Current trends in concrete bridges

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Bridges form an important component of infrastructure, and require huge investment. Often, they are also important landmarks in any terrain. The developments in bridge engineering can perhaps be a yardstick of the economic growth of a country. Concrete bridges have been successfully adopted beyond the spans not considered viable a few years ago, and underline the vision and courage of the engineers in adopting unconventional materials and methods of construction. The development of ultra high performance concrete (UHPC) may lead to extending the spans further, besides aesthetic and economical structures. The paper discusses some of the latest trends in bridge engineering encompassing bridge cross sections, external prestressing, extradossed structures, cable supported bridges, new materials, aesthetics and architecture, repairs and rehabilitation, and bridge inspection. The discussion is mainly with reference to long-span bridges constructed in the last two decades.

Several fascinating and spectacular bridges have been designed and built in the last decade than at any other comparable time in the annals of civilisation. These structures were preceded by the developments in materials and construction techniques, and reflect the vision and courage of the engineers in adopting unconventional methods. Consequently, concrete bridges have successfully adopted spans not considered viable a few years ago.

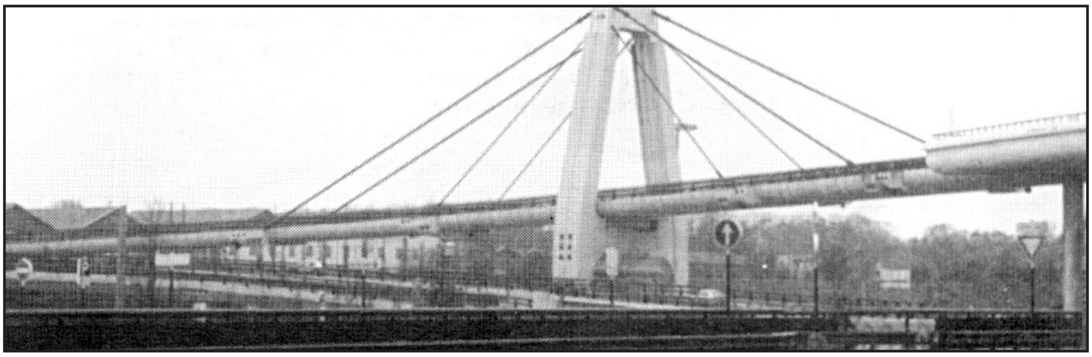

Figure 1. A typical cable-stayed bridge (Milano airport, Italy)

Further, bridges form a significant part of infrastructure, and require huge investment. Often, they are also important landmarks in any country. The developments in bridge engineering can perhaps be considered as a yardstick of the economic growth of a country than any other infrastructural parameter.

Though the cantilever construction technique and incremental launching technique were developed more than four decades ago, their adoption to new structural profiles is worth noting. Similarly, the cable stayed bridges have come a long way from the plump deck girders of the Stroemsund bridge (Sweden, 1954)[1]. The first bridge (barely above the water level) described as 'ugly duckling' led to the architecturally alluring Alamillo bridge (Spain, 1993)[2]. Presently, cable supported bridges are the standard solution for road as well as pedestrian bridges. Figure 1 depicts the cable stayed bridge that provides access to Milano airport (Italy) while Figure 2 is a cable supported footbridge over railway lines in Germany.

The concepts of tension band below the main beams to stiffen the structure and extend the possible spans of bridges, first described by Friedrich Arnold in his book published in 1819[2],

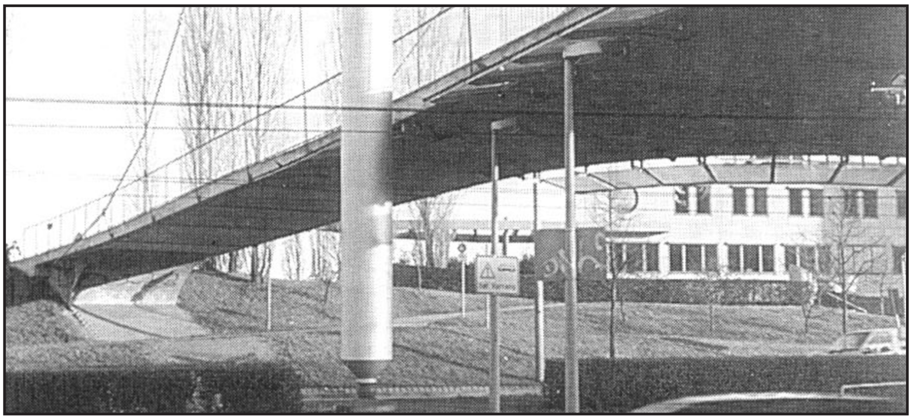

Figure 2. A typical cable-supported footbridge (Nordbahnhof bridge. Stuttgart, Germany

were adopted with considerable refinement to achieve economical solution to difficult structural problems posed by the ground conditions[3].

Medium and long-span concrete bridges are necessarily prestressed to reduce dead load effects and sustain live loads efficiently. Nevertheless, the well known concepts of prestressing have been stretched to incorporate external prestressing and extradossed structures[4].

High performance concrete (HPC) with the performance characteristics of not only high strength but also high workability, compaction, and durability found extensive applications in bridges. The compressive strength of concrete increased to about 120 MPa generally, but strengths of the order of 810 MPa were obtained using reactive powder concrete (RPC) technology[5].

Besides high performance, self-compacting concretes have also been developed, and adopted extensively in several countries such as Japan, Canada, Denmark, Sweden and Taiwan[6, 7]. One of the notable applications being the substructures and anchorages of the longest span (1991 m) suspension bridge, the Akashi Kaikyo bridge, Figure 3[8]. These developments have extended the possible spans of concrete structures by a wide margin.

The principles of composite construction have been extensively adopted in the pylons, anchorage zones of stay cables, as well as in the bridge decks for economy and elegance. Flexible cross sections with concrete deck and steel crossbeams, instead of the conventional rigid box girder sections, have been adopted with advantage. Though in experimental stages, several bridges are built using composite plastics. The repair and rehabilitation techniques are made more effective than before with the advent of composite materials.

Some of the recent developments in the design and construction of concrete bridges are discussed in this article with specific reference to new innovations and concepts.

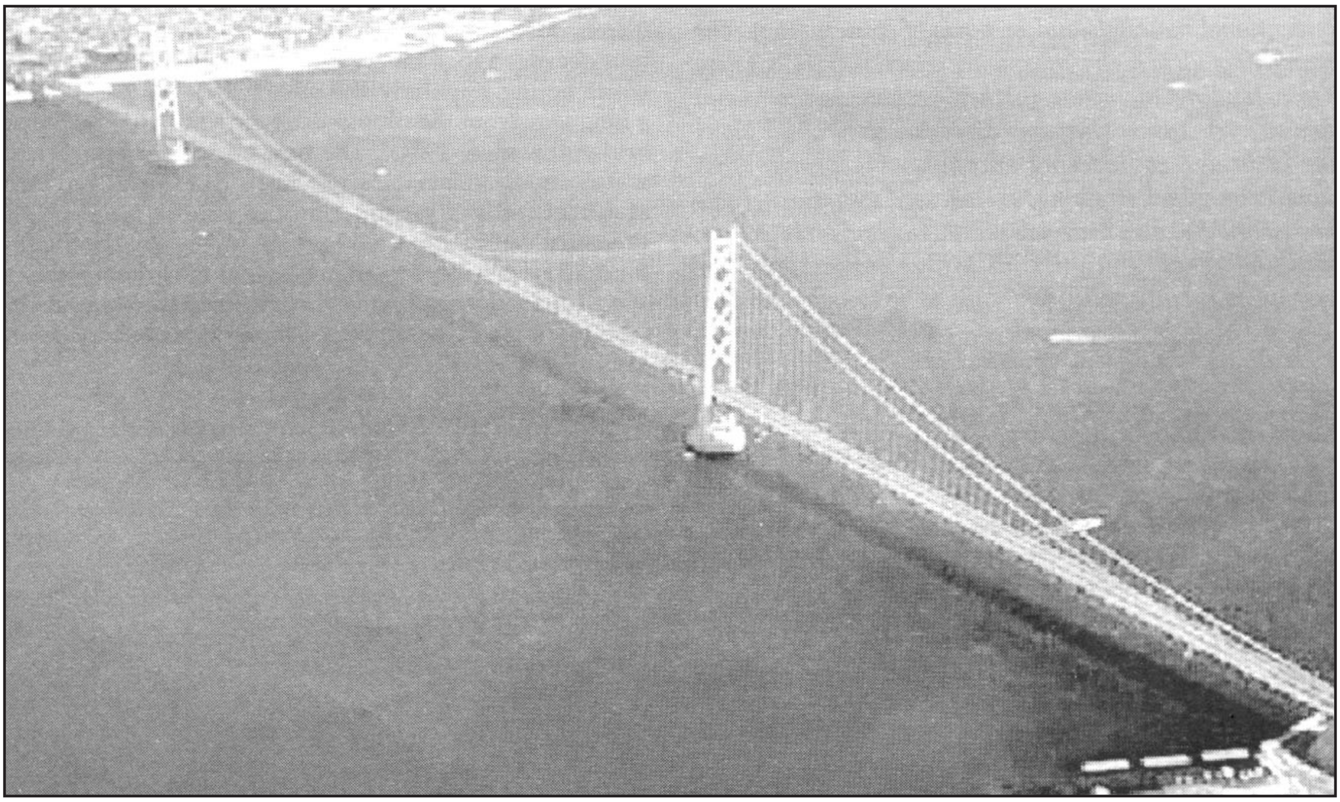

Figure 3. The Akashi Kaikyo bridge *(Source: www.labse.ethz.chiserbackissuesiabstracts.sei0101/TenYearsOISELpdf)*

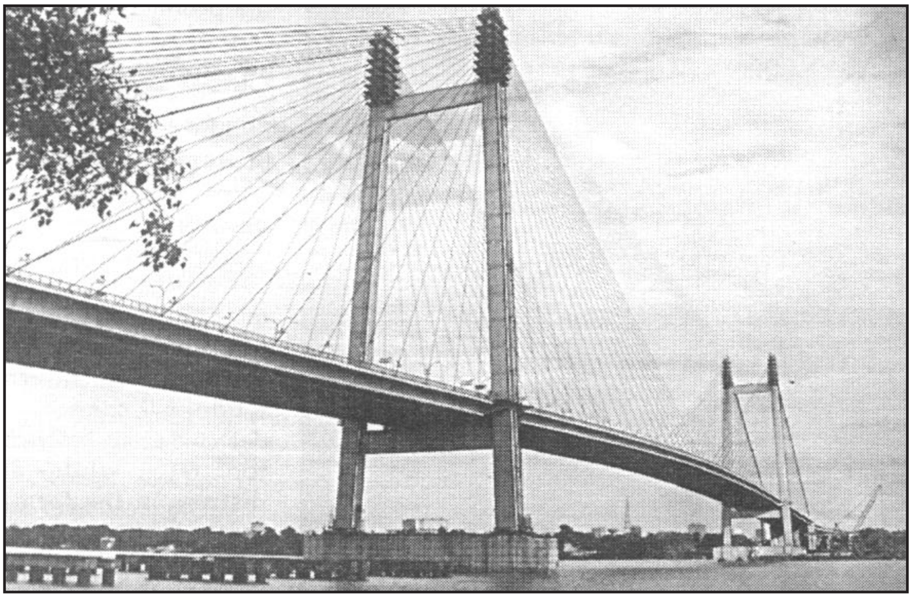

Figure 4. The second Hooghly bridge, India

(Source: Gammon India Ltd, Mumbai)

Bridge cross sections

The bridge cross sections have been modified considerably from rigid box girders to flexible composite steel I-beam and concrete slab (Second Hooghly bridge, India, Figure 4, and Alex Fraser bridge, Canada); slabs with edge beams (Vasco da Gama bridge, Portugal), and without stiffening edge beams (Evripos bridge, Greece) were also adopted without any detrimental effects (cracks or deflections) in cable stayed bridges[9]. The slender Evripos bridge, with a deck slab of 450 mm thickness, Figure 5, could flex more easily over cross beams than longitudinal beams without developing high stresses. The 90 + 215 + 90 m long bridge having 14.14 m width was designed with the deck connected monolithically to the cross bars and pylon legs, thereby eliminating the bearings at the pylons, besides the conventional longitudinal girders. The bridge model was checked for flutter in a wind tunnel because of its slender profile.

Steel trusses have replaced the webs of box girder sections in several bridges. The innovative design of the viaduct Tully (Switzerland, 2001) comprises of two adjacent cross sections of concrete deck slab with 2.9 m triangular tubular trusses[10]. The composite concrete slab and steel truss bridge, consisting of 23 spans (29.925 + 21 x 42.75 + 29.925 m) was designed with steel trusses as cross girders at the supports, Figure 6.

In some cases, folded plates are adopted for the webs (Hontani bridge, Japan). The earlier designs of wide box girder bridges with large side cantilevers propped by inclined precast struts (Eschachtal and Kochertal bridges[11, 12] are adopted with steel tubes replacing the external concrete struts in the Piou viaduct (France, 1998) [4].

More and more elegant and economical cross sections have been evolved, especially for cable stayed bridges. The cross section proposed for the 2460.0-m long Millau viaduct with 6 main spans of 342 m each comprises of a trapezoidal box girder of 4.6 m depth tapering to about a metre at the edges. The 27.75-m wide bridge section has thin top and bottom flanges supported by struts, Figure 7[4].

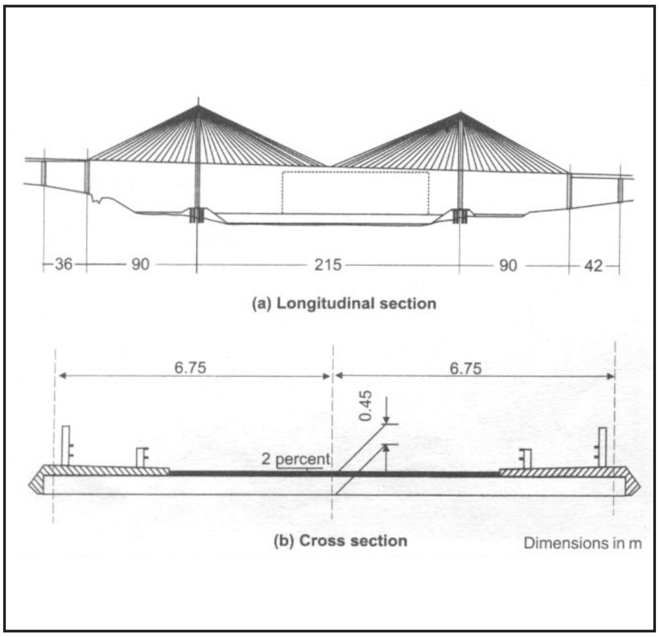

Figure 5. Evripos bridge, Greece[4]

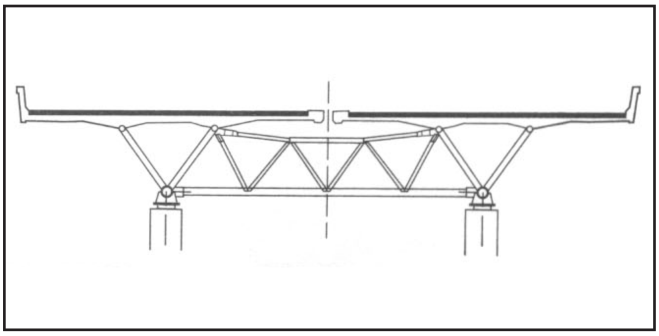

Figure 6. Cross section of Viaduct Tully (Switzerland, 2001)[4]

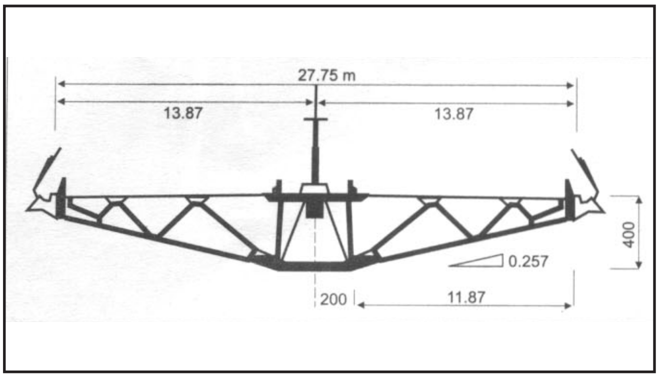

Figure 7. Cross section of Millau viaduct (2460 m long cable stayed bridge with six spans)[4]

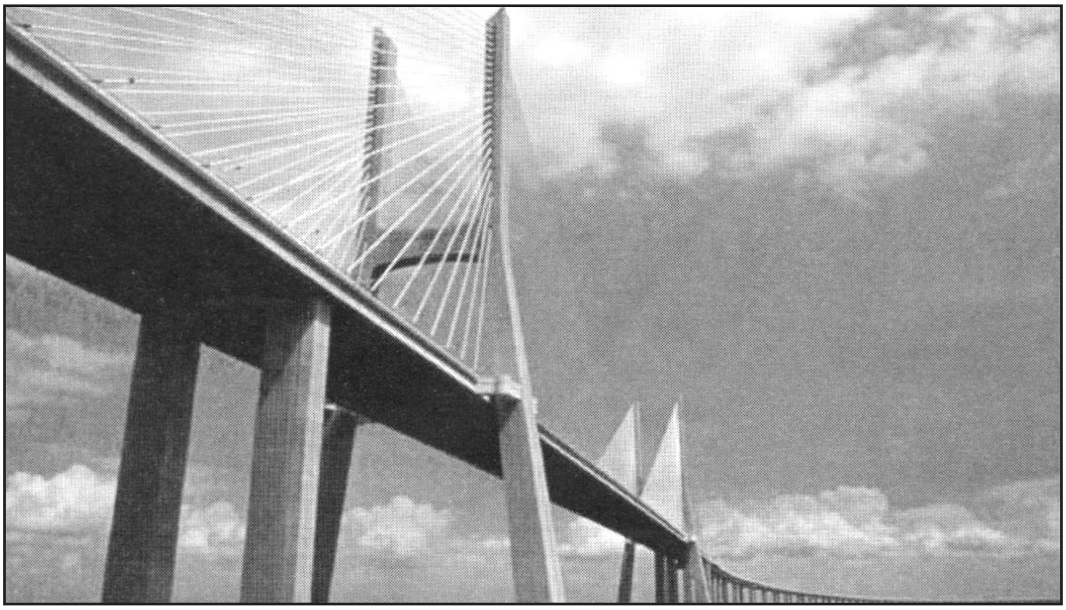

Figure 8. The Vasco da Gama bridge, Portugal
(Source: havilwww.structurae deieniphotosrimg5360.php Photo by Jean-Marc Morand)

External prestressing

External prestressing was adopted widely in the 1960s but was later abandoned in favour of internal prestressing (grouted ducts installed within the cross section). However, external prestressing was required in several bridges in mid 1970s for rehabilitation or strengthening. In most of the cases, additional prestressing was required due to underestimationof creep and shrinkage losses, and of thermal stresses. The technology was developed with high density polyethylene (HDP) ducts, and was found to be advantageous even in new bridges.

Several segmental bridges using free cantilever technique adopted external tendons in place of internal tendons in the USA, France, UK and Germany. Internal prestressing is banned in some countries for specific applications because of the problems posed by corroded internal tendons on account of poor grouting. Some bridges in India (Thane Creek bridge, Mumbai and Mandovi bridge, Goa) developed severe distress, and in some cases collapsed, because of the corrosion of internal tendons. The corrosion in internal tendons cannot be detected easily before it is too late, while any distress in the form of breaks in strands or poor quality grout is easier to detect in external tendons.

The five-span 476-m long Stoney Trail bridge (Canada, 1998) constructed by the incremental launch method, adopted external prestressing tendons during the launching stage; these were removed after stressing continuity tendons resulting in significant savings[13].

While well designed, properly installed and grouted internal tendons constitute an excellent solution, external prestressing has the advantages of easier inspection and replaceability than internal tendons.

Composite construction

Composite construction implies not only the bridges with concrete deck slab on steel beams; steel and concrete have been combined in several innovative ways in some of the recent bridges. Bridge sections were developed comprising steel

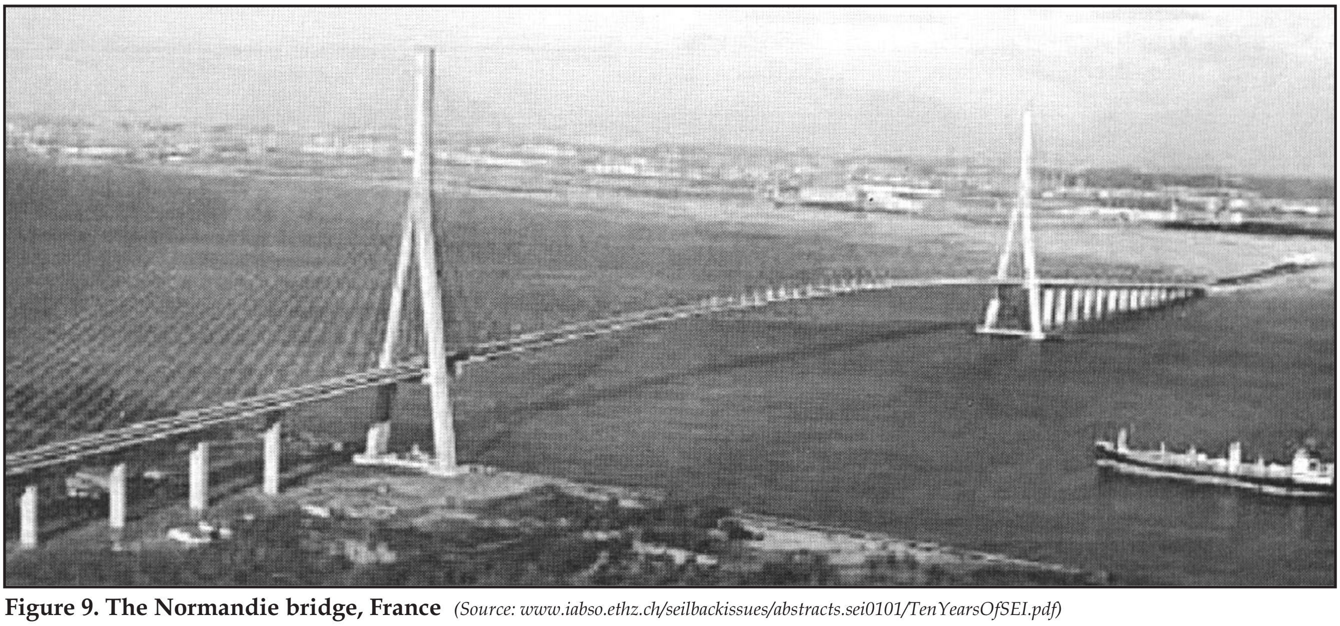

Figure 9. The Normandie bridge, France *(Source: www.iabso.ethz.ch/seilbackissues/abstracts.sei0101/TenYearsOfSEI.pdf)*

struts and concrete slabs (Piou viaduct), while the top and bottom slabs were connected by steel tubes in the precast segments of Boulonais viaducts (France)[4]. The Millau viaduct is another excellent example of combining steel web elements and concrete flanges, Figure 7.

Chevire' bridge at Nantes (France) comprises of a steel orthotropic span simply supported on prestressed concrete cantilevers extending from piers. Similar concepts were adopted in some of the bridges in Spain by providing continuity between steel and concrete segments.

The access spans of cable stayed bridges were built in prestressed concrete, while the main span was steel orthotropic box girder in Tampico bridge (Mexico). Such concept, adopted in several bridges, takes advantage of a light steel segment in the main span and of heavy access spans to tie the deck to piers. Steel tubular arch with concrete deck (Antrenas overpass, Czech Republic), and concrete arch supporting steel deck (Morhiban bridge, France) are some of the innovative examples, which take advantage of light steel sections to reduce construction forces on the structure[4].

Cable stayed prestressed concrete bridges with edg beams connected by steel cross girders were adopted successfully in several projects (Vasco da Gama bridge, Portugal, Figure 8)[4] .

While the pylons are usually designed in concrete or steel, composite pylons in concrete with steel anchorage elements are also extensively adopted (Chalon sur Saone and Normandie bridges, France, Figure 9)[4]. The Owensboro bridge (366 m main span and 152 m side spans, USA) has A-shaped concrete pylons with steel frames to anchor the cables[14]. The stay cables of the proposed cable-stayed bridge over Yamuna at Allahabad (India) are anchored to steel plates protruding from concrete pylons in the top region [15] .

Arch bridges

Arch bridges, in combination with cables, require much less material than other structural systems, and are considered suitable for spans in the range 80-150[16, 17]. Such structural systems are known as bow string girders, tied arches with hangers, and cable network arches. Arches have been adopted in bridge construction not only for structural efficiency (small bending moments) but also for aesthetics.

The arch bridge may comprise of structural steel arch supported by vertical or inclined cables (hangers) anchored to the slender beams at the edges of the concrete deck slab prestressed in the longitudinal direction for tie action. The deck slab is usually of 250 - 300 mm thickness with edge beams of about 500 mm depth. Such a system with inclined cables intersecting each other, further reduces the steel requirements leading to extremely slender appearance. The Bolstadstraumen bridge (Norway, 1963) with a span of 84 m is considered to be the world's most slender structure with span to depth (of the deck slab and arch section) ratio of about 125 [16,17]. The proposed structures of Rugsund (172 m span) and Akviksund (135 m span) bridges in Norway involve even larger slenderness ratios of the order 200. Several such bridges are constructed in Norway and Sweden, and planned for construction in the USA[17].

The new bridge over river Main in Marktheidenfeld (Germany) consists of steel arches of 135 m span and 24 m rise with intersecting cables (cable network) for a 16 m wide roadway[18]. The steel arches comprise of sections of 1.2 m constant width, and depth varying from 0.80 - 1.2 m, welded of 53-mm thick steel plates. The composite deck is about 2 m over all depth. The steel arch system with cables, weighing about 10 MN, was pre-fabricated and transported to site: total construction time for the 360 m long bridge was barely 26 months.

Figure 10. The third Godavari bridge, India *(Source: BBR India Ltd. Bangalore)*

The third Godavari railway bridge, comprising 28 spans spaced at 97.55 m, is another example of reinforced concrete twin arch system supporting a prestressed concrete box girder with 12 pairs of hangers per arch (bow string girders of 94 m effective spans), Figure 10.

Cable-supported bridges

Cable-supported bridges can be classified into the following three categories, depending upon the location of the cables.

1. Bridges with tendons within the cross section (cantilever construction)
2. Extradossed bridges with tendons anchored outside the cross section up to a height of a tenth of the main span
3. Cable-stayed bridges with tendons anchored outside the cross section at a height of about one-fifth of the main span.

Bridges with external prestressing fall into the first category, while the cables are visible above the deck in the other two cases, and are generally known as cable-stayed bridges. However, the extradossed bridges are considered a special category not only because of the short pylon height, but also because of the higher stresses permitted in the cables compared to the usual cable-stayed bridges.

Cable-stayed bridges are generally considered to be economical for main spans over 150 m, when overall costs are considered but extradossed bridges are generally economical for the span range of 80 -150 m, due to the smaller girder depth and height of pylon[19].

> **Cable-stayed bridges have been widely adopted all over the world because of the economy as well as aesthetics**

Extradossed bridges

The concept of extradossed bridges has an interesting history. Christian Menn designed the Canter bridge (Switzerland) with rigid prestressed concrete walls completely encasing the tendons on each side of the short pylons[4]. Later on, other designers took advantage of classifying the supporting cables from short pylons as prestressing tendons instead of cable-stays and obtained competitive designs; the economy resulted from the specifications for cable-stays being more stringent than those for prestressing tendons. The concept caught on with other designers, with French, Portugese and Japanese engineers adopting the concept widely.

Such bridges have a low ratio of pylon height to main span of about 10. The low height of pylon results in a flat cable profile (inclined about 10^0- 25^0 with horizontal) leading to large longitudinal forces in the girders. Especially in the case of rigid connection between bridge deck and piers, the stress variation in cables is much smaller than that in cablestayed bridges, which justifies the classification of the cables as extradossed tendons and not as stays. However, for simply supported spans longer than about 200 m, the stress variation in cables could be appreciable, and it would be desirable to limit the maximum stresses as per the specifications applicable to stays.

The span-to-depth ratio for extradossed concrete bridges is much larger than that in cable stayed bridges, being about 30 to 35 at supports and 50 to 60 at supports. In view of the small inclination, extradossed tendons carry only about 10 to 30 percent of the vertical loads. However, the extradossed bridges are economical because of the larger permissible stresses; the maximum permissible tension in tendons is $0.60\ \sigma_{pu}$ compared to the corresponding value of $0.40\ \sigma_{pu}$ in cable stays (cs σ_{pu} is the ultimate tensile strength of tendons). Most of the codes permit higher stresses in concrete in extradossed bridges than in cable-stayed structures. Creep and shrinkage losses are similar to those in prestressed concrete bridges, and hence significant, resulting in a tensile stress loss of about 80 to 120 MPa in the tendons [4].

Though extradossed bridges are considered to be economical for main spans in the range of 80 - 150 m, they have been successfully adopted for much longer spans also[4, 19]. The Soniberg bridge (Switzerland), and the bridges over the Ibi and Kiso rivers in Japan have main spans of a little over 270 m.

Cable-stayed bridges

Cable stayed bridges have large pylon heights, of the order of about one-fifth the main span length, resulting in steep cable inclinations (about 30^0 to 80^0). Consequently, the cables carry much larger fraction of vertical loads (about 85 to 95 percent), and are subjected to stress variations of about 80 to 130 MPa under live loads.

The deck beam depth is small in cable-stayed bridges with a usual span-to-depth ratio of about 80 to 100, resulting in slender structures of low dead weight. The large inclination of cables results in significant changes in the cable tension due to deck deformations under live loads. Since most of the vertical loads are carried by the cables, the bending moments are small, often requiring a permanent prestress of about 3 to 7 MPa for safety and durability. The effects of creep and shrinkage are also small resulting in a tensile stress loss of about 20 to 30 MPa in the stays[19].

Cable-stayed bridges have been widely adopted all over the world because of the economy as well as aesthetics following the completion of Stroemsund bridge in Sweden (1955). Several bridges have been built with increasing span lengths since then, such as Saint Nazaire bridge (orthotropic box girder, 404 m, France, 1975), Fernandez Casado bridge (prestressed concrete, 430 m, Spain, 1983) Anacis Island bridge (composite steel I-beams-concrete, 465 m, Canada, 1986), Ikuchi bridge (composite, 490 m, Japan, 1991), Skarnsund bridge (prestressed concrete, 530 m, Norway, 1991), Yangpu bridge (composite, 602 m, China, 1993) and Normandie bridge (composite, 856 m, France, 1995). Presently, Tatara bridge in Japan with a main span of 890 m concrete deck, completed in 1999, is the longest cable stayed bridge[4].

Precast segmental box girder construction is also widely adopted because of the economy and speed of construction. The Sunshine Skyway bridge with a 360 m span between two pylons is the longest cable stayed bridge in the USA constructed with precast segments[20].

A recent trend in cable-stayed bridges is composite steel concrete construction with steel I beams, and reinforced concrete deck slab

Though spans in excess of 800 m are generally considered to be the domain of suspension bridges, it should be no surprise that the spans of cable-stayed bridges have increased beyond 800 m (Normandie bridge, and Tatara bridge). The Duesseldorf - Flehe bridge (368 m, 1979) with single pylon would have been twice as long with two pylons[21], indicating a possibility of extending the spans beyond 700 m.

Composite bridges

A recent trend in cable-stayed bridges is composite steel-concrete construction with steel I-beams, and reinforced concrete deck slab. The earlier bridges relied on concrete or orthotropic steel deck. The Second Hooghly bridge (457.2 m, India, 1993, Figure 4) is the first structure conceived as cable stayed composite bridge in about 1972. However, usually Anacis Island bridge, Canada is given the credit by virtue of its being completed earlier in 1986.

The main advantage of composite construction is the reduced load the cables have to carry during construction. The Second Hooghly bridge, for instance, comprises of two longitudinal steel I-beams of 2-m depth spaced at 29.10 m, joined by cross girders at 4 m spacing; a third steel girder runs longitudinally mid-way between the two main beams[9]. The main beams were supported by the cables, and the concrete slab was cast over the steel grid so created to provide an overall width of 35 m.

Flexible decks

Another perceptible trend in cable-stayed bridges is the adoption of flexible cross section in several bridges from the 1970s compared to the rigid box section profile. The Second Hooghly bridge (India), with two steel I-sections and concrete deck slab, can be classified as a flexible structure[9].

Prestressed concrete slabs with stiffening edge beams were first adopted by U. Finsterwalder, and used in bridges in America, Malaysia and Portugal. However, because of the poor torsional rigidity of flexible decks, additional precautions are necessary to limit aerodynamic effects; baffles between main beams and Haired edges for streamlining the wind flow are some of the common methods. The main bridge of Vasco da Gama crossing in Portugal (420 m, 1988, Figure 8) has an overall width of 30.9 m with a concrete slab supported on edge beams; baffle beams are provided between the edge beams to reduce torsional wind effects[9].

Dieppoldsau bridge (97 m, Switzerland, 1985) designed by Rene' Walther, and the Evripos bridge (215 m, Greece, 1993) designed by Jorg Schlaich have rectangular cross sections without edge beams[4,9].

The stringent French serviceability specifications were overcome by Virlogeux in Bourgogne bridge (151.80 m, France, 1995) by means of two ribs of 1.03-m depth connected by a top slab of 220-mm thickness for road traffic, and cantilevered slabs on each side at the soffit level of the ribs [4]. The bridge has an overall width of 15.54 m. Beaucaire-Tarascone bridge (410 m overall length, France, 2000) has a deck slab of only 830 mm.

The proposed Yamuna Cable Stayed Bridge (India) planned near the confluence of Ganga and Yamuna between Allahabad and Naini is another example of flexible deck system, Figure 11. The original proposal was a concrete box girder structure a 120.0 m spans in free cantilever construction.

Figure 11. Pylon work in progress of the Yamuna bridge, Allahabad

(Source: Hidustan Construction Co. Mumban

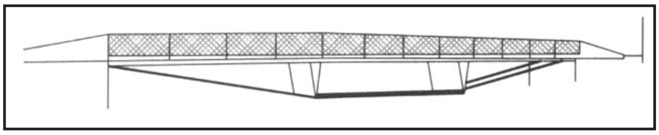

Figure 12. Bridges with prestressing tendons below the deck[2]

The alternative proposal comprises 13 x 25.0 + 60.0 + 115.0 + 260.0 + 115.0 + 60.0 + 7 x 60.0 m spans; the deep channel section of 630.0 m length is spanned by cable stayed system[15]. The cross section of the cable stayed structure comprises two longitudinal beams of 1.40 m width and 1.37 m depth with a deck slab of 250.0 mm thickness and cross beams of 1.5 m depth spaced at 5.0 m for an overall width of 26.0 m (3.0 m long cantilevers on each side). The cross section accords a slender appearance to the bridge with a main span of 260.0 m. The pylons with double in-plane semi-fan configuration are 90.0 m above the foundations and rise to about 60.0 m above the bridge deck level. The diamond shaped towers are supported by double D-shaped well foundations reaching to 40.0 m depth below the river bed.

The pylon legs are 30.0 m apart at the deck level, reducing to 18.2 m at the top cross beam level. The width of the legs varies from 5.0 m below the deck level to 2.2 m above the deck level; the corresponding thicknesses (in the direction of span) are 4.0 m and 2.5 m, respectively.

The Danish engineer Veje adopted stay cables anchored to steel plates protruding from the pylon legs, possibly for the first time. The 13.425-m deep anchorage plates configure to a semi-fan type system - much different from the 18.0 m deep closely spaced cluster of anchorages (flower pot) adopted by Schlaich for the Second Hooghly River Bridge (Kolkata, India, 1993) with 457.2 m main span[9], Figure 4.

Precast segmental construction is adopted when access from below is restricted in urban areas, over rivers or due to environmental restrictions

The 1510.0 m long bridge was scheduled to be completed in 2002[15]. Ribbed slabs with streamlined profiles are also recommended for flexible decks[4,9].

Multiple bridges

The concept of multiple cable-stayed bridges was first put forward for the bridges over Ganga at Allahabad (1966) and Patna (1971) by Leonhardt[22]. Both the bridges were about 4 km long, and comprised of a series of repeated prestressed concrete structures of equal spans. The proposals involving high quality suspension cables and partial prestressing were considered much ahead of local practices, and hence were not accepted by the regional authorities[9]. Similar structure was proposed by Schlaich for the 12-km long crossing to link Prince Edward Island, Canada in 1992. The structure comprised of a two-span units of 400 m length (L + 0.8 L) - similar to the Ganga bridges proposed earlier, but was never constructed[9]. Kwang Fu bridge (2 x 134 m, Taiwan, 1978) has two successive spans of 134 m each, while Colindres bridge (2 x 125 m, Spain, 1993) has two spans of 125 m each. Mezcala bridge (311.44 + 299.46 m, Mexico, 1993) and Ting Kau bridge (475 + 448 m, Hong Kong, 1998) are similar bridges but with much longer spans. The central 194-m high pylon of the Ting Kau bridge is stiffened by connecting its top to the end pylons at the deck level by diagonal cables, while the end pylons are stiffened by the conventional backstays. The three pylons are stiffened in the transverse direction by cables running from the top of pylons to the anchorages below the deck by enclosing the deck (like that of a ship's mast)[4].

Arena viaduct (5 x 105 m, Spain, 1993) is possibly the only structure that would qualify as multiple cable stayed structure with five main cable-stayed spans of 105 m each.

The Macau bridge (China, 1994) comprises several spans of 35 m each, built with prefabricated prestressed concrete beams of 1.7 m depth, has two main cable stayed spans with double pylons to provide clearance for navigation across the South China sea between Macau and Taipa. The two main openings are in multiples of 35 m (35 + 105 + 35 and 35 + 105 + 35 + 105 + 35 m); the piers at the larger openings were replaced by cables from pylons[9].

Multiple cable-stayed bridges may present typical problems of stiffening the pylons unlike that for Macau bridge with only two main spans separated by smaller spans (35 m). When one span of multiple cable-stayed bridge is loaded, the adjacent pylons are bent towards the span; adjacent spans will be lifted upwards in the absence of backstays. This increases bending moments in the pylons, alternately in one direction and then in the other as the load moves from one span to the other. This problem was addressed in some of the recent proposals by distributing the stiffness between the deck, piers and pylons[4]. The pylons suggested have inverted Vshape in the longitudinal direction of the bridge for adequate stiffness.

Cable-stay cradles

A new development in the cable-stayed bridges is the cradle system tested recently and proposed for the Maumee river bridge[23]. The conventional anchorage of cables from the deck to the pylon is replaced by continuous cables, passing over a cradle on the pylon, connecting the deck on both sides. The cable strands pass through individual stainless steel sleeves in the cradle assembly.

Such a system eliminates the anchorages at the pylon leading to a slender pylon and reduced costs compared to conventional system. Other advantages claimed are easy inspection and replaceability of cables at any time, reduced costs and construction time besides aesthetics. The system will be adopted for the 370-m long span Muamee river bridge with a 120-m tall pylon, slated for completion in 2006.

Cables below bridge decks

Several bridges have been successfully built with tendons below the soffit of the deck, Figure 6. These may not be classified as external tendons, (though they are outside the bridge cross section) since the bridge develops large changes in stresses due to deflections (unlike external or extradossed tendons). They are also not extradossed tendons, since they lie below the bridge deck.

The concept is not totally new, however, since some of the 19 century structures comprise steel tension members similar to the cables. The recent advancements in prestressing and the high efficiency of such structural systems have led to the adoption in several recent bridges [3,24].

The single span (44 m) bridge over river Tessin and the three-span (15.25 + 38 + 15.25 m) bridge over river Capriasca (Switzerland) are some of the recent examples[24]. The conventional prestressing tendons in the end regions (spans in the latter bridge) are taken below the soffit of the central span to form the tension band. The tension band is connected to the concrete deck by V-shaped struts, Figure 12.

The stresses in the bridge deck can be reduced significantly, leading to an efficient and economical solution, by optimal selection of tension band, the number of struts and their location[24].

Erection techniques

The techniques of the 1960s, such as free cantilever construction and incremental method, have been modified extensively by adopting external prestressing in the final structure, in addition to internal tendons during erection. The emphasis has always been on the speed of construction, besides economy.

Precast segmental construction is adopted when access from below is restricted in urban areas, over rivers or due to environmental restrictions. Linn Cove viaduct in Grandfather Mountain was constructed using progressive cantilever placement method; only the area required for piers was disturbed on the ground, while the rest of the forest area was preserved[20].

As the projects have grown in size, heavy prefabrication involving complete spans and foundations is adopted. The size of projects comprising a few kilometres of bridge structure often justifies the use of heavy and expensive construction equipment. Large floating cranes are used in marine conditions with advantage; Japan and the Scandinavian countries adopt large-scale prefabrication and erection.

Large capacity derrick cranes on moveable platforms, erection towers and form travellers have been developed and used for various types of long span cable-stayed bridges. Engineers have the tendency to adopt unique designs for long span structures that are unlikely to be repeated. One of the disadvantages of such construction is the short life of the erection equipment and structures that are scrapped later [25].

New materials

High performance concrete

The last two decades witnessed several developments in concrete technology, leading to the development of what is today known as high performance concrete (HPC). The performance criteria not only include high strength, but also high workability, compaction, durability, etc. High strength of concrete is of distinct advantage only when stresses in concrete are critical as in the case of long span bridges constructed by adopting the method of incremental launching. Though high strength is not specifically advantageous for small and medium span bridges, long term durability merits its applications.

Concrete with a characteristic strength of 60 MPa is fairly common, while a characteristic strength of 100 MPa was adopted in some bridge structures. However, some of the difficulties with ultra high strength concrete (> 80 MPa) should be appreciated before its adoption. High strength concrete has lower ductility than normal concrete; brittle failure should be avoided with adequate reinforcement in longitudinal as well as transverse directions. Further, high strength results in reduced thickness of cross sectional elements, which may lead to higher second-order effects. The high prestressing forces that can be sustained by high strength may lead to high stress concentration in anchorage zones, which require additional care in design.

The compressive strength of concrete increased to about 120 MPa, and is often limited by the strength of aggregates. The strength could be enhanced further by using the concept of reactive powder concrete (RPC) with a maximum aggregate size of 0.5 mm, steel fibres, admixtures, curing at high temperatures and application of multi-axial pressure during compaction[5]. Compressive strength of 550 Mpa without the application of compaction pressure, and 810 M Pa with pressure was obtained by curing at 250 °C. The tensile strength of concrete also increased significantly to about 11.4 MPa in direct tension and to 58 MPa in flexural tension with 4 percent steel fibre content (ultra-high strength concrete)[26]; the corresponding compressive strength was 225 MPa and Young's modulus was 43 Gpa.

The compressive strength of concrete in the flanges of the 3.3-m wide and 60-m long Sherbrooke footbridge in Canada is 200 MPa with a deck slab thickness of 30 mm. The compressive strength of concrete tubes in the diagonals confined by 150 mm diameter 2-mm thick stainless steel is 350 MPa. The strength of concrete is 7 MPa in direct tension and 40 MPa in flexural tension. The bridge is a post-tensioned open web space truss[27].

Besides high performance, self-compacting and self-curing concretes have also been developed, and adopted in bridges (Akashi Kaikyo bridge, 1999)[6, 7]. These developments have enhanced the possible spans by a wide margin.

Fibre-reinforced plastics

Corrosion of steel is the primary cause of deterioration of concrete structures exposed to humid and aggressive environments. One of the most promising solutions to overcome this problem is the use of non-metallic materials that do not corrode. Composite materials such as fibre-reinforced plastics are a possible replacements to prestressing and reinforcing steel in concrete structures.

A few bridges using FRP have been constructed successfully on experimental basis. The German engineers used glass fibre reinforced plastic (GFRP) tendons to prestress experimental bridges in the early 1980s. Pedestrian bridges using FRPs with glass fibres, aramid fibres and carbon fibres have been constructed in several countries; Westminister Cathedral footbridge (UK, 1974), Virginia Pedestrian bridge (USA, 1978) and Adolf Kiepert Pedestrian bridge (Germany, 1983) are some of the notable examples[28]. Aberfeldy Golf course footbridge (Scotland, 1992) is the first bridge to be completely built in fibre composites; it is a cable stayed structure with a main span of 63 m, overall length of 113 m and a deck width of 2.23 m.

The two-lane, 15-m wide Ulenbergstrasse bridge (Germany, 1986) which is a continuous structure of spans (21.3 + 25.6) m is the first road bridge with GFRP prestressing tendons. Several bridges using FRP are built in China, Japan, Europe and America[28].

Fibre reinforced plastic (FRP) bars were used in place of steel reinforcement in the concrete deck slab of McKinleyville bridge, USA[29]. The 229-mm thick concrete deck slab of the 54-m long, three span continuous bridge, supported on three steel main girders, was provided with 13 mm diameter FRP bars at 152 mm in the transverse direction, and 9 mm bars at 152 mm in the longitudinal direction.

Fibre composites are extensively adopted in most of the repair jobs in preference to conventional or polymer concretes, despite the high costs

The primary disadvantage of non-metallic materials is their brittleness and little plastic deformations. Any underestimation of local stresses may lead to failure with no possible redistribution of forces. Further, so far there are no standards for FRP composite products or for the design of structures using them. Every structure used a different data on materials to facilitate any standards to be developed. It is likely that without approved standards for design and FRP products, it may take a few more years of coordinated research before FRP bridges become competitive[30].

Bridge architecture and aesthetics

Bridge forms have come a long way from being utilitarian in the ancient times (early Roman bridges) to the emphasis on artistic skills during the medieval times. However, the rapidly expanding railroads of the nineteenth century and the interstate highway systems of the twentieth century necessitated a fast rate of construction with utilitarian structures and standard designs; aesthetics were often only incidental[31]. With their increased spans and high visibility, bridge structures have become important landmarks all over the world. A well proportioned bridge with its slender form covering vast expanses, should merge with the surroundings harmoniously rather than stand out craving for attention. Aesthetics of bridge structures is one of the significant criteria for selecting the bridge form. Sometimes, the architectural considerations outweigh even the economical aspects of bridge structures. Indeed science, technology and aesthetics merge to create beautiful structures that are utilitarian and honest[32]. The current emphasis is on holistic approach rather than treating aesthetics as an exclusive aspect of bridges.

The single pylon of the new Maumee river Bridge under construction is to be provided with backlit-glass facing on the upper 60 m from aesthetic considerations [23]. The decorative designs on the Broadway bridge, Florida (USA) include 3.1-m high lass-tile mosaics of wild life on the walkways and piers[20].

The most fascinating, yet controversial, structure is the Alamillo bridge (Spain, 1993) designed by the renowned architect Calatrava; its strong inclined pylon supporting a slender deck with stay cables gives it an appearance of a giant harp, Figure 13. However, while it is considered an architectural master piece, it is criticised for its extravagant design in the absence of back stays[2, 4]. A similar bridge, built over river Elbe in Aussig (Czechoslavakia, 1998), has 75 m high steel pylon for a main span of 123.3 m, but is designed economically without back stays and to merge well with the surroundings[33].

'Logic of form, is the essence of structural design, as referred often by Torroja[34]. The aesthetic quality of bridges will be determined by the harmony of the proportions within a logically defined structural form. Good aesthetics can only result from ensuring the flow of forces through the structure in the most efficient way[3].

Quantification of bridge aesthetics through a rating paradigm comprising 177 statements with different weightages for overall appearance, details, site and special features was reported by Zuk[35].

It is well to note that the cross section of a bridge is never seen, and does not form a part of its image. Bridge appearance is often dictated by the fascia and details comprising railings, light posts and signs, corners, joints, besides the piers and drainage system. The most neglected aspect of bridges is often its drainage system, leading to unsightly pipes sticking out or to ugly stains caused by rainwater flowing over the surfaces[36].

Bridge inspection

Inspecting and maintenance of structures is as important as construction in order to ensure long service life. A distinctly noticeable current trend in bridges is to make the structures accessible for inspection, and design certain components for possible replacement, when required[3]. External prestressing tendons are specifically developed and deployed for ease of inspection and replacement, if necessary. Other such components are POT bearings, hand railings and stay-cables[37].

The design includes facilities to access every component of structure for inspection and replacement or repair, when necessary. The inspection comprises of routine and detailed jobs. The former involves visual observations on various components and simple in-situ tests; performance of bearings, joints and drainage system and cracks are recorded. Binoculars and digital cameras are deployed for routine inspections, and specific equipment for detailed jobs.

A comprehensive inspection requires close access to every structural component by means of specially-designed equipment or auxiliary equipment (scaffolding, ladders and safety belts). Adequate clearances, 1.2 m horizontally and 2 m vertically, are provided for easy movements of personnel[37]. The safety of the inspection personnel should not be jeopardised in any case.

Box girder bridges are designed with access doors, and diaphragms with openings for passage. Access is provided through the interior of hollow columns to inspect bearings and joints at the top. Elevators may be considered for very tall columns, along with winches to lift equipment from the ground. Electrical lighting is provided within hollow columns and box girders to facilitate good visibility; the lighting system has to be inspected and maintained periodically as well. Bridge inspection vehicles and equipment are available to provide access to the soffit of the structure and anchorages for close inspection.

However, the Owensboro bridge (366 m main span and 152 m side spans, USA) was designed to facilitate inspection without any special equipment[34]. The A-shaped concrete pylons are designed with large trapezoidal chambers at the top to house 12 steel frames each to anchor four cables at the corners. These steel frames sustain the entire cable forces, and are provided with platforms and openings for ladders to enable inspectors and maintenance crew walk to every anchorage. Heavy duty hooks are attached to the top slab of the tower to facilitate lifting of jacks up to 90 kN weight so that the jack can be lifted from the deck level through the opening in the bottom slab; the jack can be moved to any anchorage location. The anchorages at the deck level are located at the deck level behind the barrier with an access path for inspection; no special equipment will thus be needed for inspection or replacement of cables.

Similar access is provided in the Normandy bridge (France) as well but of a different design.

Repairs and rehabilitation

Repairs and rehabilitation of bridges are usually necessitated by the deterioration of concrete or corrosion of steel. Deterioration in concrete bridges occurs usually at the end beams, bridge deck, joints and supports. Stay cables may require replacement due to corrosion or deterioration of anchorages[38]. In some cases, the damage to concrete structures may be caused by the impact of moving vehicles[39].

Deteriorated bridge decks were overlaid with steel fibre reinforced concrete (SFRC) in Sweden resulting in high wear resistance, low chloride ingress and high salt freeze-thaw resistance[40].

Fibre composites are extensively adopted in most of the repair jobs in preference to conventional or polymer concretes, despite the high costs. The applications include confinement of concrete columns, flexural and shear strengthening of beams and slabs, and corrosion protection; the technique was found to be effective in moderate as well as extremely cold conditions of North America[41]. Both glass fibres and carbon fibres are used in such repairs.

Extensive damage, caused by a truck carrying heavy equipment higher than the road clearance, to a highway bridge was repaired by external prestressing, and internal splices where required[39]. Prestressing tendons were damaged and large amount of concrete spa lied off due to the impact in five of the eighteen prestressed concrete longitudinal girders of the bridge. The damaged girders were pre-loaded to create compression in the recast areas after repairs; about 400 kN load was applied to cause a deflection of 12-15 mm. Moderate damage (exposed tendons and reinforcement) to ten girders and minor damage (cracks and nicks) to one girder were repaired by grouting the cracks and delaminated zones.

The West Gate Bridge (Australia) was strengthened recently using carbon fibre reinforced plastic (CFRP) laminates in order to offset the higher prestress losses than estimated during its design in the 1970s, and to satisfy the revised load specifications[42]. The job involved strengthening the 35.62 m wide concrete box girder section with wide cantilevers in torsion and shear. The use of carbon fibre composites was found to be more economical than external post-tensioning and external steel-plate bonding.

It can be seen that repairs and rehabilitation of bridges is a specialised subject with a vast potential.

Conclusion

Some of the long span concrete bridges constructed recently, and their features are described in this paper. Several spectacular structures have been designed and constructed in the last decade than at any other time of human civilisation. The developments include materials as well as technology. Extradossed bridges, external prestressing and bridges with prestressing tendons underneath the deck are some of the new design concepts adopted extensively. Ultra-high strength concrete, and self-compacting concrete have extended the possible economical spans by a wide margin. Fibre reinforced plastics are replacing conventional materials in rehabilitation and repairs of bridges, besides the efforts to adopt them in long span bridges. The developments in bridge cross section, bridge configuration, materials and construction technology are also discussed briefly. The developments in bridge architecture and aesthetics, hitherto neglected aspects, are appraised.

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References

1. WENK, H., Die Stroemsundbruecke (The Stroemsund bridge), Der Stahlbau, April 1954, Vol 23, No 4, pp 73-76 (in German).
2. DIETRICH, R. J. Faszination Bruecken, Baukunst -Technik - Geshichte (Fascination of bridges, the art of construction, technology and history), Callwey, Munich, 1998, p 271 (in German).
3. SCHLAICH, J. The gap between quality and technology, Concrete International, August 1995, Vol 17, No 8, pp. 58 - 64.
4. VIRLOGEUX, M. New trends in prestressed concrete bridges, Structural Concrete, June 2002, Journal of the FIB, Vol 3, No 2, pp 67 -97.
5. RICHARD, P. Reactive powder concrete: Anew ultra high-strength cementitious material / Be'ton de Poudres Re actives: Une nouvelle ma trice cimentaire a res' Haute Performance, Fourth International Symposium on Utilisation of High- Strength / High-Performance Concrete, 1996, Paris, Vol 3, pp 1343 - 1349.
6. OKUMURAH H. et al, Self-compacting concrete, Structural Concrete, March 2000, Journal of the FIB, Vol 1, No 1, pp 3-17.
7. CAMPION, M. J. and Joss, P. Self-compacting concrete: expanding the possibilities of design and placement; Concrete International, April 2000, Vol 22, No 4, pp 31-34.
8. KASHIMA, S. et al, Application of self-compacting concrete made with low heat cement for bridge substructures of Honshu -Shikoku Bridge Authority, Proceedings of the International Workshop on Self-compacting Concrete, Kochi, 1999, pp 255 - 261.
9. HOLCATE, A. The art of structural engineering: The work of Jorg Schlaich and his team, Edition Axel Menges, Stuttgart, 1997, p 294.
10. DAUNER, H.G. Der Viadukt von Lully: Eine Neuheit im Verbundbruecken, (The Lully viaduct: an innovation in composite bridges), Stahlbau, January 1998, Vol 67, No 1, pp 1-14 (in German).
11. RAO, PRAKASH D.S. New developments in bridge engineering in West Germany, Concrete International, May 1981, Vol 3, No 5, pp 46-52.
12. RAO, PRAKASH D. S. Recent developments in the method of incremental launching, The Indian Concrete Journal, July 1982, Vol 56, No 7, pp 187-192.
13. SKEET, J. A. et al, Incremental launch : the Stoney Trail bridge; Concrete International, February 1998, Vol 20, No 2, pp 53 - 57.
14. Hsu, R. and CHANDRA, V. First user-friendly cable stayed bridge in US, Concrete International, February 1998, Vol 20, No 2, pp 58-60.
15. VEJF, E. eta!, The Yamuna cable stayed bridge at Allahabad, India: design and construction aspects, Structural Concrete, Journal of the FIB, September 1999, Vol P1, No 3, pp 1 - 9.
16. TVFIT, PER, A bridge suitable for India, Journal of the Indian Concrete Institute, April - June 2000, Vol 1, No 1, pp 7-10.
17. TVFIT, PER, Optimal design of network arches, IABSE Symposium, Melbourne, IABSE Reports, Vol 86, September 2002.
18. ____ Neue Stabhogenbruecke ueber den Main (New strut arch bridge over River Main), Stahlbau, September 2002, Vol 71, No 9, pp 685 (in German).
19. OISUKA, H. et al, Comparison of structural characteristics for different types of cable-supported prestressed concrete bridges, Structural Concrete, Journal of the FIB, March 2002, Vol 3, No 1, pp 3 - 21.
20. FIGG, JR., F. C. Segmental and cable-stayed bridges, Concrete International, June 2002, Vol 24, No 6, pp 37-42.
21. SVENSSON, H. Fritz Leonhard ts Schraegseilbruecken (Cable stayed bridges of Fritz Leonhardt), Stahlba it, July 1999, Vol 68, No 7, pp 474-485 (in German).
22. WITTFOHT, H. Building bridges: History, technology and construction, Beton Verlag, Duesseldorf, 1984, p 327.
23. PATE, W. D. and CARBALW, M. F. Cable-stay cradle system improves bridge aesthetics and economy, Concrete International, July 2002, Vol 24, No 7, pp 82-85.
24. MUTTONI, A Bruecken mit vorgespannter Stahlunterspannung (Bridges with prestressed steel band underneath), Stahlbau, August 2002, Vol 71, No 8, pp 592-597 (in German).
25. LEVITNOV, B. Construction equipment for cable stayed bridges, Concrete International, November 1995, Vol 17, No 11, pp 24-29.
26. BEHLOUI., M., BERNIER, G. and CHEYREZY M. Tensile behaviour of reactive powder concrete (RPC) / Comportement en traction des be'tons de poudresre'actives (BPR), Fourth International Symposium on Utilisation of High-Strength / High-Performance Concrete, 1996, Paris, Vol 3, pp 1375-1381.
27. BLAIS, Y. P. and Coma, M. Precast prestressed pedestrian bridge— world's first reactive powder concrete structure, PCI Journal, September - October 1999, Vol 44, No 5, pp 60-71.
28. KHALIFA M. A. et al, Bridges constructed using fibre reinforced plastics, Concrete International, June 1993, Vol 15, No 6, pp 43-47.
29. THIPPESWAMY H. K. et al, FRP reinforcement in bridge deck, Concrete International, June 1998, Vol 20, No 6, pp 47-50.
30. SCALZI, J. B. Will FRP composites ever change bridge engineering?, Concrete International, April 2000, Vol 22, No 4, pp 56-58.
31. GRACIA, A. M. Treasure or trash, Concrete International, August 1995, Vol 17, No 8, pp 48-53.
32. BURKE, Jr. M. P. Achieving excellence in concrete bridge design; Concrete International, August 1995, Vol 17, No 8, pp 34-38.
33. CRHAN, J. et al, Neue Schraegkabelbruecke ueber Elbe in Aussig (New cable stayed bridge over River Elbe in Aussig, Stahlbau, January 1999, Vol 68, No 1, pp 56-61 (in German).
34. MAESTRO, M. B. et al, Aesthetics in the design of precast prestressed bridges, Concrete International, August 1995, Vol 17, No 8, pp 39-44.
35. ZUK, W. A rating index for bridge aesthetics, Concrete International, August 1995, Vol 17, No 8, pp 15-47.
36. RAO, PRAKASH D. S. Drainage in bridge structures, The Indian Concrete Journal, August 1983, Vol 57, No 8, pp 194-201.
37. DE BRITO, J. et al, Inspectionability of bridges, Structural Concrete, March 2002, Journal of the FIB, Vol 3, No 1, pp 29-34.
38. SAUL, R., Cable stayed bridges—the German connection, Concrete International, February 1998, Vol 20, No 2, pp 71-75.
39. FELDMAN L. R. et a!, Repair of bridge impact damage, Concrete International, February 1998, Vol 20, No 2, pp 61-66.
40. PAULSSON J. and SILFWERBRAND J. Durability of repaired bridge deck overlays, Concrete International, February 1998, Vol 20, No 2, pp 76-82.
41. NEALE, K. W. AND LABOSSIF.RE, P. Fibre composite sheets in cold climate, Concrete International, June 1998, Vol 20, No 6, pp 22-24.
42. ONKEN P. et al, Verstaerkung der West Gate Bridge, Melbourne, (Strengthening of the West Gate Bridge, Melbourne), Beton-und Stahlbetonbau, February 2002, Vol 97, No 2, pp 94-104 (in German).

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