TO NEW FRONTIERS FOR PRESTRESSED CONCRETE DESIGN AND CONSTRUCTION

Fritz Leonhardt
Stuttgart University
Stuttgart
Federal Republic of Germany

The art and practice of prestressing concrete structures has stirred the imagination of civil engineers during the past 30 years. This challenge will continue and the future outlook for prestressed concrete promises even greater interest and excitement.

Freyssinet's imaginative idea, to use high strength steel wire with more than 4000 kg/cm^2 (56,000 psi) allowable prestress, led to great success and progress in prestressed concrete construction. His first publication on prestressed concrete was titled "Une Révolution dans l'Art de Bâtir" (A Revolution in the Art of Building). Indeed, a revolution was started which opened large new fields of application of concrete as a construction material.

The prestressing revolution began with a period of creativity mainly by European engineers, inventing different prestressing systems, developing special prestressing steels and providing larger and larger tendons allowing forces up to 1000 tons (2200 kips) or concentrated tendons with prestressing forces of more than 10,000 tons (22,000 kips). Special hydraulic jacks and other special equipment for stressing, anchoring, coupling, and grouting of tendons were invented. Practical experience, systematic research, and special design theories combined to provide a reliable body of knowledge of the behavior and the load carrying capacity of prestressed concrete structures.

Principles and recommendations for design could be established, and the joint effort of FIP and CEB (Comité Européen du Béton) produced a universal code to guide the design of thousands of prestressed concrete structures throughout the world.

This revolutionary period is essentially ended, the pace of new inventions in the field has slowed, and we are now entering a period of optimization, that is, selecting the technically and economically best systems and methods, free from patent prestige or other nonrational criteria. A variety of systems will still remain because their unique technical properties and advantages are needed for different applications.

PHILOSOPHY OF DESIGN

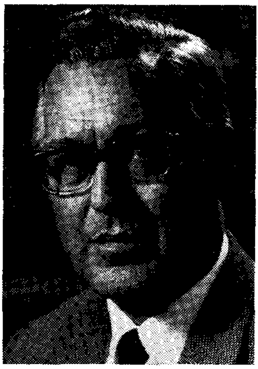
We now envision a period of critical reflection, one of questioning familiar and accepted practices, to ensure we get the best serviceability from our structures.

This paper is based on Dr. Fritz Leonhardt's Keynote Address presented at the FIP/PCI Congress in New York City, May 26, 1974.

The author reflects upon the philosophy of prestressed concrete design and suggests we should eliminate "classes of prestressing."

Rather we should use "partial prestressing" with bonded mild steel reinforcement and base our design on crack width considerations.

He explores the future construction market of prestressed concrete and predicts that prestressing will be used increasingly in long-span bridges, massive structures, mass transit structures, sea structures, and especially ships.



Dr. Fritz Leonhardt

We have to check whether our philosophy of prestressed concrete design is sound or whether it carries unwanted prejudices or ideologies gathered during the initial period of enthusiasm.

Degree of Prestressing

One item, which deserves critical reflection, is the suitable degree of prestressing. In Freyssinet's original philosophy, only full prestressing was acceptable, that is, no tensile stresses were permitted in the concrete under service load conditions (Fig. 1). This concept was self-deceiving, from the beginning, because only the stresses due to loads and prestress, as calculated by the classical bending theory, were considered.

For example, significant tensile stresses due to temperature and shrinkage gradients, bond between steel and

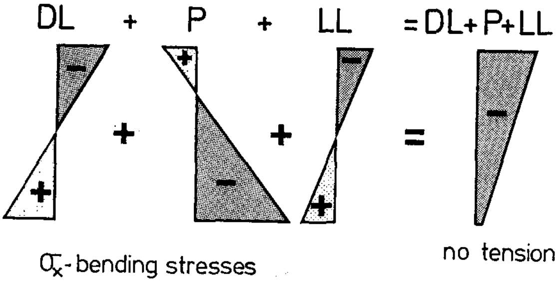


Fig. 1. Flexural stresses for "full prestressing" (i.e., without allowing any tensile stresses in concrete).

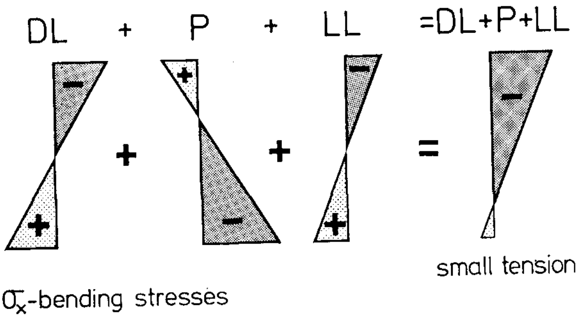


Fig. 2. Flexural stresses for "limited prestressing" (i.e., allowing small tensile stresses in concrete).

concrete, or changes of direction of compressive stresses were neglected. These secondary tensile stresses have caused serious damage in several prestressed concrete bridges, in some cases leading almost to collapse.

We could, in principle, avoid these secondary tensile stresses by prestressing in three directions. However, this would not only be impractical and uneconomical, but would also be unnecessary to provide for good serviceability of the structures. With a small amount of bonded non-prestressed reinforcement we can prevent any danger from these tensile stresses.

In fact, Finsterwalder was the first to recommend that tensile stresses be allowed under service load conditions (Fig. 2). His influence in formulating the German Code DIN 4227 led to the concept of "limited prestressing" as early as 1951. This lower degree of prestressing proved to be sound and advantageous and was soon generally accepted.

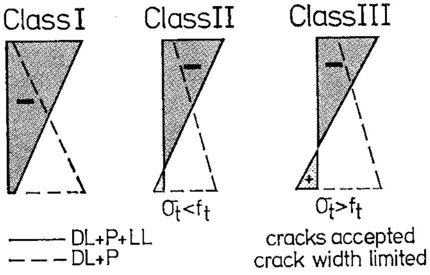


Fig. 3. Flexural stresses for Classes I, II, and III of prestressing using an allowable crack width.

Classes of Prestressing

When the joint FIP-CEB Committee discussed its recommendations, published at the Prague FIP Congress of 1970, there had been sufficient experience to prove the advantages of lower degrees of prestressing.

Agreement was reached to allow degrees of prestressing between full prestressing and conventionally reinforced concrete by establishing the well-known three classes of prestressing (Fig. 3):

Class I. Full Prestressing—Under unfavorable combinations of service loads, no tensile stresses due to bending are permitted.

Class II. Limited Prestressing—Tensile load stresses due to bending up to limits below the tensile strength of concrete are allowed. For loads of long duration, however, tensile stresses must be avoided.

Class III. Partial Prestressing—No limit on tensile stresses, but conditions for crack control by limiting the crack width must be met.

This system of classification brought about an undesirable side-effect. Many people considered the three classes as a differentiation of qualities. Consequently, many clients, especially engineers of government agencies, demanded only Class I criteria.

With bridges, for example, even when specified live loads were enormously high, many thought they were getting a better structure with Class I rather than with Class II or III criteria. If, however, we look at the result objectively, we find that the Class I bridge costs much more and, moreover, has a greater risk due to higher stresses and a larger number of closely spaced tendons that reduce the effective concrete cross section (Fig. 4).

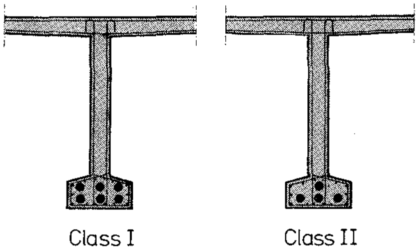


Fig. 4. Tendons in tension flange for Classes I and II of prestressing.

Thus, the concrete in the tensile chord, full of ducts, is subject to very high compressive stresses under dead load in Class I, and, therfore, creeps excessively. For example, in long-span bridges this creep can occur for more than 20 years—causing an upward deflection (camber) which makes it necessary in many cases to level the roadway surface by additional topping layers.

Non-Prestressed Bonded Reinforcement

All these undesirable effects can be avoided if the degree of prestressing is chosen simply to get the best serviceability under load conditions which act continually during most of the structure's life. Safety for load capacity, that is, maximum specified loads multiplied by the safety factor with reduced material strength values, can always be satisfied by additional mild reinforcing steel if the prestressing steel for Class II or III criteria does not suffice.

This additional reinforcement is also helpful in reducing creep deformations under dead load, for crack control under full live load, and for reducing tensile forces in the webs of girders due to shear.

Secondary Stresses

I can give you even more examples that show it is wrong philosophically to consider these classes of prestressing as classes of quality and, indeed the Recommendations say this quite clearly. We have to keep in mind also that the criteria again neglect secondary stresses.

It is well known that, in structures exposed to open-air conditions, especially in moderate and cold climates, the tensile stresses due to temperature effects can easily reach values which exceed the tensile strength of concrete. Consequently, we risk and actually can experience cracking in Class I structures.

SERVICEABILITY CONSIDERATIONS

We must realize that fine hairline cracks will not harm the serviceability of concrete structures subject to extreme but rare loadings which occur during perhaps 0.1 percent of the structure's life. Furthermore, such hairline cracks can even be harmless under more frequent loads, if the environment is noncorrosive.

Crack Width Control

With today's knowledge of crack width control we can guarantee crack widths of 0.1 or 0.2 mm (0.0039 or 0.0078 in.) under full service load. Further, we can choose the degree of prestressing so that the cracks are tightly closed by compression under permanent loads and during the great majority of loads applied to the structure.

In zones with occasional tension, a small amount of bonded reinforcement can be added near the surface to control cracking. Preferably, this reinforcement should be in the form of a welded wire mesh with 5 to 8 mm (0.20 to 0.31 in.) diameter ribbed wires at about 50 to 100 mm (about 2 to 4 in.) spacing. This cracking is limited because the strains remain small due to the prestressing.

The more we learn about crack control, the more we become convinced that this "skin reinforcement" (the French call it "armature de peau"), which can be provided so easily with welded wire mesh or mats, will be the prevailing approach of the future.

This reinforcement can also be used to withstand principal tensile stresses caused by average shear and torsion, by bending the mats or mesh into the shape of stirrups. In future design simplifications, we need not verify shear or torsion reinforcement up to specified limits if we provide a certain amount of such skin reinforcement.

If we introduce crack control as a governing criterion for serviceability, and if we limit crack widths depending on environmental conditions, then, as a consequence, we should be able to remove all limits on tensile stresses due to loads because they are only of academic interest as long as we neglect the many secondary tensile stresses.

Creep Deformation

The second requirement for good serviceability of prestressed concrete structures is to avoid large creep deformations. This means that we have to choose the degree of prestressing and the dimensioning of chord members of girders in such a way that (a) longitudinal compressive stresses under permanent load conditions are not too high and that (b) the range between stresses in the tensile and compressive chords is not too great. Again, this indicates that usually full prestressing should be avoided.

SUGGESTED RECOMMENDATIONS

I would suggest the following recommendations for consideration:

1. Eliminate the designation "Classes for Prestressing."

2. Establish good serviceability criteria, e.g., no flexural tensile stress and, consequently, no open cracks for sustained and frequent loads in structures exposed to weather or water; and limit the maximum crack width to 0.1 or 0.2 mm (0.0039 or 0.0078 in.), depending on the severity of the environment, for full service load plus temperature effects.

3. Specify mild steel reinforcement in areas with possible tension under full service load depending on maximum strain and crack width limitations.

The percentages of full live load, which must be considered as frequent or sustained load, should be based on statistical evaluations of measured actual loads. For bridges they should correspond to those loads which occur more than about one million times during the expected life of the bridge.

For building structures protected against weather it may be sufficient to require no tension under dead load only or even under 80 percent of dead load. The prestressing in such cases should be aimed at reducing crack for-

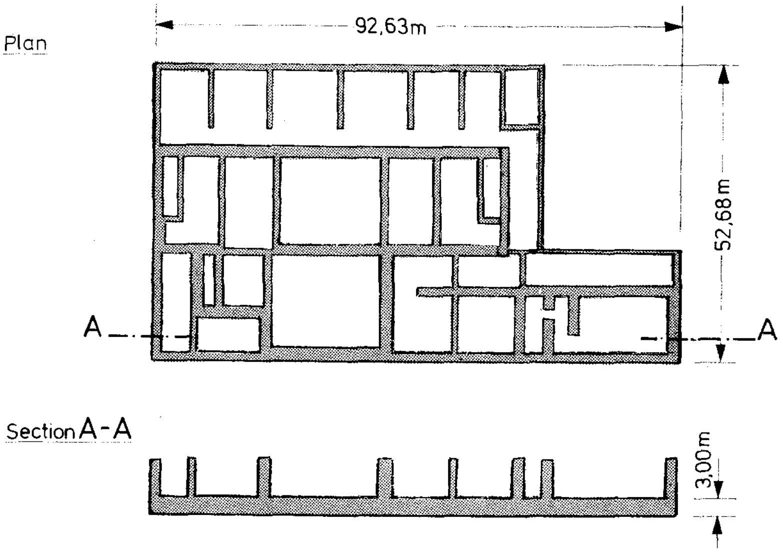


Fig. 5. Foundation slab of nuclear power plant.

mation and limiting deflections for required serviceability.

I am aware that my proposal for new criteria related to the degree of prestressing must be studied carefully by engineers experienced in observing the real life behavior of prestressed concrete structures. In my experience, the proposal will lead to more economy, to simpler construction, to better serviceability, and to owner satisfaction. It will be an improved philosophy for prestressed concrete structures.

FUTURE APPLICATIONS

Let me now give you the outlook of future possibilities for prestressed concrete applications. I see these possibilities mainly by extending the concept of post-tensioning which allows us to prestress large structures and which is much more versatile than pretensioning.

Massive Structures

First, we will have applications to massive structures of large dimensions, such as foundations, hydro-electric power plants, or sluices, and other structures that resist large forces by water or earth pressure.

In such structures we usually place a high amount of bonded steel reinforcement, using very large diameters of deformed bars, quite often in many layers.

Unfortunately, we overlook the fact that such heavy congested reinforcement does not necessarily solve all the problems. For example, we risk cracks due to high bond stresses, or we may experience loss of bond by spalling off the concrete cover.

In many cases the bars will never be fully stressed to make use of their potential strength. If we calculate the stresses in such structures for the uncracked state, we may find that the

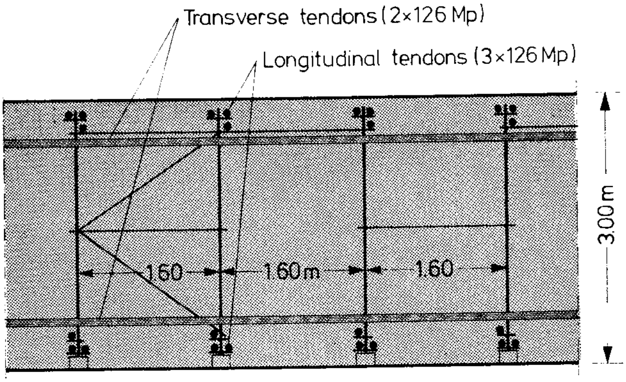


Fig. 6. Arrangement of tendons for foundation slab.

stresses in the concrete remain rather low.

Therefore, we need only have a comparatively small amount of prestressing force to avoid tensile stresses in the concrete and cracks under service conditions.

Usually, the corresponding amount of prestressing steel is adequate for verifying the necessary safety, i.e., if we check safety with reasonable load factors. For this limit state load condition we can logically accept cracks even without limiting crack width.

Here are two examples of prestressing such massive structures:

Example 1—The foundation slab of an atomic power plant in Germany is 90 m (297 ft) long, 60 m (198 ft) wide and 3 m (10 ft) thick (Fig. 5).

It is loaded by a system of longitudinal and transverse load-carrying walls with spacings up to 27 m (89 ft), and has to resist an average soil pressure of 35 tons/m^2 (7000 lb per sq ft). The slab also resists a temperature differential of 50 C (122 F).

The loads and the temperature gradients can be carried safely if this thick plate is prestressed longitudinally and transversely with prestressing forces between 190 and 240 tons/m (1380 and 1740 kips per ft).

The tendons can be arranged in groups of two or three tendons near the top and bottom of the slab and spaced about 1.6 m (5.3 ft) (Fig. 6). This large spacing was chosen so that a gap-graded concrete with rather coarse aggregate can be placed easily with buckets and compacted with large vibrators.

This foundation slab rests on a sandy soil which has a low modulus of elasticity for horizontal deformations near the interface with the slab, and a low factor of friction, so that the loss of prestressing force due to the necessary deformation of the soil by the small shortening of the foundation slab is negligible.

The 90 m length and 60 m width (297 and 198 ft) were constructed in strips without any expansion joints. The walls of the power plant also have no expansion joints so that the whole structure is homogeneous and will give a high safety against catastrophic loads.

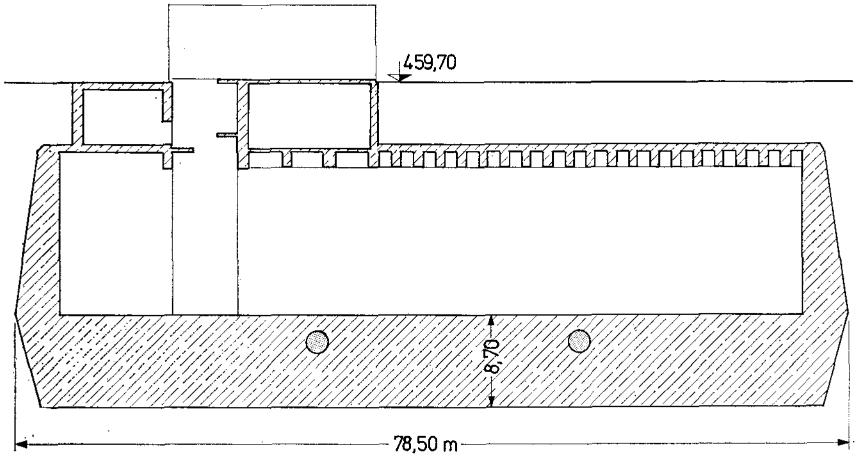
Example 2—The second example is a hydro-electric power station at the low level water reservoir of a pumping storage plant (Fig. 7). The structure has 3 to 9 m (10 to 30 ft) thick walls and foundation slabs, because it has to withstand buoyancy.

On the one side it has to resist 23 m (76 ft) of water pressure; on the other side are earth pressures and it is loaded on top with 6 m (20 ft) of earth fill. The power station is almost 80 m long and 32 m wide (264 and 106 ft).

This massive structure was also built without any expansion joints and it was partially prestressed in all three directions. It is founded on a rock-like hard shale which has a modulus of elasticity of 30,000 kg/cm^2 (430 ksi) for horizontal deformation.

We calculated, and checked by a model test, that 18 percent of the longitudinal prestressing force in the founda-

Longitudinal section



Cross section

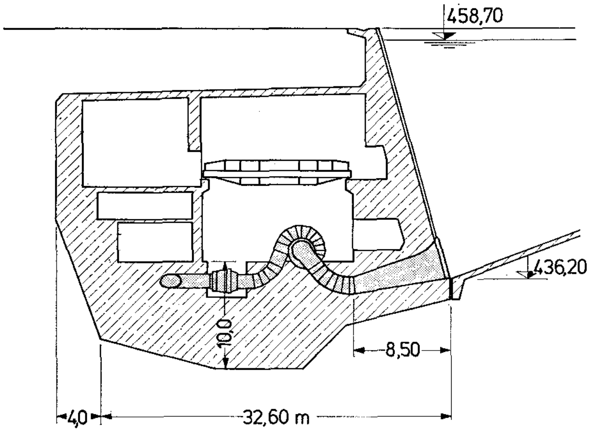


Fig. 7. Pumping storage plant. Expansion joints are avoided by prestressing.

Fig. 8. Cast-in-place segmental bridge construction

tion slab will be lost in getting compatibility between the deformations of the soil and the structure. The amount of prestressing provides longitudinal compressive stresses in the concrete of values only between 8 and 12 kg/cm^2 (115 and 170 psi).

This stress level was sufficient to avoid any through cracks in the water-retaining wall. We accepted, of course, hairline cracks at the outside of the reservoir wall due to freezing temperatures in the winter time.

The structure has been in service for 12 years and it withstood several very cold winters without any damage in

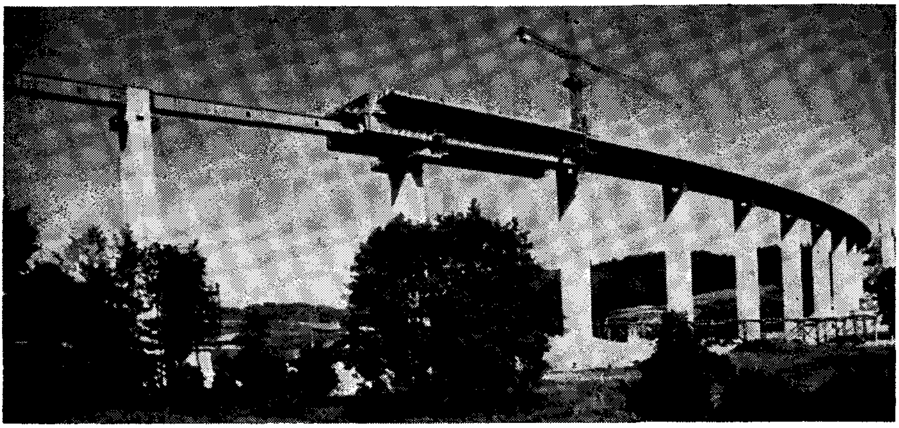


Fig. 9. Traveling steel girders carrying formwork for span-by-span bridge construction.

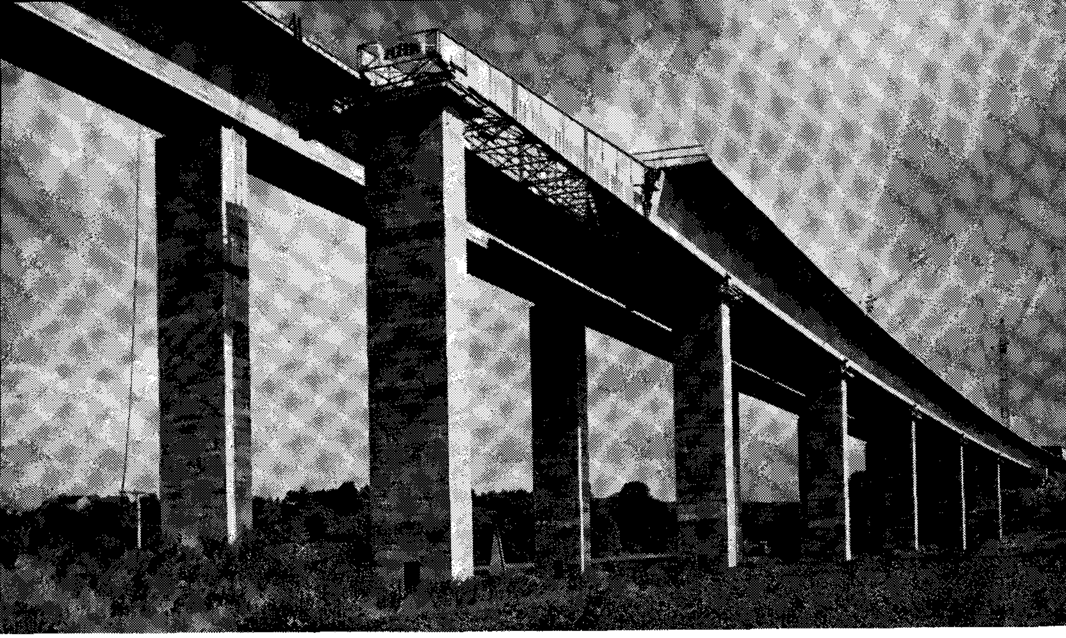


Fig. 10. Incremental launching of continuous bridge girders, fabricated behind abutment (Taktschiebeverfahren).

spite of the fact that the water level varies each day between 5 and 10 m (16.5 and 33 ft).

There are many opportunities whereby the performance of massive structures can be improved, expansion joints avoided, or bad cracks eliminated by use of prestressing.

Bridges

The second field, in which new possibilities for prestressing are predicted, is in bridges. Prestressed concrete already accounts for most of the bridge construction in Europe. For example, in Germany about 90 percent of the bridges are being built of prestressed concrete and they proved to be both lower in cost and better than steel bridges for spans up to about 120 m (396 ft). Improved prestressed concrete systems will make it possible to build highway bridges up to 400 m (1320 ft) span that are less costly and more durable than steel bridges.

First let me say a few words on recent design and construction methods for bridges with normal spans. In some countries, segmental construction with prefabricated segments are favored, but for the joints full prestressing is still required.

In competition, other methods like cast-in-place segmental construction (Fig. 8) or span-by-span construction on movable steel girders carrying the formwork (Fig. 9), proved to be more economical. Of course, very long bridges with many equal spans, like the Rio Niteroi Bridge in Brazil, may be exceptions.

In Germany the incremental launching method (Taktschiebeverfahren) proved to be more economical for straight or uniformly curved continuous bridges with at least four or five spans between 40 and 120 m (132 and 396 ft) (Fig. 10).

This method combines the advantages of prefabrication under a roof and

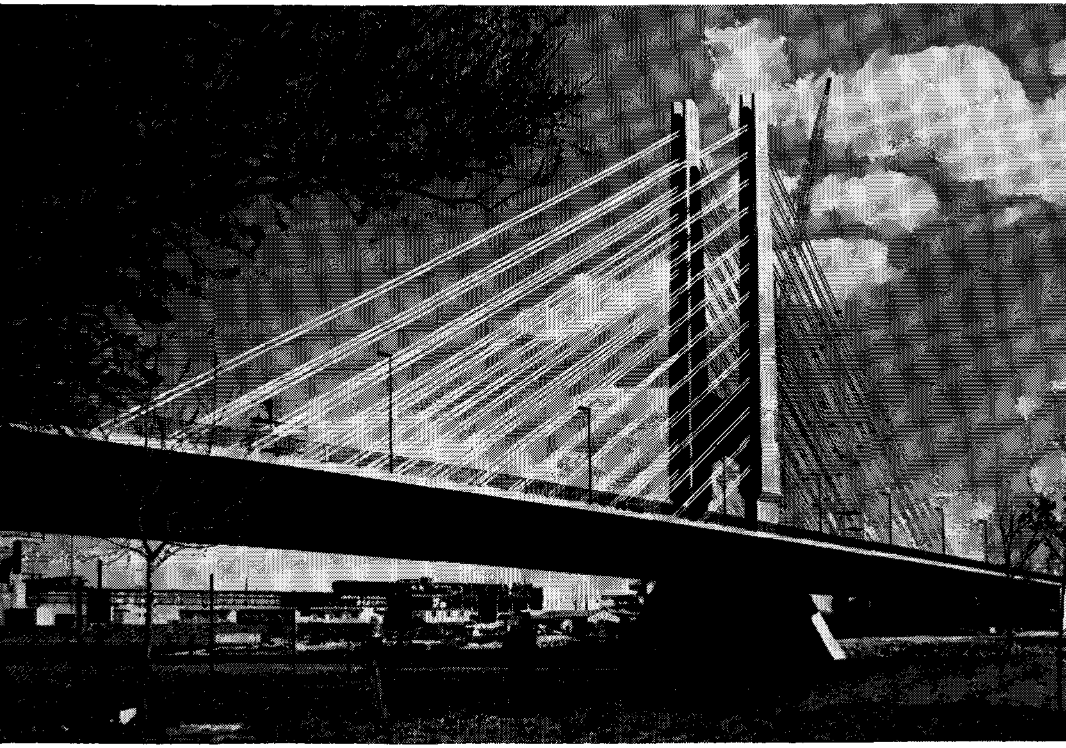


Fig. 11. Multiple stay cables for Mainbrücke Hoechst.

casting in place—thus avoiding all jointing problems. The bridge is built in 20 to 30 m (66 to 99 ft) long segments, just behind the abutment. The segments are then hydraulically launched on teflon sliding bearings, using a light steel cantilever at the head in order to reduce cantilever moments until the next pier is reached.

Each following segment is concreted directly to the end of the former segment. The whole bridge moves step by step out of the fabrication plant where each week one or two segments can be made, protected against inclement weather.

Even a sharply curved bridge has been constructed in this way by an Italian firm in the Alps (Fig. 9), curving the highway from one direction to the other on opposite sides of the deep valley.

Such new methods with low costs for investment and labor open new possibilities to prestressed concrete bridges in many countries.

Even more exciting are the new possibilities for very long spans by recent developments in cable-stayed bridges. Morandi made the first daring designs of prestressed concrete bridges with stayed cables, after German engineers had built some cable-stayed steel bridges.

We remember the famous Maracaibo Bridge, for which Morandi's first design envisioned a 400 m (1320 ft) span. This bridge could not be realized with

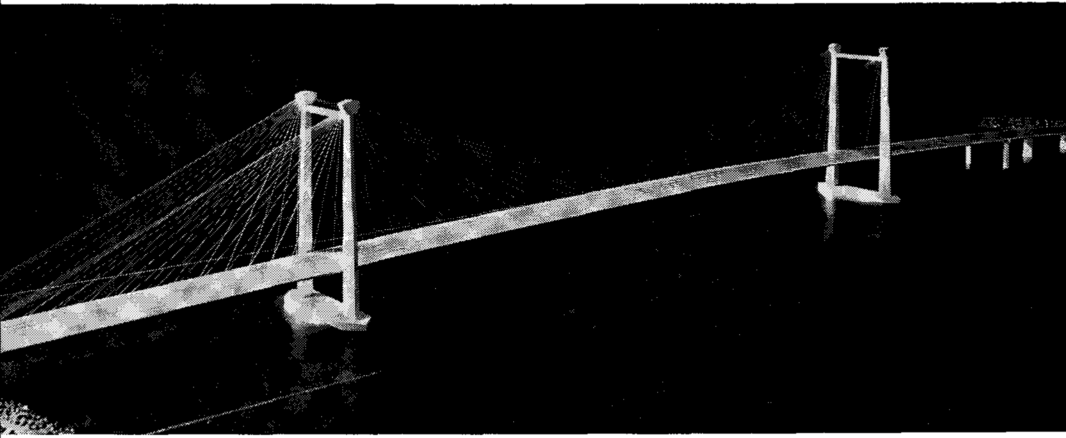


Fig. 12. Fan-type stay cables for Columbia River Bridge, Pasco Kennewick (300 m span).

his system because it had only one stay cable from each tower head to help carry the beam girder. The 235 m (775.5 ft) spans were built with very costly equipment.

Morandi's 276 m (911 ft) Wadi Kuf Bridge in Libya, using the same one-stay cable system, is the world's longest span of this type.

In the steel bridges crossing the Rhine River, we used more stay cables to obtain smaller spans between cable supports. Using this scheme, the bending moments were reduced and shallow slender beams with less dead weight could be employed. Wittfoth has designed several bridges with spans up to 300 m (990 ft) using multiple stay cables. Unfortunately, none of these bridges have so far been built.

In the competition for a bridge across the Great Belt in Denmark, Finsterwalder's design used multiple stay cables and spans up to 350 m (1155 ft) with a solid, heavy slab as a bridge deck. Meanwhile, this same engineer

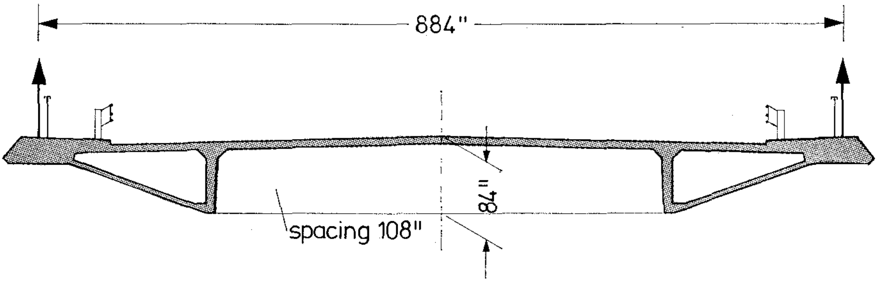


Fig. 13. Cross section of Columbia River Bridge.

has built a similar bridge for a railroad crossing over the Main River near Frankfurt with a main span of 148 m (488 ft) (Fig. 11).

Finsterwalder used a special type of cable, with parallel wires, to support the live load in composite action with a thick-walled steel tube. This modified system is helpful in reducing the oscillating live load stresses.

I, myself, have given much thought since 1953 to developing aerodynamically safe steel bridges with spans between 600 and 1500 m (1980 and 4950 ft). We have found by wind tunnel tests, dynamic model tests, and numerous design studies that flat superstructures with triangular box girders along the edges produce aerodynamically safe long-span bridges.

Furthermore, we discovered that, in multiple cable-stayed bridges, resonant oscillation is completely eliminated with the structure's damping system. Finally, we could prove that a cable-stayed bridge with many stay cables is economically and structurally superior to the classic suspension bridge.

This knowledge can now be applied in prestressed concrete bridges. Together with Arvid Grant and Associates, we designed the soon to be constructed Columbia River Bridge.

This cable-stayed prestressed bridge will join the cities of Pasco and Kennewick in Washington and have a span of nearly 300 m (990 ft) (Fig. 12). The cross section is made up of triangular edge boxes which provide anchorage for the stay cables at any point (Fig. 13).

The cables are spaced so that the bridge can be built from the towers by cantilevering the prefabricated segments from cable to cable by a short steel cantilever truss. The free cantilevering from the cables could also be done by casting the segments in place, as was done many times by the Dywidag method.

This type of cable-stayed bridge under German price conditions will be cheaper than steel bridges up to 400 m spans (1320 ft). In addition, the structural detailing is relatively simple.

High Speed Mass Transit Structures

In many countries, new high speed transportation systems similar to the Japanese Tokaido Line will be built.

We made a study of a long span bridge for similar fast trains with speeds up to 300 km/hr (187 miles per hr). From the investigation we found that a heavy and rather stiff superstructure is needed to withstand undesirable dynamic effects.

This required stiffness and mass inertia can easily be provided for high-speed trains with prestressed concrete superstructures having spans of 250 m (825 ft) or more using a cable-stayed system.

Of course, the cables must have a high fatigue strength at the anchorages and should have allowable stresses as high as 7000 kg/cm^2 (100 ksi) to make them very stiff. Such special cables have been developed by my consulting firm in collaboration with BBR Zurich, which now supplies fabricated cables for service load forces up to 1200 tons (2650 kips).

The cables are shipped on reels after first being placed inside polyethylene tubes, which give good protection against corrosion during shipping and the subsequent life of the bridge.

With these high capacity cables and prestressed concrete bridge decks, there will be minimal maintenance costs for such long span bridges (provided the use of deicing salts in winter is prohibited).

Sea Structures

The most important challenge for new and useful applications of prestressed concrete comes from the re-

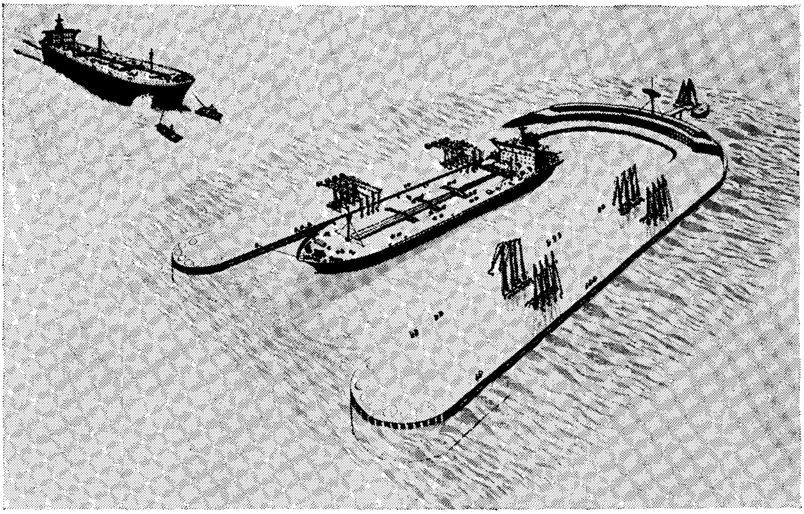


Fig. 14. Floating harbor proposed by Finsterwalder.

quirements for large sea structures.

There will be ever-increasing demands for harbors, off-shore ocean terminals for bulk cargo and supertankers, founded or floating platforms to service oil production, underwater storage of gas or oil, floating airports, off-shore nuclear power plants, submerged floating tunnels, and even for large ocean-going ships and barges.

It was again Freyssinet who first envisioned this large field for prestressed concrete when he wrote in 1954: "transport by water will . . . be transformed to prestressed concrete structures. Prestressed concrete will enable us to build ships of such dimensions that the biggest waves will only be a choppy sea to them . . . floating islands will be made carrying machinery to extract precious minerals from the depths of the sea."

Freyssinet was indeed a good prophet. Currently, many engineers are working hard to implement these ideas.

There are already a large number of major proposals and projects underway. The famous Ekofisk oil storage tank now situated in the middle of the stormy North Sea is only one noteworthy example. Even more daring projects of larger magnitude and scope are planned for the future.

There is no doubt that prestressed concrete is a suitable and reliable material for sea structures if we apply all our modern technology, including the possibilities of improving resistance and durability, for instance, by polymer impregnation.

Prestressed concrete with dense "skin reinforcement" has satisfactory ductile performance at high and low temperatures—down to cryogenic temperatures for storing liquified gases and up to the elevated temperatures present in hot oil storage.

Undoubtedly, prestressing is the best way to make concrete sea structures safe against enormous forces of waves or ice action, and to ensure against corrosion of reinforcement.

We have now accumulated sufficient know-how and experience in design and

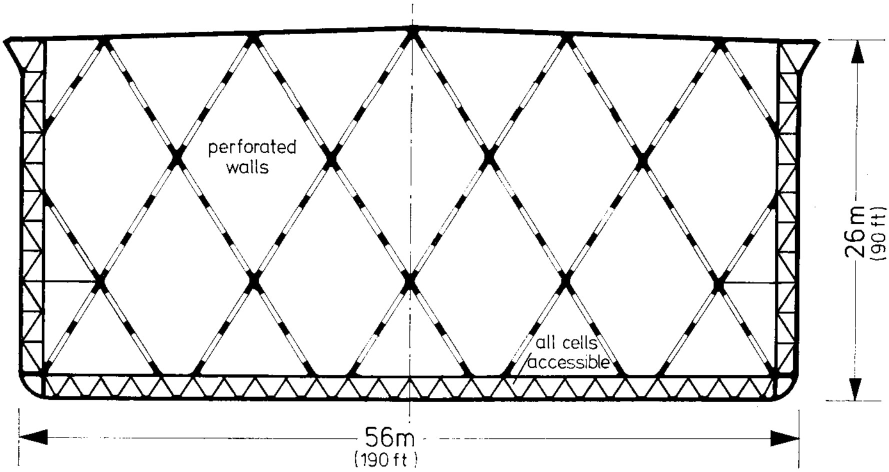


Fig. 15. Cross section of prestressed concrete oil tanker; concreted in vertical position with sliding forms; 60-m long segments.

construction of large prestressed concrete structures so that we can go with confidence into this new field with its unusual and unprecedented challenges.

It was the excellent idea of our new FIP president, **Ben C. Gerwick, Jr.**, who is a leading engineer in this field, to have arranged, with our Russian friends, the 1972 FIP Symposium on Sea Structures in Tbilisi, Georgia, USSR, and to have founded the FIP Commission on Concrete Sea Structures, which has already produced its first design criteria for such structures.

It is also very beneficial to have this Congress in the United States, where many noteworthy design studies and much valuable research is in progress for off-shore sea and submarine structures. Recently, it has been shown that concrete shells can resist deep water pressures to a depth of 900 m (2970 ft).

It is my personal conviction that we will soon build many such sea structures and that we will eventually build 100 or 200 m (330 or 660 ft) high prestressed concrete towers, sink them into the sea, and anchor them safely on the ocean floor. Floating platforms can have deep buoyancy legs with rather large diameters reaching to depths of 150 m (495 ft) to reduce wave effects in rough seas.

Finsterwalder believes we can build huge floating harbors in 600 m long by 240 m wide (1980 and 792 ft) U-shapes, where the tankers can moor inside the U-legs protected against rough sea and can feed pipelines or storage tanks (Fig. 14).

Prestressed Ships

Ocean-going ships of prestressed concrete may become larger than today's oil tankers, but they should have double plate hulls to give them even more safety than steel ships.

Tankers of this size should be designed along new lines, different from steel tankers. For instance, they should have internal triangular perforated folded plate stiffening to avoid transverse frames (Fig. 15).

Thus, long segments can be built in a vertical position quickly with inexpensive slip forms. These segments can then be launched into deep water, rotated into position, and coupled while afloat by large prestressing cables.

The British engineer Rowland G. Morgan wrote, in his 1973 Report on *Sea Structures* (published by the Concrete Society, London), that "the structural designer in concrete . . . seems almost reluctant to recognize that naval architecture and ocean engineering are demanding disciplines in their own right and it is not merely a case of substituting concrete for steel."

How right he is! Thus, ocean engineering with prestressed concrete will indeed challenge the creativity and resourcefulness of civil engineers in the days ahead.

CLOSING REMARKS

Let me close with an appeal to all my engineering colleagues.

I consider this plea more important for the future of mankind than mere technical progress, as highly interesting and materially useful as it may be, and that is not to neglect the aesthetics of the structures we design.

They stand in an environment where people live; their beauty or ugliness will have a sustained impact on our well being, and on the health of our soul which is equally important as our physical health.

Technical progress is only meaningful and acceptable if it serves the health and happiness of both body and soul of all mankind!

Discussion of this paper is invited.
Please forward your discussion to PCI Headquarters by February 1, 1975, to permit publication in the March-April 1975 PCI JOURNAL.