ADVANTAGES

This system is extremely industrialized, which means it achieves the largest output possible by employing the fewest personnel and least equipment possible and keeping them both constantly busy. The production cycle is as short as the material allows, and its course is fully adapted to the final product. Any and all operations that are not absolutely necessary are avoided, thus considerably reducing their number. Finally the system is as simple and as clearly arranged as possible. Five men handle the equipment for girder production, six men that for building the deck; including the supervisor this makes one dozen people.

Once the equipment is mounted it is easy to handle; it is self-propelling, so to speak. No heavy hoisting gear is required. For a 140-ft span the equipment weighs less than 100 metric tons or 220 kips. The heaviest part, one side of the form, weighs approximately 26 tons or 57 kips compared with the 113 tons or 250 kips of a girder.

Because of the special treatment of the concrete, the production cycle can be set at 24 hours for the girders as well as for the slab. Day after day both crews perform the same work. Every day the same equipment is handled at the same hour. Day after day the same type and amount of material are needed at the same time.

Because the slab can be driven over with heavy equipment 2 days after pouring, all supplies can be brought in over the bridge itself. The system is fully independent of the ground underneath, which needs never again be touched once the substructure is finished.

Reinforcing is easy: there are only four sizes of rebars, and more than half of them are straight and uncut. Most bent bars are used over and over with regular spacing. The number of conduits is relatively small and their positioning not at all problematic because there is no inversion; this also alleviates installation of the tendons. There are no coupler joints.

Because the system is repetitious, rational, and easily understood, break-in of the crew is fast and uncomplicated. The same holds true for all other people involved. The remarkable simplicity of the system results in considerable facilitation of the engineer's task: design, calculation, and supervision are much easier. Estimating, bidding, scheduling, organizing, implementing, settling of accounts, and dealing with subcontractors are easy for the contractor. And, of course, the job is just as easily manageable for the owner.

ECONOMIC ADVANTAGES

That a simple construction method like the one described herein yields savings in material, labor, overhead, and maintenance is not at all astonishing. The magnitude of these savings can be illustrated by a comparison of two different designs for the superstructure of a typical bridge, that across the 150-ft deep Waldnaab Valley near the town of Weiden, Germany. It has 8 spans 140 ft 3 in. long, a construction height of 9 ft 0 in., and a width of 46 ft 0 in., with 3 girders per span at 15 ft 4 in. on centers. This bridge was designed and costed out as a continuous box and as simple T-beam according to the system described here (Table 1). The latter was executed.

TABLE 1 Comparison of Continuous Box and Simple T-Beam

	Continuous Box	Simple T-Beam	T-Beam as Percent of Continuous Box
Concrete B 45 (yd^3/ft^2)	0.085	0.058	68.5
Reinforcing steel (lb/ft^2)	12.3	5.7	46.7
Post-tensioned steel (lb/ft^2)			
Longitudinal	3.3	2.9	87.5
Transverse	1.54	0.96	62.7
Working time (hr/ft^2)	0.186	0.093	50.0
Maximum compression (psi)			
During construction	3,570	800	22.4
In-service	2,175	1,203	55.3
Maximum diagonal tension (psi)	145	52	36.0

The continuous box must endure two-thirds more compression during construction than under service conditions, but the simple T-beam must endure one-third less. Under service conditions the maximum compression in the simple T-beam is only half that in the continuous box, the diagonal tension merely one-third. Because the concrete of girders and slab is of such density and appearance that it requires neither finishing nor upkeep, maintenance is practically nil.

If applied correctly and executed in the right manner, this system guarantees a superstructure without cracks, thereby avoiding most of the problems encountered with prestressed concrete today. This system also costs less both initially and in the long run.

CONCLUSION

Cracks are by no means inevitable, but they are fatally dangerous to prestressed concrete bridges. There is no way to predict the time of failure of such structures. Narrow cracks are barely less perilous than wider ones because their width increases in time. There is no way to distribute them evenly over a continuous prestressed concrete girder.

Because cracks are dangerous they must be avoided. Prestressed concrete, by virtue of its definition and of the idea which led to its invention, has no cracks. To avoid cracks need not necessarily be expensive.

The system described in this paper produces crack-free concrete economically. The success of the system is demonstrated by the bridges that have been built using it.

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Rehabilitation of Steel Truss Bridges Using a Superimposed Arch System

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ABSTRACT

A system for reinforcing steel truss bridges has been developed. The system consists of superimposed arches with hangers supporting the existing floor beams, which may be reinforced or replaced with new ones, as well as additional intermediate floor beams. To date this system has been applied to three bridges ranging in span from 74 to 136 ft. The first application was to a 100-year-old, 74-ft Pratt truss bridge at Coudersport, Pennsylvania. For a total cost of $62,000, including painting of the bridge, the borough of Coudersport was able to increase the posted weight limit of the bridge from 3 to 20 tons. Given reasonable routine maintenance, the bridge could provide service for another 100 years. During the installation of the reinforcing system, which took 3 weeks, traffic flow was maintained.

In the U.S. highway network there are still many steel and wrought-iron truss bridges of the prefabricated, pin-connected type built during a 50-to-60-year period around the turn of the century. These bridges were designed for loads considerably lighter than the AASHTO H-20 or HS-20 loadings, to say nothing of the trucks that are permitted and contemplated on our Interstate system. Over the years little has been done to improve the carrying capacity of these bridges; in fact, accidents and limited maintenance have usually led to serious deterioration.

There is ample evidence that many steel truss bridges on secondary highways and local roads are in need of replacement or major structural repair. These truss bridges typically have pin connections, and rust as well as corrosion and fatigue damage to the pins and the eyes of the truss members cannot be detected. It is clear that all of these bridges cannot be replaced and that the problem is worsening. When resources are limited, all bridges, particularly aged ones, should be looked after. Thus a cost-effective program of reinforcement and rehabilitation of these aging truss bridges is needed.

The present procedure for determining the maximum safe live load capacity of existing bridges is supposed to consider the effect of deteriorated portions of the bridge such as (a) rusted and dislocated end supports, (b) deformed and corroded members, (c) stretched or otherwise loosened I-bars that can no longer be counted on to carry their planned share of the load, and (d) inconsistent and uncertain quality of the material of the members.

The most critical regions, where most structures fail, are the joints. These portions are virtually impossible to inspect to determine the extent of deterioration. The only way to inspect such portions accurately is to completely disassemble the bridge joints, which would typically require the disassembly of the entire bridge. In the absence of such detailed inspection and evaluation of the joints, the presently posted weight limits for steel truss bridges are questionable, yet they severely limit the utility of many of our rural roads.

Many of the old, locally owned bridges are narrow. However, there is little evidence that serious accidents occur on these bridges, primarily because of the openness of the truss structure that permits easy visibility of oncoming traffic and the low volume of traffic on most of these bridges. Therefore it would be a low-priority use of public funds to provide wider bridges at many of these locations. Many of the roads leading to these bridges are only slightly wider than the bridges themselves; providing a modern-width, two-lane bridge would make little practical sense.