Prestressed concrete in Indian road bridges

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The successful completion of the Palar Bridge in 1955 ushered in the era of prestressed concrete for the construction of road bridges in India. The three decades since then have seen the construction of several types of bridges in prestressed concrete, commencing with simply-supported spans and followed by more sophisticated forms of construction. The path of development taken in India has, however, differed from that prevailing abroad in certain respects in that local conditions have favoured the adoption of long spans and have militated against the use of prefabricated pretensioned units in prestressed concrete road bridges. The trend in the future will be towards the adoption of even longer spans and will call for changes in the concepts prevailing today. Optimisation will also involve changes in the codes of practice to permit the use of limit state methods of design and partial prestressing. There is also scope for the use of lightweight concrete in combination with concrete of normal weight or by itself.

Bridge building is almost as old as civilization. For centuries, the materials available, namely, wood and stone masonry, limited the technology for bridge construction. Then, about three hundred years ago, ste;.1 began to replace wood, and concrete at times replaced stone masonry in bridge construction. Stronger and easier to use, these materials made the construction of much longer spans possible, though the structural form remained essentially the same.

This was only a first step towards what was to follow. The weakness of concrete in resisting tension had till then prevented its utilization in members subjected to bending and restricted its ,scope for bridge construction. However, Resal, a French engineer, introduced the concept of combining the compressive strength of concrete and the tensile strength of steel to create reinforced concrete, a material destined to play a significant role in bridge building for a long time to come.

An even more revolutionary concept in concrete technology was introduced by Eugene Freyssinet in the form of prestressed concrete, where a permanent beneficial stress was applied to the concrete to counteract the tensile stress developed under load. This enabled construction of spans in concrete that were unthinkable earlier. The forties saw the systematic utilization of this technology in France under the leadership of Freyssinet and later under his disciple and colleague, Yves Guyon. The technology spread through the neighbouring countries, and the fifties saw its spread outside Europe— westwards towards North America, and eastwards towards Russia, Japan, India and the countries of the Middle East. The completion of the Palar Bridge in 1955 heralded the era of prestressed concrete technology in India, and it became a milestone in the development of bridge construction in this country. Today, it is widely used in the construction of bridges in a variety of forms and its usefulness, particularly for developing countries has been amply demonstrated, alleviating as it does the strain on the natural resources of these countries by reducing consumption of cement and steel. The specific considerations in its favour are:

1. The possibility of using high-strength concrete leads to a reduced concrete section and, in turn, to reduction in the self-weight. The latter is of supreme importance for economy in long-span bridges, where self-weight constitutes the major portion of the total load carried by the structure.

2. The possibility of reducing, or even totally eliminating, tensile strain and the resultant cracking in concrete permits the use of economically viable high-tensile steel without unsightly cracking. It also renders feasible the incorporation of smallsectioned concrete tensile elements in long and light open-webbed spans, generally described as a bowstring, and in suspended and tied cantilever superstructures. These

considerations have the same significance, namely savings in materials and their resulting advantages for long spans.

3. The possibility of a rapid, easy and technically sound assembly of precast or cast-in-situ elements, without in any way affecting continuity, leads to savings in formwork, labour and time and to savings or the total elimination of scaffolding by adopting one of the various forms of launching that are feasible or by adopting the cantilever construction technique. The scope for using temporary prestressing to take care of the temporary stress configurations that may arise during construction has further augmented constructional feasibilities.

Types of bridges suitable in India

The suitability of prestressed concrete as a structural material, particularly for long-span bridges, does not lead quite automatically to the construction of long span bridges. As a matter of fact, the very question of adoption of such bridges in preference to short span bridges must be viewed from the perspective of the prevailing external conditions, both natural and artificial. It is these external conditions that favour some of the inherent advantages of a particular technique in preference to others, set the direction and determine the extent of development. It will be particularly interesting, in this context, to compare the external conditions, commercial and technical, operating in India and in certain other areas, especially the developed countries of the world.

The economy in the costs of labour, form work, false work and time, which results from the use of precasting methods, combined with the economy in the consumption of concrete and steel, has in the industrialised European countries led towards the mechanised mass production of pretensioned beams for bridges with small spans of lengths ranging from 8m to 25m. There is also evidence of progress towards mass production of longer post-tensioned beams for spans upto 35m in segments having dimensions convenient for transportation. The mass production technique has developed in the economically developed countries, on the one hand, because of the prohibitive cost of construction labour as compared to mechanised processes and, on the other, because of the facilities that exist for both road and river transportation, the easy availability of sophisticated erection machinery and, principally, because of the very large demand. However, mass production techniques have yet to become standard practice all over Europe, and the majority of bridges, particularly those for which longer spans are necessitated from technical considerations, are still either precast at site or cast-in-situ by techniques which have changed little in the last 25 years.

In India the situation is in many ways different from that prevailing in Europe. First, labour is still cheap as compared to Western countries. Second, the initial investment for setting up sophisticated mechanised units for mass production and handling is quite large against the background of low labour cost. Third, transportation from factory to bridge site is both costly and difficult owing to a dearth of good roads and poor navigability of many rivers during the construction season. Fourth, the limited allotment made by the exchequer of funds for bridge projects is also a deterrent factor against mass production as continuity of demand over several years within the economic transportation radius can seldom be assured.

Apart from the commercial reasons mentioned above, certain technical reasons make the adoption of short. spans uneconomical to even contemplate in many cases. In India most rivers, particularly in the northern region, are still in their formative stage. They flow with very large variations in discharge on alluvial beds and without well defined banks, which may even be miles apart when the river is in spate. Under situations such as these the bridges have to be designed against the odds of very deep scouring taking place when the river flows through restricted waterways under the bridge. Thus, the foundations for these bridges work out quite expensive and the designers' natural inclination is to reduce the number of foundations to the minimum. This consideration has led to the adoption of long-span bridges. Moreover, in the sub-mountainous regions of India the turbulent rivers may not permit any pier on their beds, and a bridge with a long single span may he the only answer under the circumstances. In some other cases, the gorge may be very deep and the intermediate tall piers may be too expensive to justify their construction in number; the choice has to be, once more, a long-span bridge. In keeping with the ahove observations the path chosen during the evolution of bridge construction in India has been in the right direction, namely towards longer and longer spans. The primary reasons have been the unsuitability of mechanised production and the necessity to curtail the heavy expenditure on foundation work.

As stated earlier, it was the successful completion of the Palar Bridge that ushered in the era of prestressed concrete bridges in India. Out of the three decades of Indian experience in this field since then, the first decade was marked largely by the pioneering contributions made by a numerically small, but intellectually and creatively very active, set of contractors and consulting engineers. A more general acceptance of the technique became apparent only from the second decade onwards.

In the short period that prestressed concrete has been in use India has produced, in addition to an enormous number of prestressed concrete bridges with simply supported spans ranging from 20m to 50m, also some very outstanding bridges of other types and having longer spans. The results are excellent, considering the rather restricted number of Indian specialists in the field, the early difficulties in obtaining prestressing materials and the relatively brief period in which most of this progress has been achieved. The first batch of bridges in this category was for obvious reasons, of the simply-supported type. These bridges were either cast in-situ or were precast and launched or side-shifted into position. The type of section extensively used in India is in the form of special webbed precast T-or I-beams with cast-in-situ filler deck slabs. The longest simply-supported span in the world is the Mayo Orlo Bridge in the Cameroons with a span of 83m. In India the

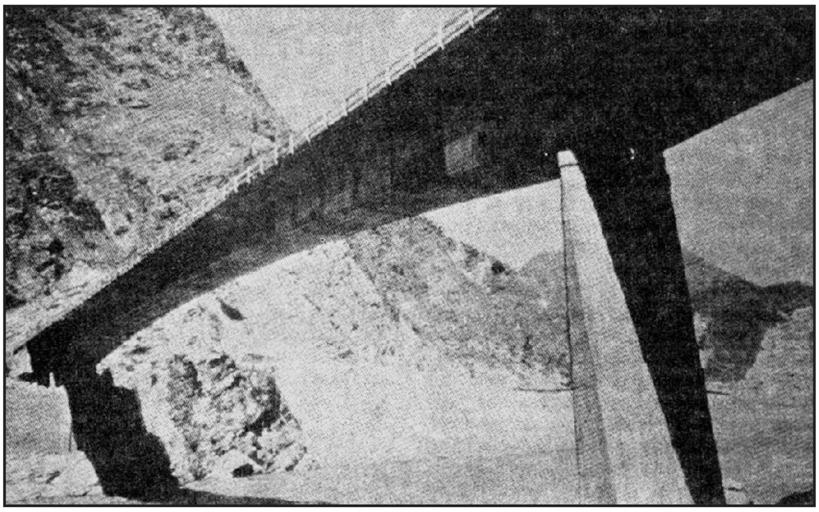

Figure 1. Bridge on river Chanab at Riasi, which spans a deep gorge with a main span of 95m

corresponding length is 52m. Limitations in the size of launching equipment and in the skill required to construct longer spans act as deterrents to the adoption of longer simply-supported spans; besides, they cease to be competitive.

For longer spans the types of bridge structure that can be effectively and profitably introduced are the open-webbed, simply supported triangulated trusses or virendeels or more commonly the bowstring and the tied beam structures, the balanced or unbalanced cantilever, the continuous beam, the rigid frame or hinged cantilever spans constructed by the cantilever construction method, and the like. This class of more complicated bridge superstructure is still to some extent in the developing stages in India, though examples in the advanced countries are quite numerous. Of the types mentioned above, the continuous girder and the hinged cantilever types have gained some foothold in India during the last few years. They have become popular with engineers, particularly in view of the scope they offer for uninterrupted construction through application of the cantilever construction method by joining either precast or cast-in-situ segments through prestressing as well as on account of the overwhelming advantage they possess for doing away with staging for formwork.

Construction techniques

Developments in the techniques of bridge construction have not lagged behind innovations in design concepts. In fact, the progress in this field has been quite amazing and vast, and it is impossible to do proper justice to the subject within the limited scope of this article. The discussion of construction techniques will, therefore, be restricted to just a few special developments.

To begin with, bridges were invariably constructed in-situ on stagings. Quite obviously, this posed serious problems in the case of bridges over deep-flowing, turbulent rivers or across deep valleys and gorges. This difficulty gave rise to the technique of prefabrication and launching. This technique permits the construction of the main beams of a bridge on a bank, in working conditions which are much simpler, thus giving better results and allowing in some cases even steam curing of the concrete to accelerate construction during the cold weather. The beams are placed in position with the help of a steel launching girder. The only concrete to be poured in place is for the deck and the diaphragms. Quite a good number of prestressed concrete bridges in India have been constructed by this method.

The next significant phase of development saw the introduction of the cantilever construction method. Cantilever construction allows for the concreting of box sections in segments of variable depths by means of shuttering supported by that part of the structure already concreted. The connection between this newly constructed segment and the preceeding one is effected by prestressing cables. This method can be used equally with segments prefabricated on the bank and placed in position after curing. The choice between cast-in-situ

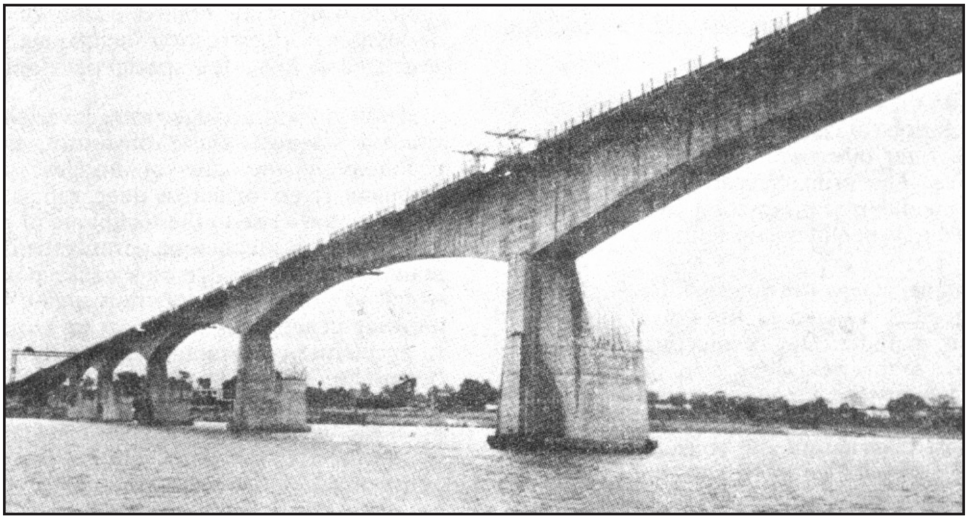

Figure 2. Bridge on river Ganga near Patna, the world's longest river bridge. This 5,575-m long bridge with spans of 121.1m each was built by the precast cantilever method

construction and precast elements depends on the size of the bridge and on the span lengths. The field application for bridges built in cantilever is very wide and covers mainly spans from 50m to 200m. The latest trend consists of using precast units for smaller spans, say, of about 35m for elevated roads or flyovers, where scaffolding must be avoided and existing road facilities maintained beneath the structure. The cantilever method of construction is virtually the only one to be considered today for spans exceeding 70m. For smaller spans it competes with other erection methods, in particular, with cast-in-situ construction using falsework, a method which is still economical if conditions are favourable and permit such construction. The cost advantages inherent in the cantilever construction technique have been amply demonstrated all over the world by the number of successful tender bids where this technique was in competition with other methods. The rapid growth of this technique is, indeed, the best proof of its value from economic considerations.

There has also been a report of a novel technique used for the construction of a bridge in Venezuela by first carrying out on one bank the casting of the entire 471-m length of box superstructure and then sliding the superstructure across the river over the supports to form a continuous bridge.

Some important constructions

It is not possible to report on all the important bridges constructed, and only a few selected structures in India and a few abroad that have been built by Indian engineers are described below.

Bridge on river Chanab at Riasi: Situated in mountainous terrain and spanning a deep gorge, this prestressed concrete bridge, Figure 1, has a central main span of 95m and two anchor spans of 25.5m each: the deck provides a clear carriageway width of 8.53m.

The superstructure consists of a single-cell box girder, the central span being constructed by the cast-in-situ cantilever method using 3.75-m long voussoirs. The approach spans were cast in-situ on staging. Freyssinet cables, made up of 12 wires of 8-mm diameter each, were used for prestressing the girders. The substructure consists of slim, streamlined piers resting on open footings which were ballasted by refilling the cores with masonry.

Owner: Central Water and Power Commission, New Delhi.
Contractors: National Projects Construction Corporation Ltd.
Consulting Engineers: STUP Consultants Ltd.

Bridge on River Ganga near Patna: The world's longest river bridge, Figure 2, is 5575m long and has 45 regular intermediate spans of 121.1m each and two end spans of 63.5m each; the bridge supports a roadway, 15m wide, with 2.4-m wide footpaths on either side and a power cable trough under the deck.

The superstructure consists of two single-cell boxes, independently supported on two hollow pier branches which spring from a single pier. About 90 percent of the length is of precast cantilever construction, using match cast precast elements with weights ranging from 28t to 80t, which were erected by a travelling bed gantry for the spans and by floating camel for the river spans. The elements were glued by epoxy and prestressed longitudinally, using the Freyssinet system. A 24-wire system of prestressing cables was improvised by threading two cables, each having 12 wires of 8-mm diameter, in a single duct and prestressing them separately. The mating cantilever arms were connected by a forged steel pendulum bearing to provide better riding qualities. The foundations consist of single-cell wells, 60in deep and 12m in diameter.

Owner: Public Works Department, Bihar.
Engineers and Contractors: Gammon India Ltd.

Bridge on River Yamuna at Kalpi. UP.: This 767-m long bridge, Figure 3, supports a 7.5-m wide carriageway with 1.5-m wide footpaths on either side. It has 8 intermediate spans of 85m

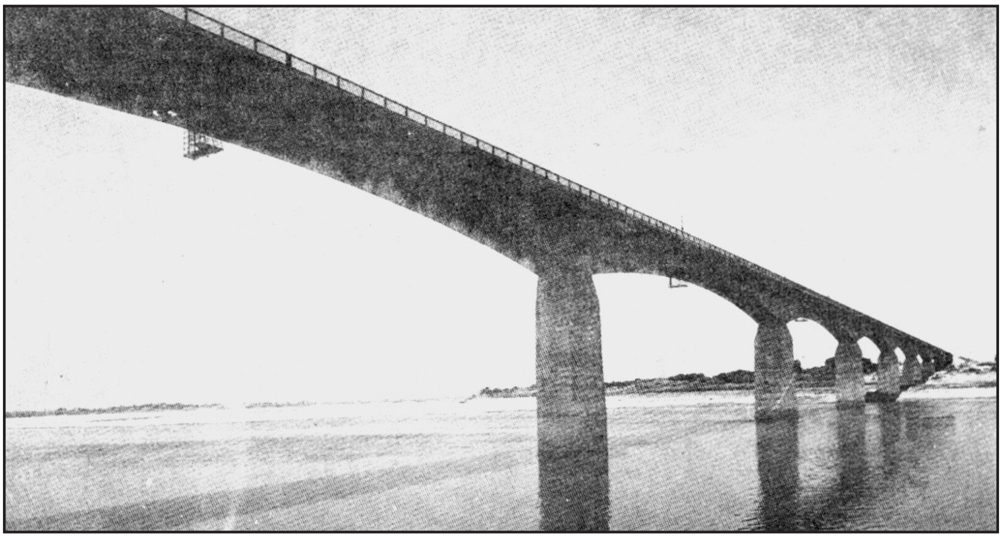

Figure 3. Bridge on river Yamuna at Kalpi, U.P., the deck of which is monolithic with the piers and was built in-situ by the free cantilever method

each and 2 end spans of 43.5m each. The superstructure consists of a single-cell box girder prestressed by Freyssinet cables having 12 wires of 8-mm diameter each. The deck is monolithic with the piers and was built in-situ by the free cantilever method.

The substructure consists of diamond-shaped cellular piers resting on circular caissons, some of which were sunk up to a depth of 50m below bed level.

Owner: Public Works Department, Uttar Pradesh.
Contractors: National Buildings Construction Corporation Ltd.
Consulting Engineers: STUP Consultants Ltd.

Teesta Bridge near Rashyap, Sikkim: This 206-m long bridge, Figure 4, consists of two double-cantilever arms of 96m each and three suspended spans of 4.6m each. The bridge supports a 7.5-m wide roadway and 1.5-m wide footpaths on either side. The superstructure was constructed by the cantilever construction method, using specially designed travelling gantries. The superstructure is monolithic with the reinforced concrete cellular piers which are supported from ,circular concrete wells, sunk to a 18.9-m depth below bed level in bouldery rock strata by a special blasting technique. The prestressing was done by the Freyssinet system. using cables having 24 wires of 7-mm diameter each.

Owner: Government of Sikkim.
Engineers and Contractors: Gammon India Ltd.

Netaji Subhash Bridge at Ahmedabad. Gujarat: Located across the Sabarmati river linking Ahmedabad city with the new state capital, Gandhinagar, this 454-m long bridge, Figure 5, has a carriageway width of 12.8m and two footpaths of 2.4m each.

The superstructure is of the balanced cantilever type with 5 interior spans of 76.2m each and 2 end spans of 36.6m each. Each of the three main spans consists of a 76.2-m central span having cantilevers of 17.5m or 25.9m. The cantilever tips of the main spans are bridged by two suspended spans of 41.2m.

The main span consists of a multiple-box section with a depth of 3.5m at the piers and of 2.4m at the cantilever tips. Freyssinet cables, made up of 12 wires of 7-mm diameter each, were used for prestressing. The suspended spans consist of six precast prestressed concrete beams, which are 2.4m deep and are connected by a cast-in-situ slab. Prestressing was done with Leoba prestressing cables, having 16 wires of 8-mm diameter each.

The substructure consists of slender wall type piers, supported on twin wells, each 7.3m in diameter.

Owner: Ahmedabad Municipal Corporation.
Contractors: Tolani Brothers and Shah Construction Co.
Consulting Engineers: STUP Consultants Ltd.

Brahmaputra Bridge, Assam: This 3,495-m long bridge, Figure 6, across the river Brahmaputra has 30 spans supporting a 7.5-m carriageway and footpaths of 1.5m on either side. A typical interior span is of 120m, being formed by cantilevers of 52.5m constructed monolithically with the piers and a small suspended span of 15m. The crosssection of the cantilevers is a single box and the suspended span consists of a two-girder system with a cast-in-situ deck. The cellular piers are supported on wells, 12m in diameter and a maximum depth of 58m.

Owner: N. F. Railway.
Consulting Engineers: N. F. Railways.
Contractors: Hindustan Construction Co. Ltd.

Interchange system at Haza Al Magam, Al Ain, UAE: This interchange at Haza Al Mariam on the outskirts of Al Ain City, Figure 7, is a high-speed clover leaf junction between two intersecting multilane expressways and provides uninterrupted and free access to traffic in all directions. The flyover is of prestressed concrete construction and consists of two intermediate spans of 25m each and two end spans of 15.75m each. With a total deck width of 27.6m, it carries three lanes of traffic in each direction.

The superstructure is in the form of shaped solid girders, precast in segments and assembled by the cantilever construction technique with epoxy-glued joints. The substructure comprises of elliptical piers, supported on cast-in-situ bored piles. The concrete in the superstructure and the piers is made with white cement and is given a special form-liner finish. The area around - and between the clover leaf is

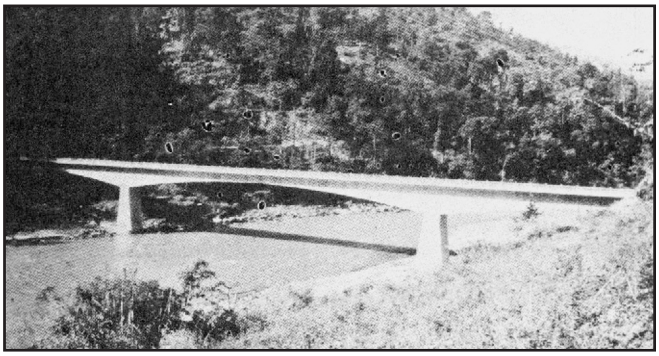

Figure 4. The Teesta Bridge near Rashyap, a graceful 206-m long bridge with two double-cantilever arms of 96m each and three suspended spans of 4.6m each

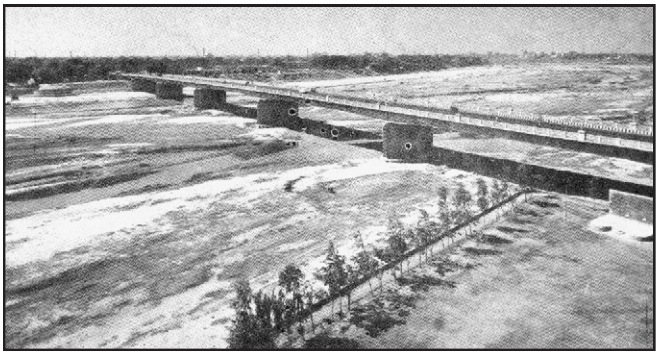

Figure 5. The Netaji Subhash Bridge at Ahmedabad is a balanced cantilever structure with main spans of 76.2m

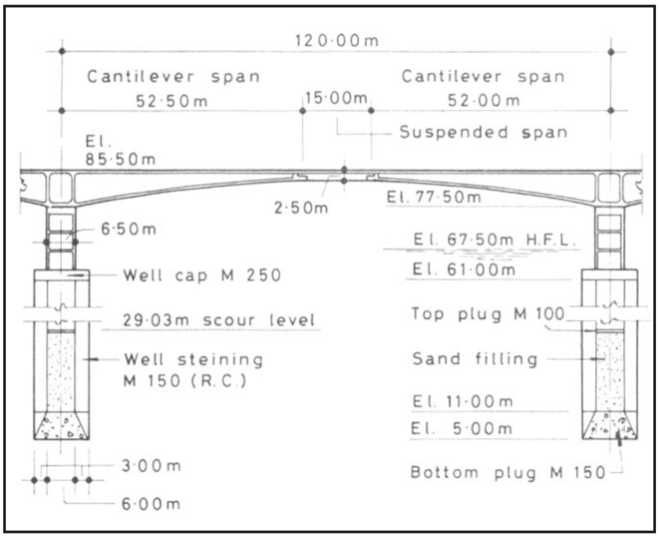

Figure 6. The Brahmaputra Bridge in Assam, which has 30 spans of 120m each

beautifully landscaped and is provided with an elaborate water supply system with underground and overhead reservoirs. Meticulous design of approach roads, hand rails, lighting systems, etc., has resulted in a highly functional and aesthetic interchange system.

Owner: Al Ain Municipality.
Contractors: Alwaha Engineering.
Consulting Engineers: STUP Consultants Ltd.

Chambal Bridge at Dholpur, Rajasthan: This is a prestressed concrete submersible bridge with spans of 45m, which perhaps are the longest spans for a bridge of this type, Figure 8.

The earlier bridge, built with continuous reinforced concrete arches collapsed due to settlement of one of the foundations. The debris of the arches occupied the area between the piers. making it impossible to construct a new foundation along the alignment of the old bridge. Therefore, the caissons had to be constructed outside the debris at spacings of 22-m centres in the direction of the current. A pier with an inverted-V shape, the arms of which are 22m apart at the bottom and 3m apart at the top, was constructed. The prestressed concrete superstructure of the box type has holes in the webs and in the soffit at every 1.5m to allow passage of water during the submerged condition, as required for stability. A model test of the box was carried out to determine the drag and the uplift forces on the box during all stages of submergence and to choose the best shape that would induce minimum horizontal and vertical forces on the superstructure. The superstructure was anchored to the pier with stainless steel bolts to resist the uplift. The superstructure was also housed in a kicker box at the piers to prevent displacement during flood conditions.

Owners: Public Works Department, Rajasthan.
Engineers and Contractors: Hindustan Construction Co. Ltd.

Princess Street Flyover, Bombay: India's longest flyover, when opened to traffic in 1967, is 731.5m long. It is a twolane overbridge connecting Princess Street to Marine Drive, Figure 9.

The superstructure consists of span lengths varying from 15m to 30m and has various carriageway widths with straight and curved decks involving both reinforced and prestressed concrete construction. It is provided with a specially-designed guard rail, just above kerb. Light multiple columns, founded on piles or rafts, are used as piers; in certain locations slim T-shaped, single column piers are adopted.

Owner: Municipal Corporation of Greater Bombay.
Contractors: M/s Bharucha and Motivala.
Consulting Engineers: STUP Consultants Ltd.

Rapti Bridge, Nepal: This is a simply-supported prestressed concrete bridge, Figure 10, designed to AASHO Standards for highway bridges for H.S. 20 loading. The bridge has a carriageway of 7.72m with footpaths of 1.64m on either side. The superstructure consists of 4 precast prestressed concrete girders. which were launched into position with the reinforced concrete slab on top. The Freyssinet system of prestressing, with strands made up of 12 wires of 13-mm diameter each, is

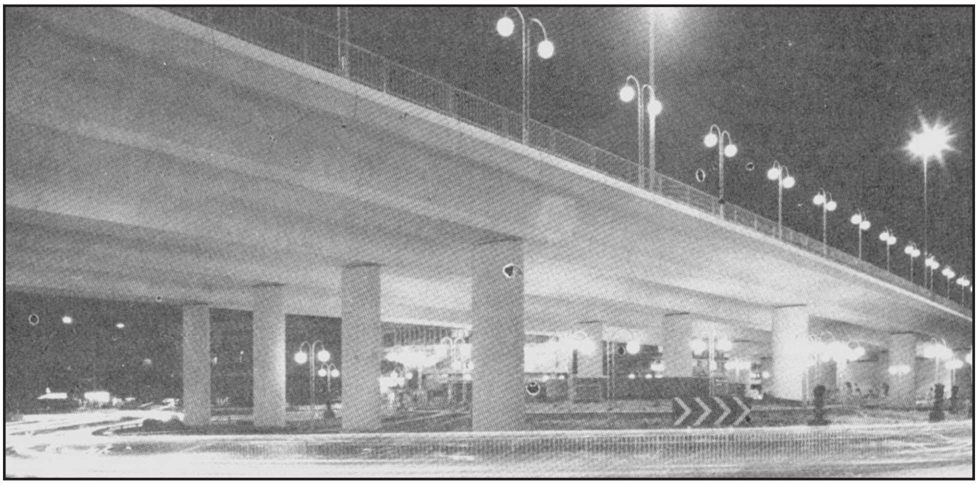

Figure 7. Interchange system at Haza Al Maqam, U.A.E., a high-speed clover leaf junction, built by cantilever construction using precast segments

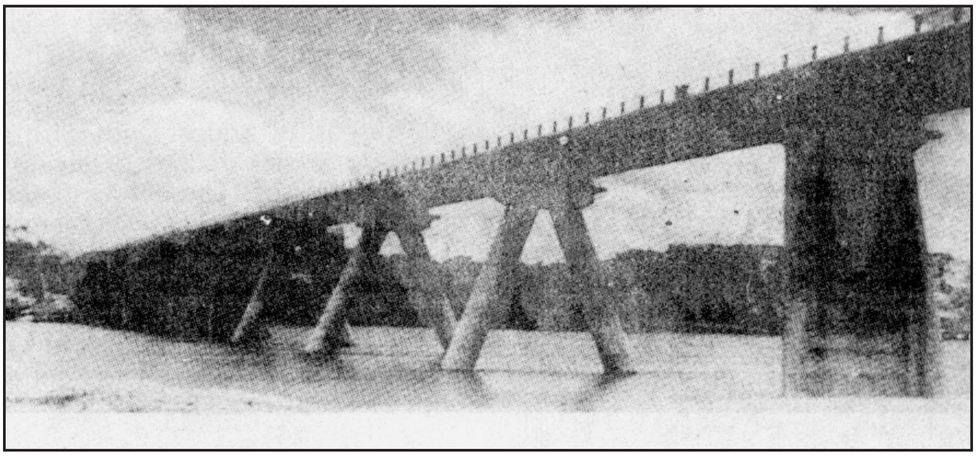

Figure 8. Chambal Bridge at Dholpur, a prestressed concrete submersible bridge with spans of 45m each, perhaps the longest for a bridge of this type

adopted. The prestressed concrete girders rest on elastomeric bearings, placed at both ends on reinforced concrete piers, supported on pile foundations. The Hochstreasser method of piling has been adopted for the 750-mm diameter bored piles.

Owners: Road Department, Ministry of Works Department, His Majesty's Government of Nepal.
Consulting Engineers: M/s. N. D. Lee, Canada.
Contractors: Gammon India Limited.

Dezfoul Bridge, Iran: Located 700km south of Teheran, this prestressed concrete bridge of 22-m width supports two carriageways of 7m each, a central median of 2m and two footpaths of 3m each.

With 3 intermediate spans of 65m each and 2 end spans of 35m each, the superstructure has continuous spans with one expansion joint at the centre. The deck comprises of two separate single-cell box sections with cantilever overhangs, built by the free cantilever method by casting 3-m long voussoirs simultaneously on either side of the pier. The substructure consists of two hollow, rectangular piers with a combined open foundation, resting on rock.

Owners: Ministry of Roads and Bridges, Iran.
Contractors: Ekbaton Company.
Consulting Engineers: STUP Consultants Ltd.

Kalyani Bridge, West Bengal: This 676-m long bridge, Figure 12, consists of 4 intermediate spans of 120m each and one of 98m besides 2 end spans of 63m and 35m, respectively. A typical interior span is formed by cantilevers of 57m, constructed monolithically with the piers, and a small suspended span of 6m. The cross-section of the cantilevers is a single box section, and the suspended span consists of a reinforced concrete two-girder-and-slab system.

Owner: Public Works Department, West Bengal.
Engineers and Contractors: Hindustan Construction Co. Ltd.

Future developments

A study of the structural evolution of bridges towards longer spans reveals that the future development is linked strongly to a reduction in the dead weight of the superstructure. With this in view, various structural forms have been evolved during the past three decades and still more, no doubt, are being sought after. At the same time, new materials and prestressing equipment of larger capacity have been developed. But, unfortunately, the corresponding refinements that were needed in various, age-old concepts and codal specifications

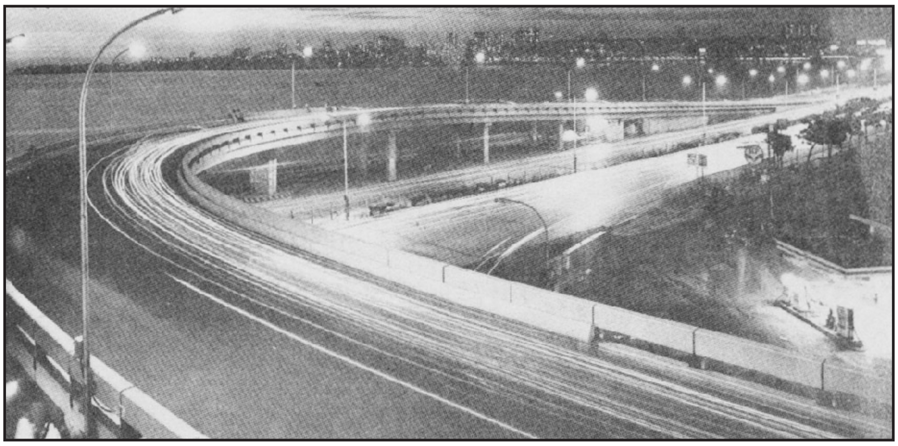

Figure 9. The Princess Street Flyover, Bombay, a 731.5-m long structure with span lengths varying from 15m to 30m, involving both reinforced and prestressed concrete construction

have in many respects failed to keep pace with these developments.

Some important factors which are likely to figure prominently in the future evolution of long-span bridges and, above all, the proper utilisation of the full capacity of prestressed concrete and the resources of ever-ingenious designers need to be understood and appreciated.

The classical concept of the factor of safety, so much a part of our codes, as a flat margin against all sorts of eventualities, is overdue for a change. The modern concept of safety is based on a statistical weightage of a particular combination of loading. This is revealed in the working stresses allowed in the case of very rare events or rare coincidences, like wind and seismic forces. But, this principle has yet to be followed in the case of the various unusual or "abnormal" loadings for which bridges in India are designed. The normal traffic on Indian highways, even with due allowances for the heavier vehicles that may appear in the future, comprises actually of much lighter vehicles than the heavy live loads specified in the codes. To apply the same factor of safety for these "abnormal" loadings as for the normal vehicular traffic is not logical and leads to considerable wastage.

A review of the various safety factors is called for also from another point of veiw. The factors of safety are viewed principally against a backdrop of uncertainties and variations in the properties of new materials or with reservations about the standard of workmanship. This is, no doubt, justified when a new material is introduced. But, it is equally justifiable to reduce this factor when more research and general experience in the use of the material through repeated usage increase one's knowledge about its behaviour and proficiency in workmanship. Indian engineers have gained valuable experience and research has enabled prediction of behaviour patterns for influences like shrinkage, creep, failure, etc. in more definite terms. At the same time, improved standards of production have brought about greater uniformity in properties. But, this added knowledge has not been taken advantage of to reduce the factors of safety (or rather the factors of fear) over the years. On the contrary, the codal provisions have become more and more conservative, and their role in making bridges costlier in each succeeding year has by no means been negligible. A comparison of many Indian codal provisions with those prevailing in many other countries leads designers to a state of frustration. Comparing codes even within the country, it is found that the standards adopted in the I.R.C. bridge codes are, in many ways, more stringent than the corresponding provisions in the I.S. codes. Glaring examples can be cited where higher permissible stresses are allowed in the I.S. codes for concrete or for reinforcement as well as where the I.S. codes accept load factor methods of design for reinforced concrete structures.

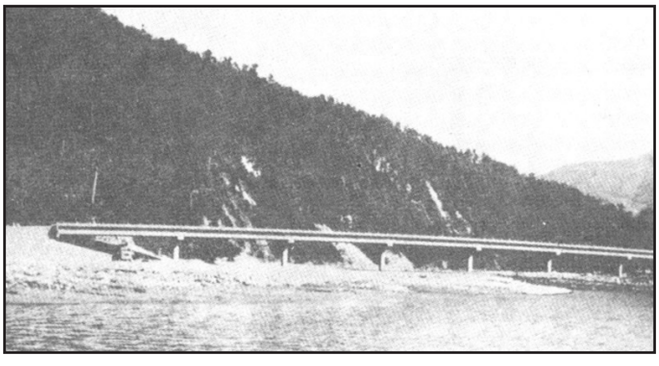

Figure 10. The Rapti Bridge in Nepal, a structure with simply supported spans which were precast and launched into position complete with the reinforced concrete slab

Excessive apprehension has led to a collosal waste of money in the case of prestressed concrete designs also. The classical concept of prestressing err-isages a state of full prestress of the concrete section and does not permit tension to develop under any circumstances, howsoever rare. Prestressed concrete members by virtue of the material's flexibility and resilience are not adversely affected by rare abnormal overloading of short duration. Even if cracking in the tensile zone occurs, the cracks close up again as a result of the compressive stresses induced by the prestressing force after removal of the abnormal loading. Full prestress entails a waste of material in the tension flanges, which are kept in a permanent state of heavy compression, since the normal live loads are only a fraction of the "abnormal" live load. A side effect of such a design principle with a large prestressing force is a large deformation due to creep, resulting in alteration of gradients in the completed structure.

The classical concept of full prestress was primarily promoted by the taboo against cracks in concrete and a fear of corrosion of high-tensile steel reinforcement. Even if temporary cracks are allowed to appear in the concrete under normal circumstances, still the chances of corrosion of the high-tensile steel are much less than for mild steel reinforcement in reinforced concrete members, where the theory of a permanently cracked section is adopted as the basis for design. The modern trend in technically advanced countries shows a departure from the concept of "full" prestress, preferring the adoption of the rational outlook of "partial" prestressing, in which the limit state (allowable) of cracking is defined by a maximum crack width, chosen as a function of environmental parameters, the position and type of steel and the risk of corrosion.

Another idea, which deserves a better deal, is the introduction of lightweight concrete in prestressed concrete construction. The most important criterion for improving the efficiency of concrete in the superstructure for long spans is the strength-density ratio for concrete. Of course, apart from this theoretical consideration which expresses the efficiency of the material to carry loads only, the practical limitations as well as the economic viability of the material must also be taken into account. It is for the latter reason that materials like epoxy resin, although quite light and very strong, cannot replace structural concrete in the foreseeable future.

Lightweight concrete can be used very effectively in combination with ordinary high-grade concrete or by itself. In

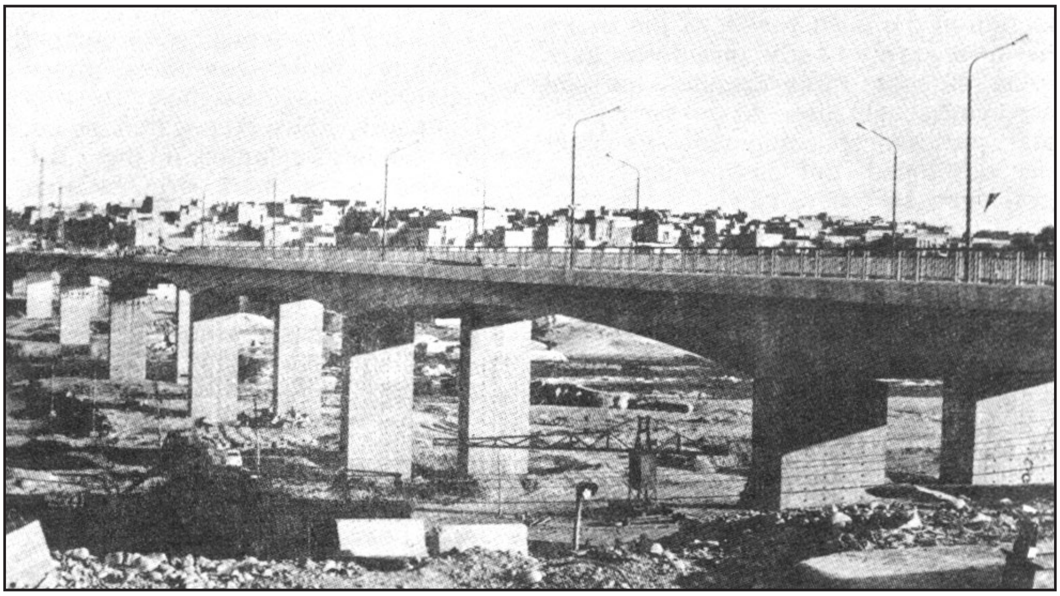

Figure 11. The Dezfoul Bridge in Iran, a continuous span structure built the free cantilever method

a structure all the parts are not under equally high stress, and there is scope for using concrete of lower strength in those parts where stresses are relatively low. Lightweight concrete, which has a comparatively lower strength than ordinary high-grade concrete, can he employed very usefully in these parts and can give the added advantage that, because of its lower density, it helps bring down the stresses to even lower levels than ordinarily attainable with ordinary concrete of comparable strength.

A wide range of lightweight concretes has been developed for structural use. These concretes contain expanded or porous aggregates and have a unit weight ranging from 1,350kg/m^3 to 2,000kg/m^3 and a 28-day cube strength ranging from 200kg/cm^2 to 600kg/cm^2. Perhaps, the most important reason for the somewhat slow development of the material and its application in India is the inertia on the part of potential users. However, with the increased knowledge of its properties through research and exploration, this obstacle is likely to be overcome and the full potential of the material explored in the near future, provided of course the codes of practice change with the times to accept and welcome the development. The important considerations which are likely to confront a designer of lightweight concrete structures are mainly the higher creep and shrinkage factors and the lower modulus of elasticity. There is, however, a possibility of minimising the high creep and shrinkage effects through the use of special expansive cements in the concrete.

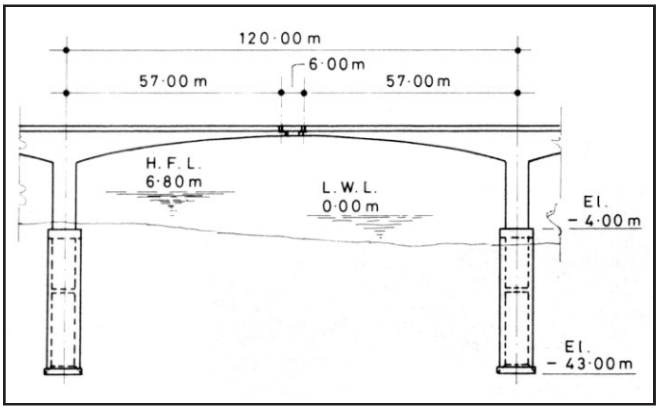

Figure 12. The Kalyani Bridge, West Bengal, with span ranging from 35m to 120m. The 120-m spans consist of two prestressed concrete cantilevers of 57m each and a 6-m suspended span in reinforced concrete

Conclusion

In the foregoing paragraphs, the constraints in the path of development of bridge building technology have been analysed and also the improvements that can he made in this branch of engineering either through rational approaches in design concepts or through the use of more suitable materials have been indicated. Whilst discussing design concepts, a reference has been made to the illogical provisions that are met with in the codes. Asking for the liberalisation of these provisions, in no way advocates the throwing of all caution to the winds; nor is it a question of bargaining between two groups of people with different ends in mind. It is, perhaps, more a matter of introspection.

It is the duty of civil engineers to build safe structures. It is equally the duty of civil engineers to bring about effective economy without in any way jeopardising the safety of the structure. Nonetheless, there is no gainsaying that bridges built in accordance with Indian codes are much safer and much costlier than they need to be, a luxury which a country with so many unfinished tasks ahead, can ill afford. The issue that arises is whether engineers should traverse the beaten track for all time to come or whether they should adopt a flexible attitude and draw upon the rich harvest of research and experience all over the world and march with the times.

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