Variety in cable-bridge design

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In recent years, the cable-stayed bridge left its infancy and the reader of current publications of bridge design may get the impression that there is a clear tendency towards box-girder bridges for shorter spans and cable-stayed bridges for longer spans[1,2,3,4]. Concerning cable-stayed bridge design itself, he may further conclude that it follows a fixed pattern, which includes even a certain typeof cables, and that the only parameters for a variation are one or two cable planes and the harp or fancable arrangements. By giving some examples from their own practice, where these restrictions were not valid, the authors want to make a contribution towards more variety in cable-bridge design.

Cable bridges for large spans only?

It is generally observed that for spans beyond, say 600ft (183m), the dead load of girders acting in bending becomes excessive and, therefore, systems with strut and tie action become a necessity: truss girders and arches supporting the deck (in case of deep valleys) or suspending it (in case of a flat topography). The latter is also considered to be the domain of cable bridges, mainly if the span goes beyond say 1000ft (305m).

It is, however, not only their small dead load which makes cable bridges attractive, but also the minimal height of their girders and their light and pleasant appearance. These special properties also open to them the small-span range.

The length of the approaches of a bridge and with that their costs, land requirement and all further environmental impact, are directly proportional to the depth of its girder. One-foot saving in girder height results in about 25-feet (7.62-m) saving in length of the ramps, Figure 1.

This argument is independent of the real span of the bridge and especially valid in congested areas, where it may be very welcome if the approaches are short and reach the zero level before crossing or joining an existing road.

Of course, it must be expected that for short spans the cable-supported bridge is more expensive than the beam bridge. The cost difference, however, becomes less or even nominal, if the width of the bridge is less than about 50ft (15.24m), or if not more than 4 lanes need to be accommodated; because this is the range which can be covered by the solid concrete slab as a most simple and economical girder of a cable-supported bridge. The features of this sort of superstructure have been demonstrated with Diepoldsau Bridge and investigated in detail by Rene Walther[5]. From there, we know that these thin slabs are also safe with regard to buckling for the cable-stayed application even for long spans. Following these lines, according to a design of the authors together with Dr Stathopoulos, there is at present the Evripos Bridge in Greece under construction, Figure 2. Its 705-ft (215-m) main span consists of a solid concrete slab of 18-in (460- mm) thickness only. Though it is monolithically connected with the tower legs to avoid bearings, its moments at those points are not higher than elsewhere, thanks to the thin and flexible slab, Figure 2(c).

If we take an average thickness over span ratio for simply supported prestressed concrete beam bridges of 1/20 and if we

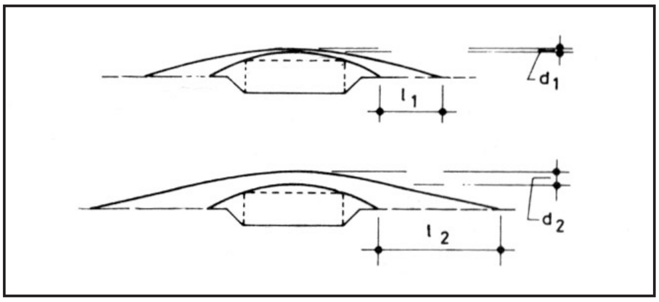

Figure 1. The length of a bridge ramp is proportional to the girder's depth

further assume for the minimum thickness of a suspended roadway about 1'-3" (380 mm) it would, already from a 25' (7.62m) span onwards be worth applying suspension. This is, of course, by far exaggerated, but shows that a cable support as against a pure girder may for such typical cases as highway or railroad overpasses, be worth considering.

The above remarks apply especially to pedestrian bridges. They are usually of small width and in view of the handicapped using wheel chairs, their ramps should not slope more than 6 percent. Beyond that it is exactly this sort of bridges, which deserve our special attention as far as aesthetics is concerned. These bridges are part of the furniture of our cities; they are much closer to their users than road bridges, they are literally in touch with them and should, therefore, be pleasant and harmonic. According to the average taste and aesthetical sense, light and transparent is considered to be more agreeable than heavy and clumsy. This is a strong argument for short-span cable bridges, Figures 3 and 4.

Is the suspension bridge out?

The cable-stayed bridge is considered to be the cable bridge, by far superior to the suspension bridge. The reasons given are the greater deformational stiffness and the smaller costs of the cable-stayed bridge. For such a discussion it should first be stated that there are, above all, constructional differences

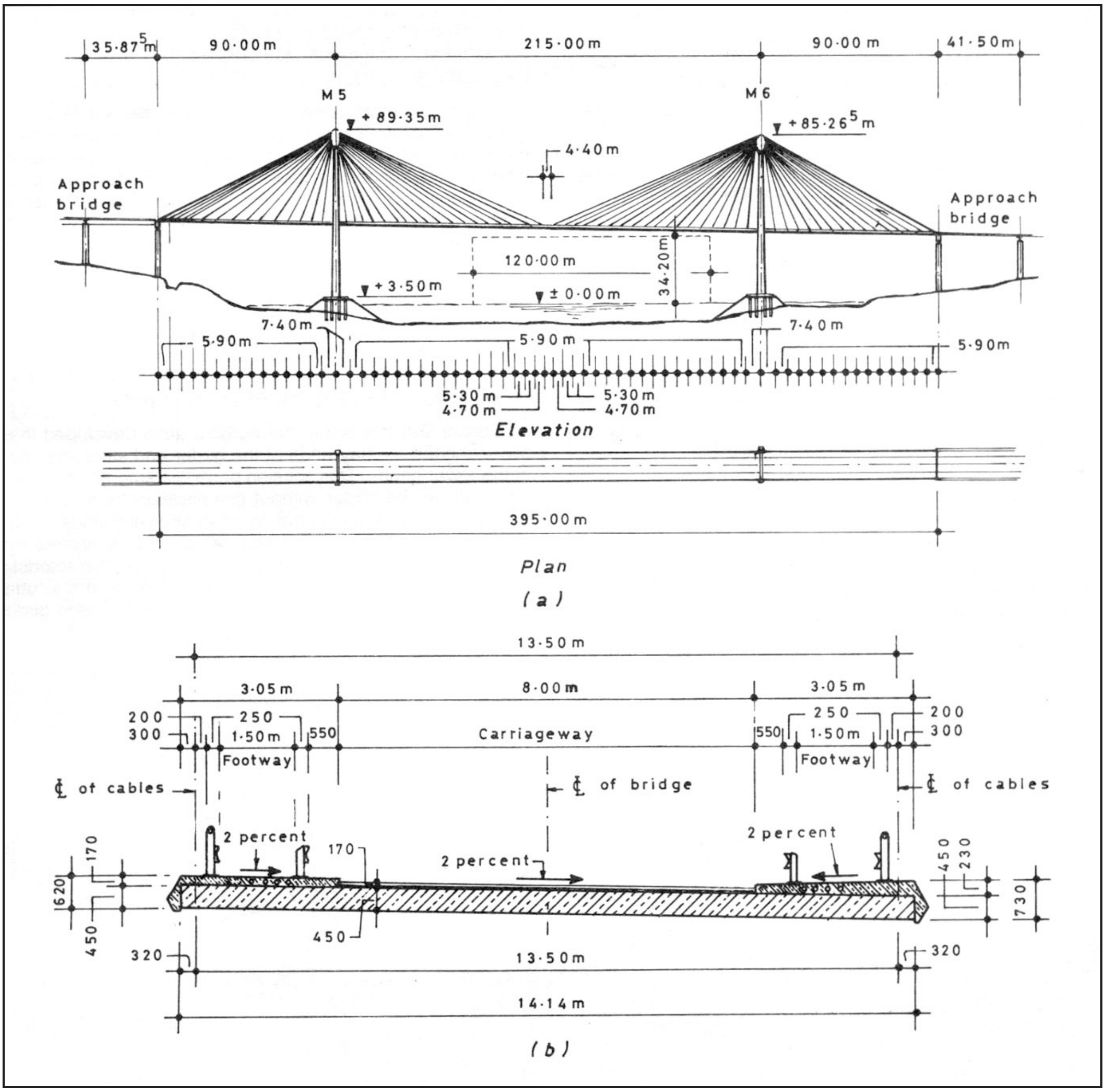

Figure 2. The Evripos Bridge in Greece (a) elevation and plan, (b) typical cross-section of reinforced concrete slab

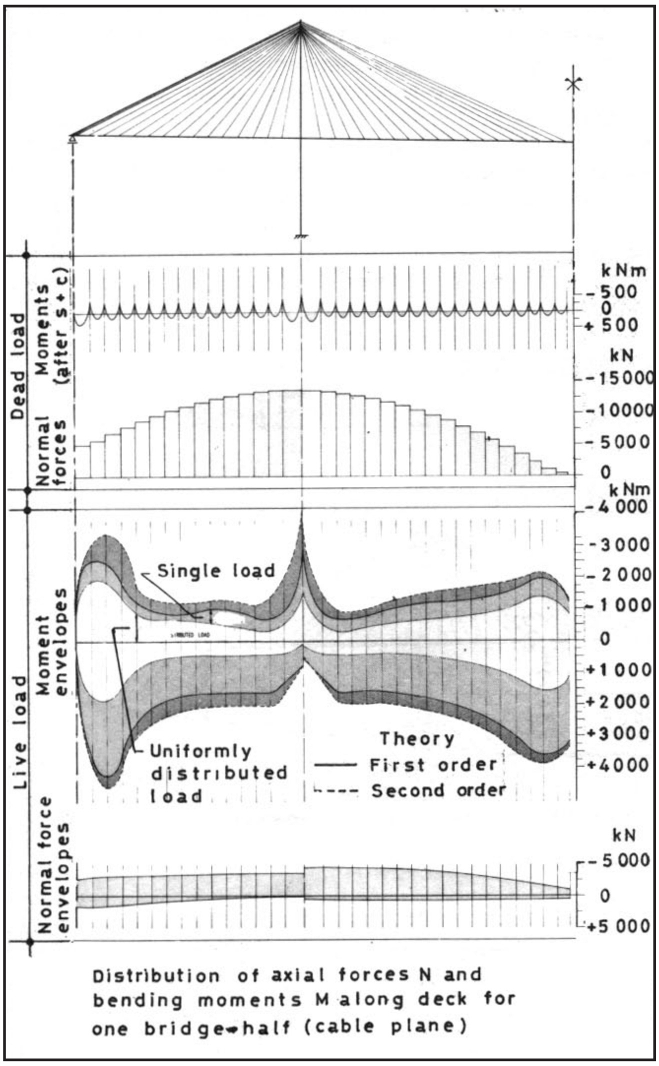

Figure 2. (c) Moments (envelopes) and forces in bridge deck of Evripos Bridge in Greece

which separate the two types, Figure 5. The cable-stayed bridge combines the advantage of the true or back-anchored and of the self-anchored suspension bridges. Its girder can be built without temporary support or framework, freely cantilevering from either side of the pylons and the horizontal components of its cable forces are balanced through axial forces acting in the girder through all stages of erection and in the final bridge. The suspension bridge, on the other hand, must either be back-anchored in heavy and costly abutments or, if these abutments are to be avoided, needs temporary supports for the construction of the girder.

From that, however, it follows that the suspension bridge is equivalent or even superior to the cable-stayed bridge, if either temporary form work causes no problem, or if there is a favourable situation for the anchorage of the back-stay cables. The latter is the case, if there is rock or if the abutments of an old bridge can be utilized. As for the first condition, the possibility to provide form work is usually fulfilled for small spans, which means that for overpasses in cities or for pedestrian bridges, the suspension bridge is a real alternative. According to the authors' taste, from an aesthetical point of view, suspension bridge is even a preferable alternative to the cable-stayed bridge. Its shape is most natural and pleasant. It is beautiful by itself, whereas the aesthetics of a cable-stayed bridge may, but not must, result from a cumbersome evolutional process. Some self-and back-anchored suspension bridges built recently may show this, Figures 3 and 4.

It should not be denied further that the cable-stayed bridge has some inherent disadvantages. Its greater stiffness must be paid for with large fluctuating stresses causing fatigue in the stays. The stress amplitudes in the main cables of suspension bridges are very small, as against those of their hangers, but they can be overdesigned and can easily be exchanged. Further, the cable details of the cable-stayed bridge are much more complicated and sensitive than those of the suspension bridge. This is so for the anchorage of the stays at the girder, with those

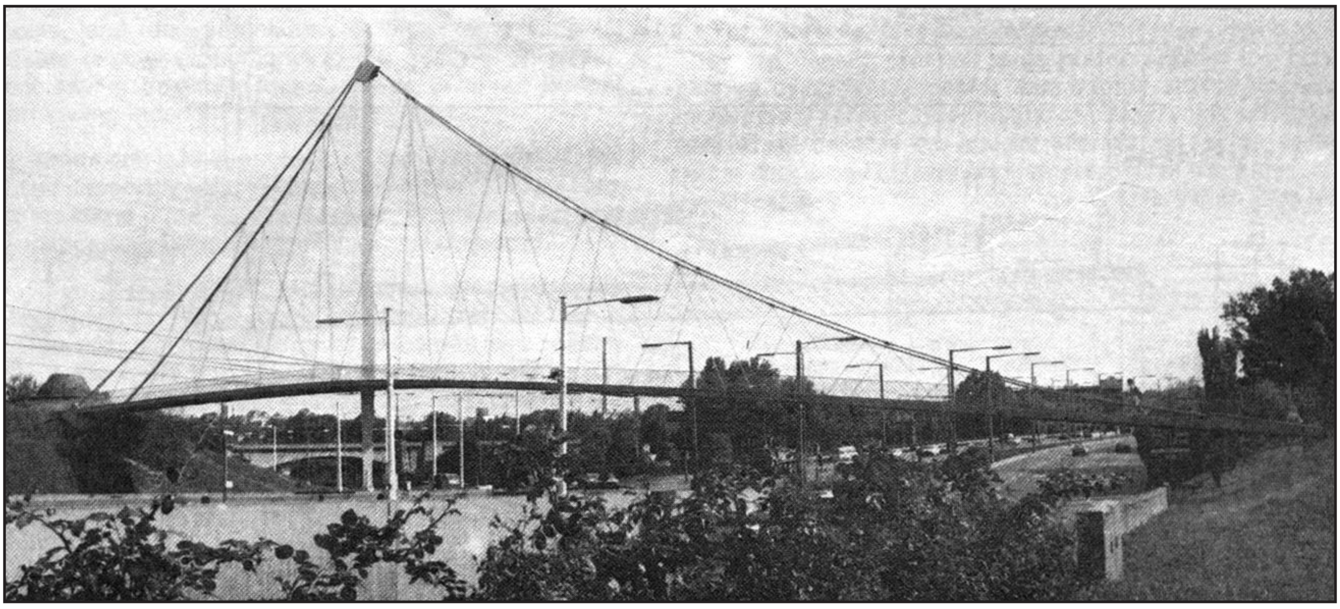

Figure 3. (a) The Rosenstein pedestrian bridge at Stuttgart, which is a self-anchored suspension bridge with a concrete slab

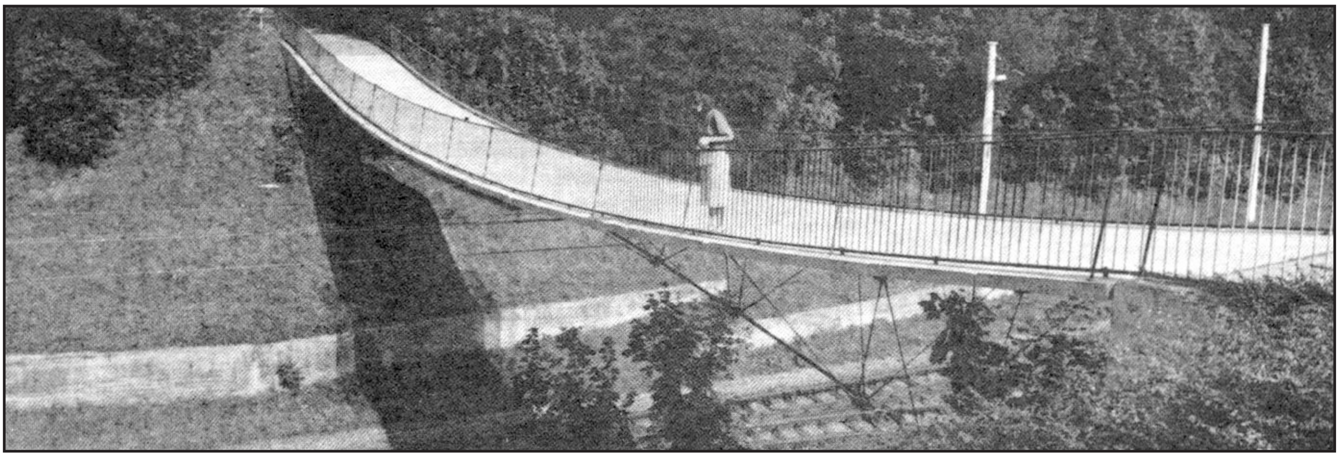

Figure 3. (b) The Rosenstein pedestrian bridge at Stuttgart, having a cable girder covered with concrete slabs

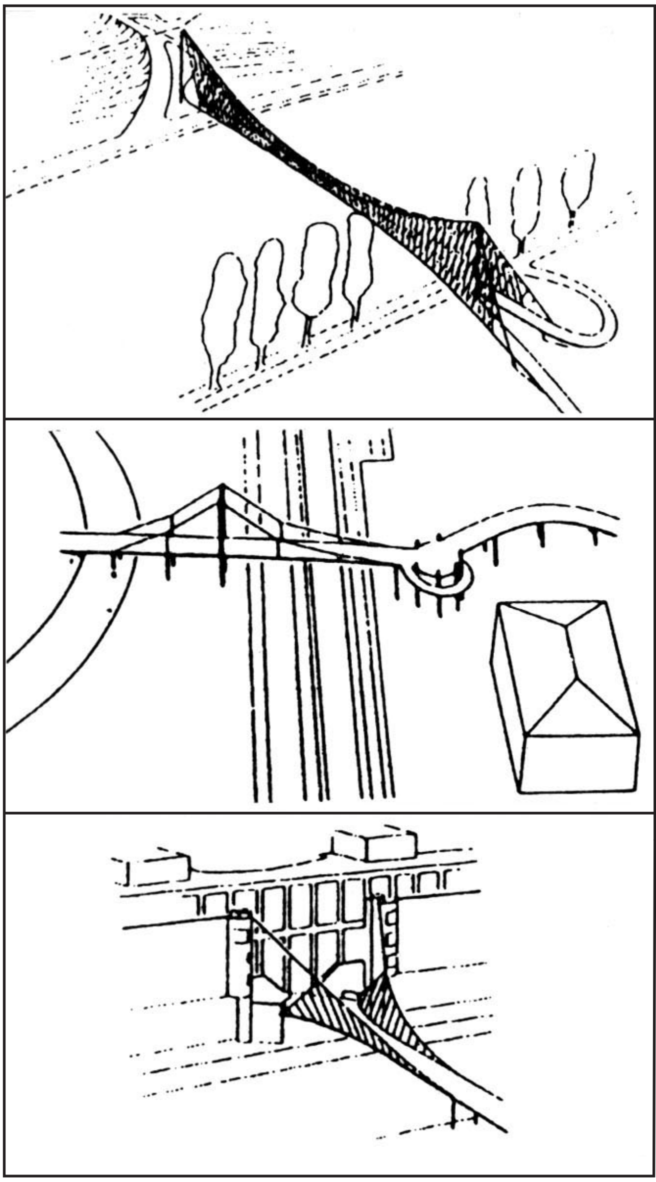
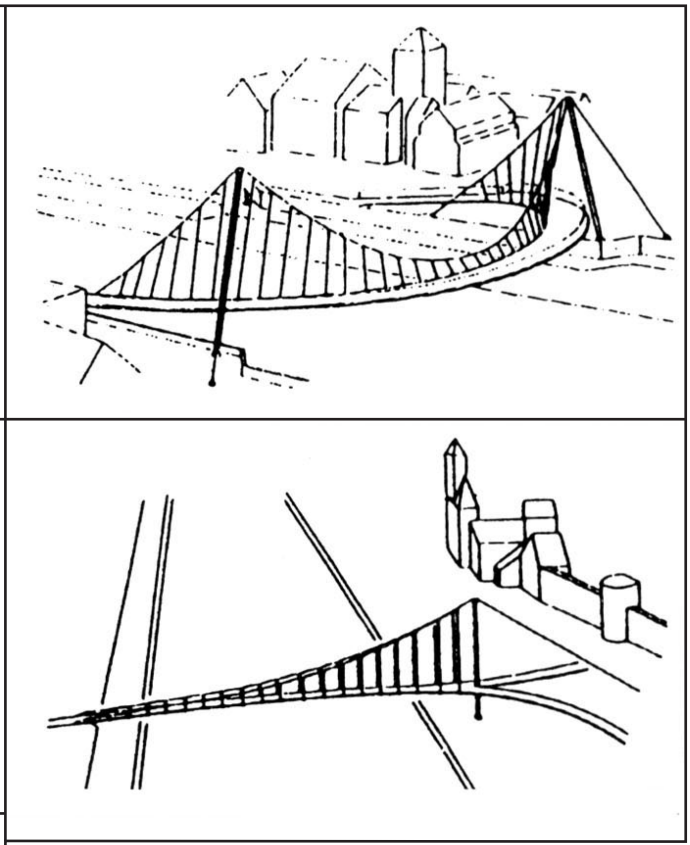

Figure 4. Some suspended pedestrian bridges recently built or under construction at Stuttgart, Kelheim, Bad Windsheim, Berching, and Stuttgart

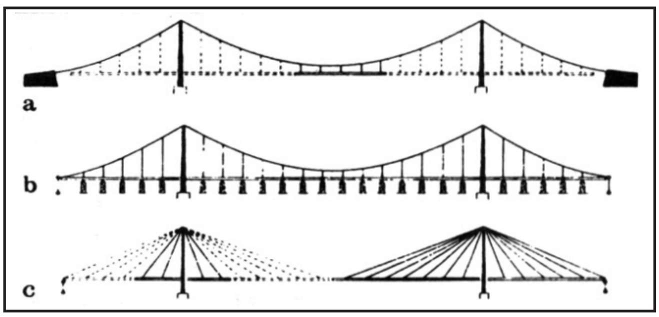

Figure 5. Construction of (a) back-anchored or true suspension bridge, (b) self-anchored suspension bridge, (c) cable-stayed bridge

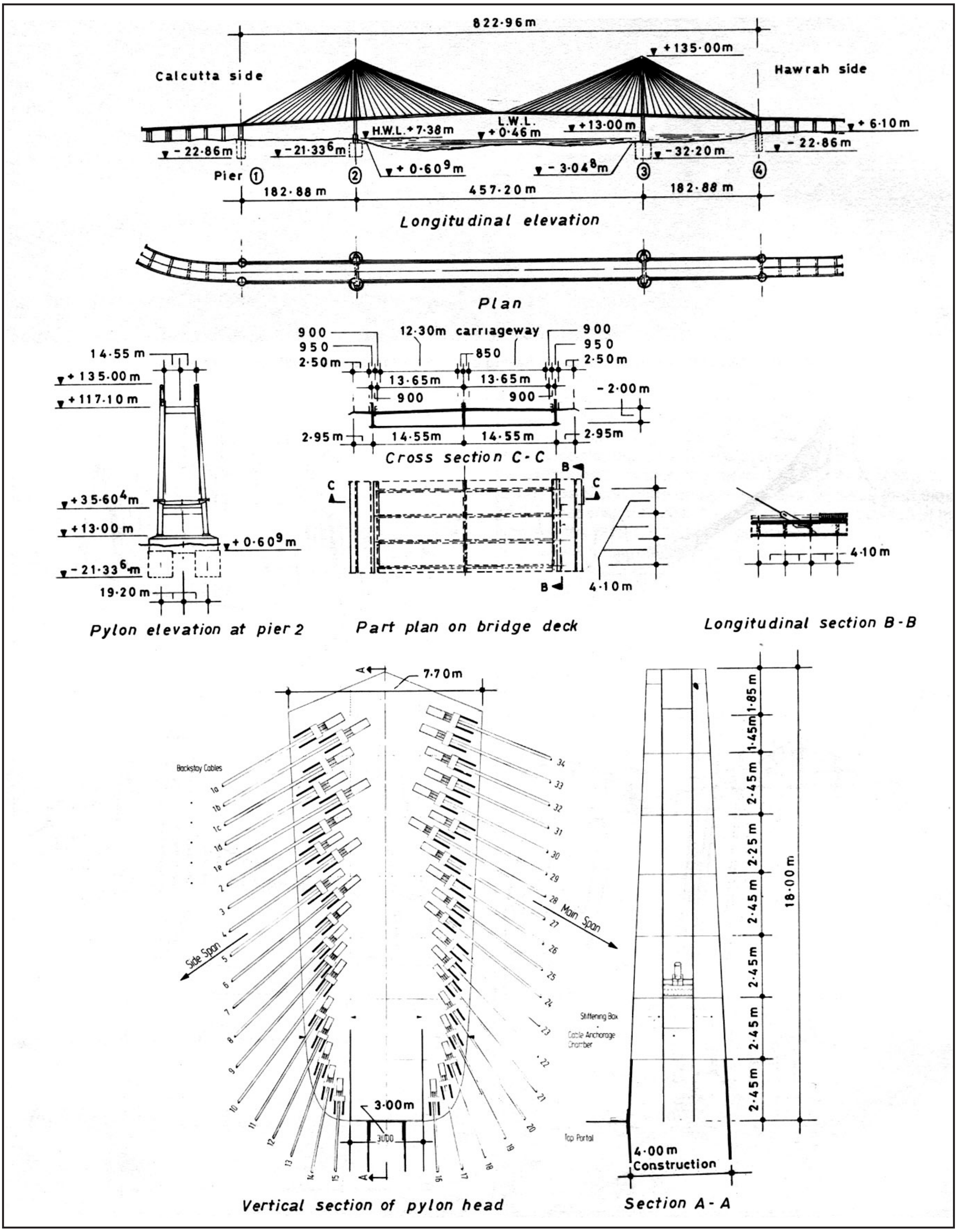

Figure 6. The Second Hooghly Bridge at Calcutta, consisting of a central cable-stayed span of 457.2m and a composite superstructure

permanently changing angles and large horizontal force components. As for the anchorages at the pylons there has been serious discussion on fan, harp, semi-harp configurations and their different impact on the required bending stiffness of the pylons. Concerning this issue, the authors have developed their own concept: fix stay ends at the girder and stressing ends at the tower heads. This solution permits a smooth and direct load-path at the girder without complication from stressing provisions, and a concentration of all stressing ends in one stressing chamber at the tower, which also simplifies the stressing procedure. It further results in a characteristic shape of the tower head. The Hooghly Bridge at Calcutta, with a 1496 ft (457.2m) centre span and a composite girder is given as an example of this arrangement in Figure 6.

If the larger deformations of the suspension bridge under concentrated loads become an argument, which is the case for railroad bridges, it may be stiffened by some additional stay cables, as was already done for the Brooklyn Bridge. In this case, the pylon height remains the same as that in the suspension bridge, i.e. substantially less than that of the cable-stayed bridge, resulting in the pleasant appearance of a cable net. This may give rise to three different configurations of the side spans, Figure 7. Depending on their lengths as related to that of the main span, the side spans can either be supported by thin piers or suspended by stays or hangers with additional stays.

It should.be mentioned that this is not written to attack the concept of cable-stayed bridges or to propagate suspension bridges unilaterally, but to instigate thinking on more variety in bridge design. This is also intended with the following remark.

Is there only one cable-stayed bridge?

The standard cable-stayed bridge, which consists of a central span and two side spans, has one or two cable planes and the harp, semi-harp or fan arrangement of cables. It may further be only half of that, that is, non-symmetrical. Is that all?

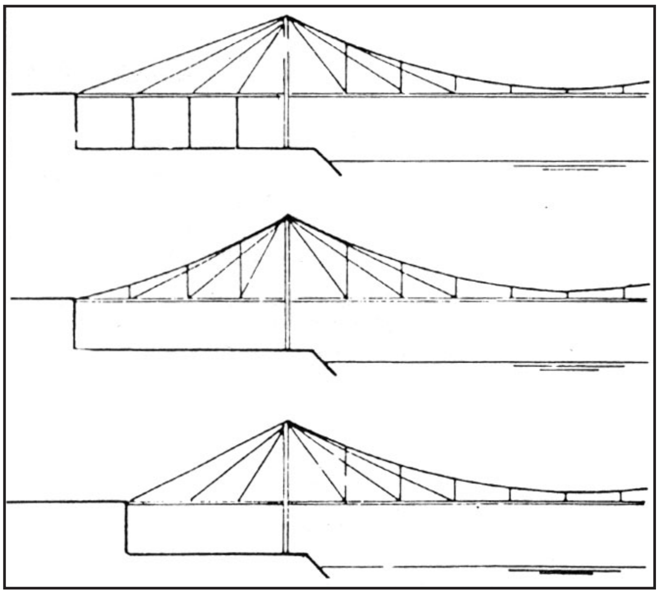

Figure 7. Different configurations for the side spans of a combined suspension-cum-cable-stayed bridge

The Argen Bridge, carrying a six-lane road, at present under construction in Southern Germany, may serve as an example to show that there are also other situations for which the cable-stayed bridge, or a special version thereof, may yield a most favourable solution[6], Figure 8. In this case an 850-ft (258-m) side span was enforced by poor soil conditions here. Out of the many solutions studied a version emerged, which combines the cable-stayed and the cablesupported configurations, Figure 8(a). The geometry of the cables thus follows logically the natural slope, and the height of the towers required is only half of that of a pure cable-stayed bridge, which is important for the given situation in the pre-Alps. The left side of this bridge, where soil conditions are normal, continues with cable-supported girders, thus making the whole bridge a formal unit. This sort of cable-supported beam or slab is by itself a bridge type worth a consideration though of course, not at all new, at least for steel girders. Cable-supported concrete beam or slab is a favourable version of what is today called external prestress. As against the standard external prestress, where the cables are inside the box-girder, this type yields a larger internal lever arm between the tensile forces in the cables and the compression in the girder. It is, therefore, more economical and visualizes better what's happening. It has ample application, for example for bridges with a large central span, Figure 9 or for frame bridges, Figure 10. Christian Menn is at present doing research on cable-supported bridge slab which shows that this makes very good-minded, durable and economical structures[7]. The axial compression forces in the girder which counteract the cable forces ensure a partial prestress there, even if no internal prestressing cables are provided.

Which cables?

The authors are of the opinion that for cable bridges, only those cables, which fulfill the following requirements should be used:

1. the wires should be galvanised
2. the inner voids between the wires should be completely filled with a durable elasto-plastic material
3. an outer coating of about 1/10 of an inch (2.5-mm) thickness with a strong bond to the wires and a high ultraviolet radiation and abrasion resistance should be applied to the surface of the cable. This guarantees that the surface of the cable is accessible for visual inspection (cables encased in tubes and filled with grout should, therefore, be ruled out). The outer coating should continuously connect with anchorages
4. zinc-filled cast steel sockets should be used
5. all cables should be replaceable.

These criteria go even further than those postulated recently by Birdsall and others[8].

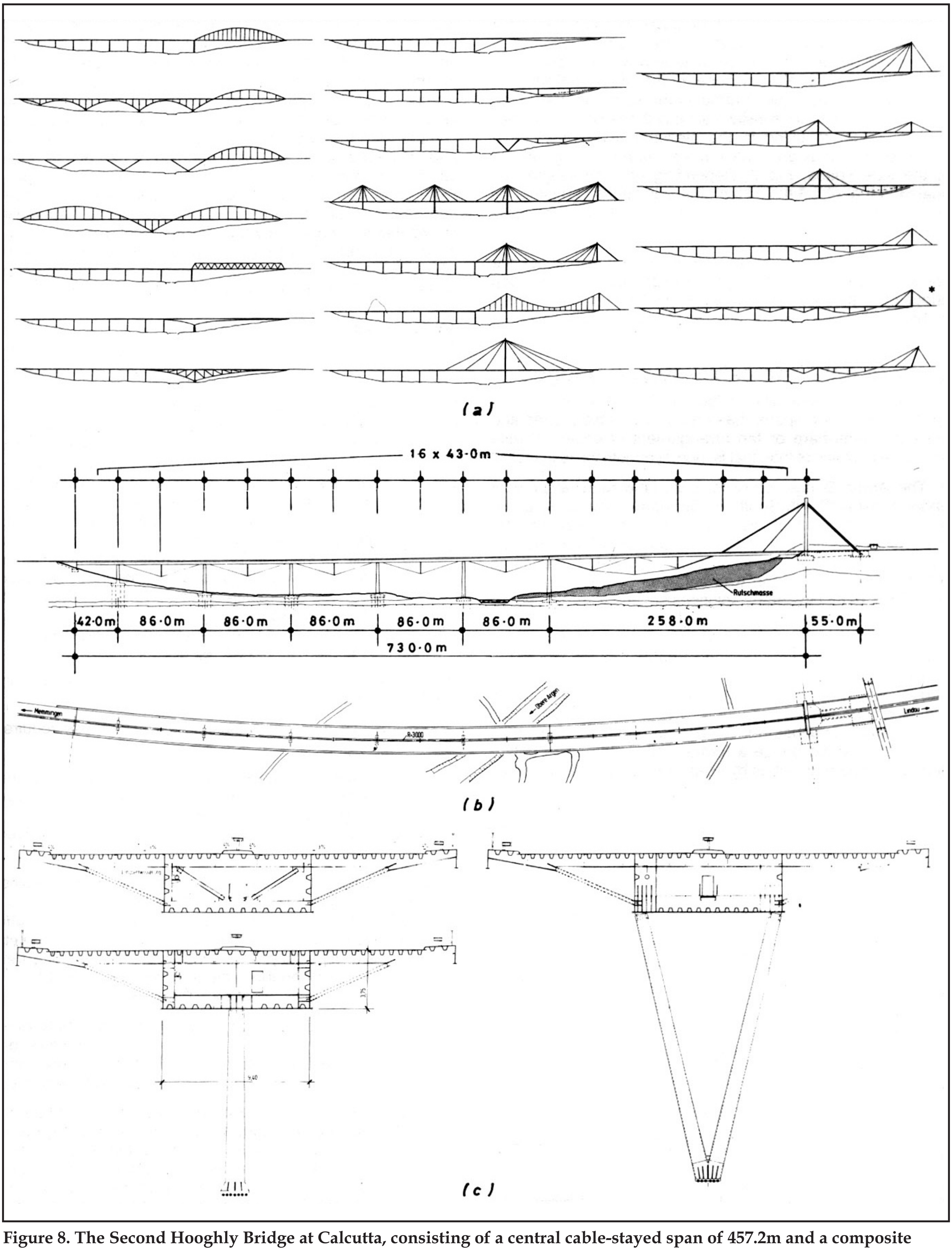

Figure 8. The Second Hooghly Bridge at Calcutta, consisting of a central cable-stayed span of 457.2m and a composite superstructure

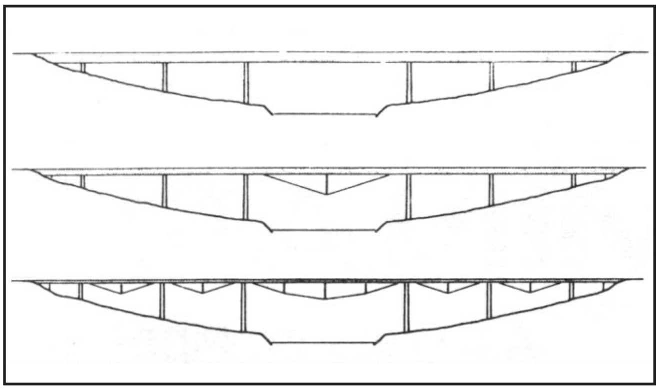

Figure 9. Cable-supported continuous girders reduce the girder length and visualize the large spans

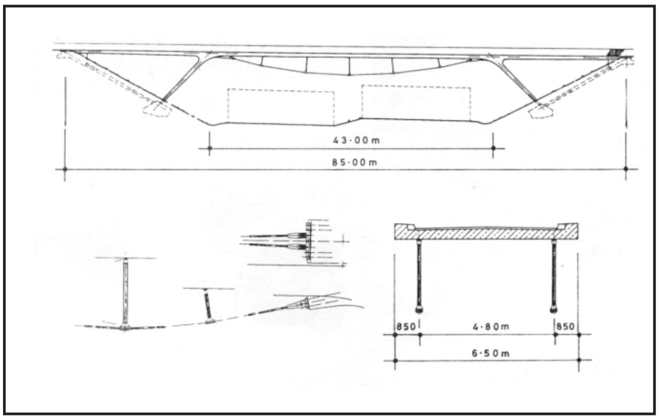

Figure 10. Cable-supported slab for Autobahn overpass

There are two types of cables, which fulfill these requirements. They are:

1. locked coil ropes, made of galvanized wires; the inner layers consist of round wires, the outer 3 layers of Z-shaped wires
2. long-lay parallel wire strands, made of galvanized wires.

The authors have ample experience with both types of cables. For hoth types the following should be ensured [9,10,11].

1. zinc poured sockets can be applied, yielding sufficient high fatigue strength, if the cast steel sockets are especially short and wide, thus avoiding fretting between the cable and the socket outlet[10,11,12]. Fatigue strength at 2 x 10^6 cycles[2].
   locked coil rope, $\Delta\alpha$ = 150 to 200N/ mm^2
   = 21000 to 28000 psi
   parallel wire strand, $\Delta\alpha$ = 200 to 250N/ mm^2
   = 28000 to 36000 psi
2. the inner filling and the outer 1/10-in (2.5-mm) thick coating consists of two-component polyurethane with a bond strength to the wires of more than 2N/mm^2, a tensile strength of more than 6N/mm^2 and an elongation of not less than 400 percent. Thus, the coat can be applied in the shop and the cables or strands can be rolled and shipped with their permanent corrosion protection already on.

This type of corrosion protection which is light (as against grouted sheeting, which is heavy) also permits the full utilization of the real Young's modulus of elasticity that is, for the
locked coil rope, E = 160 kN/mm^2 = 23000 ksi
parallel wire strand, E = 200 kN/mm^2 = 28000 ksi

The choice between locked coil ropes and long-lay parallel wire strands depends on the individual case and costs. In case of straight stays, both are technically almost identical with a slight advantage for the parallel wire strands due to their higher modulus of elasticity, their robustness and, usually, less costs. If, however, the cables have to be placed over saddles or clamped to join with other cables, the lock coil rope may have advantages, though this should and must not be made a rule but be decided, case-by-case.

The parallel wire bundles as described above and in reference 7 have successfully been applied to the first concrete cable-stayed bridge in India, with indigenous material and fabricated on site*

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