Scope for cable - stayed bridges in India

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With a view to ascertain the scope of using cable-stayed bridges in India, the paper presents a study on various facets of this bridge system such as the intrinsic engineering merits of the system, including economics; its up-to-date utilisation and performance in India and abroad; potential locations of use in India; and the current state in India vis-a-vis the capabilities that exist for analysis, design and construction of cable-stayed bridges. In the opinion of the author, this bridge form, though its advent into India has been slow and somewhat troublesome, will find wide-ranging applications during the future years in India.

The choice of a bridge system is quite often governed by the span lengths. According to modern bridge engineering practice, the lines are clearly drawn. Whereas shorter spans are bridged with different arrangements of girders, the very long spans belong to the suspension bridge, and the cable-stayed bridge system is being used extensively for the medium span range. The use of medium to long-span bridges may be dictated by one or more factors given below:

1. large navigational clearance may be required

2. it may not be feasible to obstruct the area to be bridged, or to obstruct the waterway with closely-spaced bridge piers

3. the transit system in a hilly terrain may be long and circuitous and could be cut down by adopting a longer bridge span

4. cost of foundations may be large in a particular application, and by increasing the span (and thus reducing the number of foundations), the unit cost and construction time can be reduced for overall economy in the bridge costs.

In any long-span structure, dead weights are often many times higher than live loads, and in order to achieve economy, efficient use of material affords a two-fold advantage - reduction in dead weight and saving in material. High tensile steel cables are ideally suited to serve this purpose when transferring loads through axial tension. It is, therefore, natural that long -span structures, such as the type of bridges under discussion, have used this potential of high tensile steel cables.

The cable-stayed bridge in its modern concept and form is a post-second-world-war development. Its merits are structural

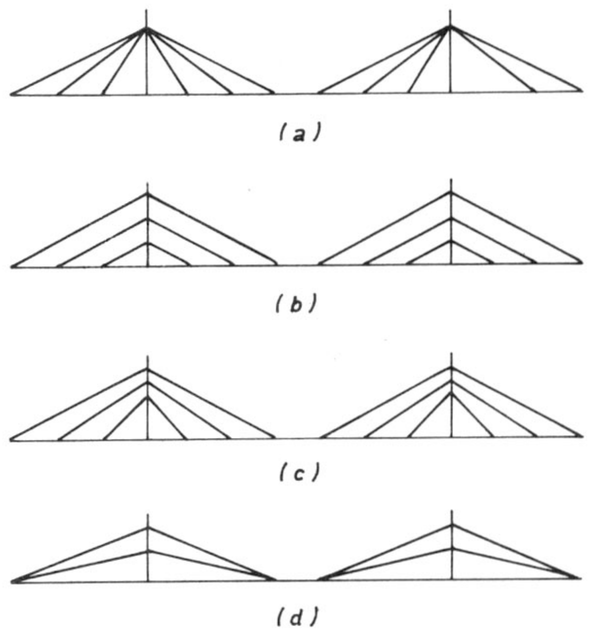

Figure 1 Longitudinal cable arrangements in cable-stayed bridges (a) radiating, (b) harp, (c) fan, (d) star

adequacy, aesthetics, and economy in time and material in its range of application. In recent years, use of cable-stayed bridges for railroad bridges and for longer spans has been encouraged due to improvements in analytical capabilities as well as in materials and construction technology. India is new to this latest development as compared to various other countries with a better technological base. Whereas the cable-stayed bridge is very much an accepted part of the repertoire of the bridge engineer in these countries, the exposure in India is comparatively recent; and despite the unquestionable merits of the system, it has not been accepted in its full measure, though it is now catching up.

Forms

Different configurations of the cable arrangement, deck and towers have been used in cable-stayed girder bridges. Longitudinally, the harp, radiating, fan and the star arrangements, as shown in Figure 1, have been employed, the first three being more common. While aesthetically the harp and fan types are considered superior, the radiating type has structural advantages because the cables make a larger angle with the horizontal and are thus more effective, leading to reduction in girder and tower moments. The harp/fan types offer the advantage of simpler connection details at the tower, in case a multiple cable arrangement is used. For very long crossings, multi-span arrangements of the type shown in Figure 2 may be adopted. However, if heavy live loads (such as due to a railway) are to traverse the bridge, use of anchor piers may become necessary. In single modules such as those shown in Figure 1, the end cables (stays) must have adequate stiffness to prevent large movements at the tower top, which could lead to large deflections of the girder spans. The stays have to be effectively anchored into abutments at each end.

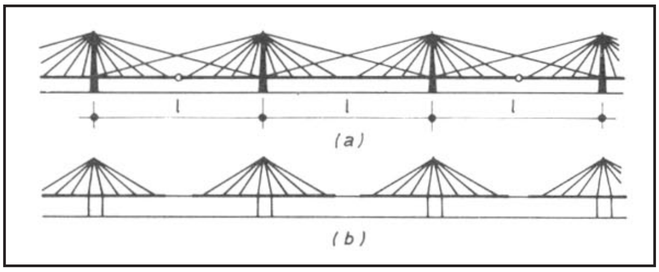

Figure 2 Multi-span configurations

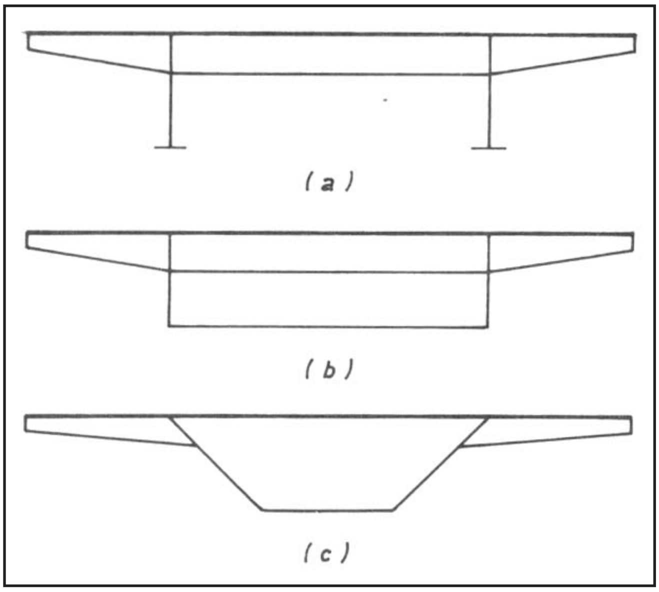

Figure 3 Typical girders for cable-stayed bridges (a) twin I', (b) rectangular box, (c) trapezoidal box

The support conditions for the bridge girder can effectively alter the distribution of forces in it. Large cable tensions develop due to the deck weight, live load, and pretensioning of cables during construction. Component of these tensile forces along the girder causes axial tension or axial compression of varying magnitude.

Various girder arrangements are seen in Figure 3. The arrangement in Figure 3 (a), (b) or (c) can be extended to use a greater number of girders. For larger spans, box construction offers the larger stiffnesses required. The trapezoidal girder with sharp ends tends to offer a better aerodynamic quality to the bridge. Figure 4 shows the cross-sectional arrangements.

The arrangement with cables in two planes is the most commonly used. The single-plane system needs to be very stiff torsionally. The material for deck and girders may be steel,reinforced concrete or prestressed concrete.

Economics

Results of comparison of the cable-stayed bridge system with other systems suitable for long-span applications could have been summarised, till a few years ago, by saying that, "the cable-stayed bridge form fills the gap between the girder bridge and the suspension bridge. However, the picture that is emerging with a better understanding of the design and construction procedures for the cable-stayed system, tends to make it competitive even with suspension bridges for larger spans[1,2,4]. This can be seen from studies presented, which compare cable-stayed bridges amongst themselves as well as with other types, with reference to economic span ranges[2,4,5,6]. These studies show that the economic span range for cable-stayed bridge systems is 150m to 300m[4,5], except the work of Leonhardt[2] and the study of New Orleans Bridge Crossing[6], which establish the system for longer spans. All the work reported was carried out in the developed countries of the West and may not be fully relevant in the Indian context

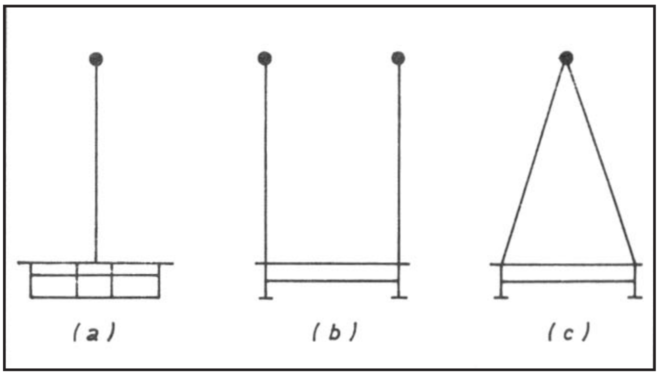

Figure 4 Transverse cable arrangements (a) single-plane vertical, (b) double-plane vertical, (c) double-plane sloping

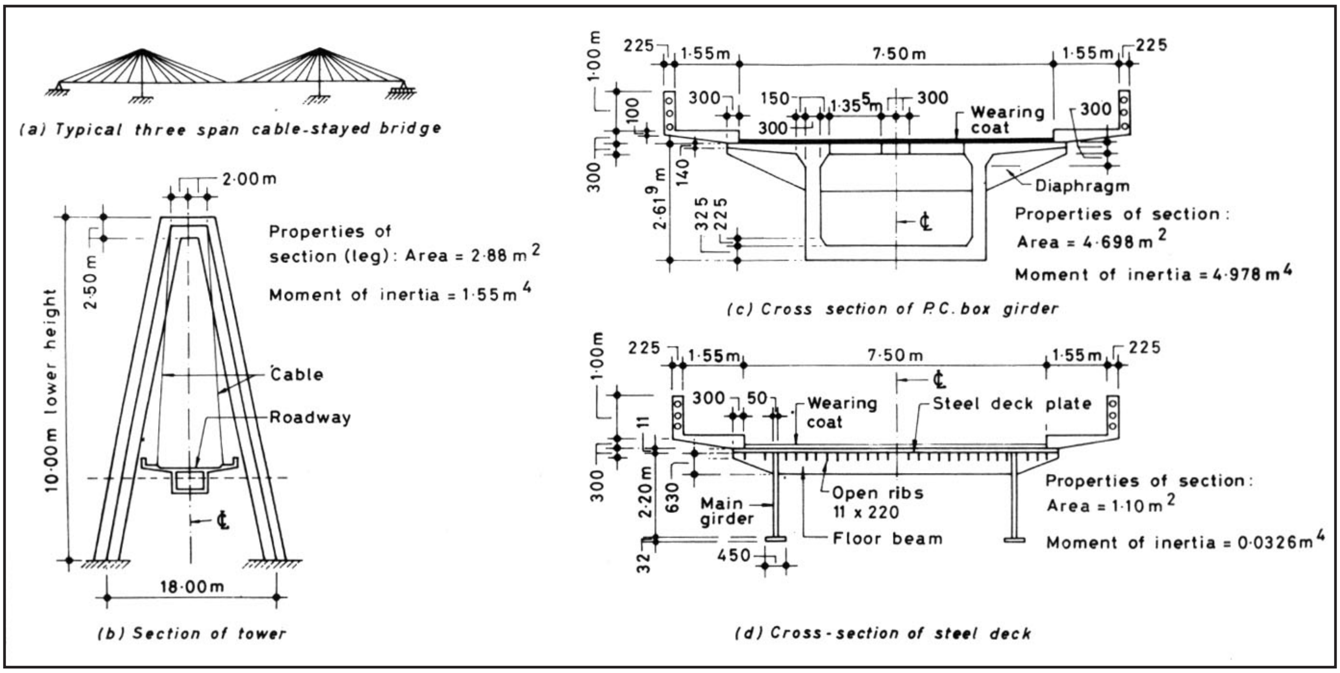

Figure 5 General arrangement of the cable-stayed bridge for parametric study on cost economics

though. qualitatively, it gives a good idea for the possible range of spans.

A prestressed concrete box girder was used in a parametric study undertaken for optimizing the cost of a three-span cable-stayed bridge[7]. General arrangement of the bridge is shown in Figure 5 (a) to (c).

Various parameters used for the study are as follows:

Central span	= 200m, 300m, 400m
Side/central span ratio	= 0.35, 0.40, 0.45
Tower height	= 1/5, 1/6, 1/7 of central span
Maximum allowable deflection	= 1/400, 1/600, 1/800 of span
Type of cables	= Parallel wire strands
Cable configuration	= Radiating type
Spacing of cables	= 10m
Maximum allowable working stress in cables	= 700 N/mm^2
Young's modulus of elasticity of cables	= 1.95×10^5 N/mm^2
Configuration of decking	= Rectangular, single-cell box girder
Grade of concrete	= M42.5

Full dead load of the deck was assumed to be carried by the cables alone. Deflections were computed on the basis of the dead load configuration being taken as datum.

The study indicated that the cost of the bridge per metre span for central spans of 200m and 300m did not vary much, but there was a significant rise for the 400-m span. Minimum cost was obtained generally for side to main span ratio of 0.40 and tower height of 1/6 of the main span. The deflection limit has a profound effect on the superstructure costs.

The choice between the use of steel and concrete depends upon economy and serviceability. In principle, use of steel offers the advantage of reduced dead weight, and thus a reduction of cable size, and to some extent, smaller foundation sizes. But the use of steel also leads to greater ratio of live to dead load tension in cables, and, greater non-linearity of cable and bridge response. Furthermore, use of steel requires greater fabrication

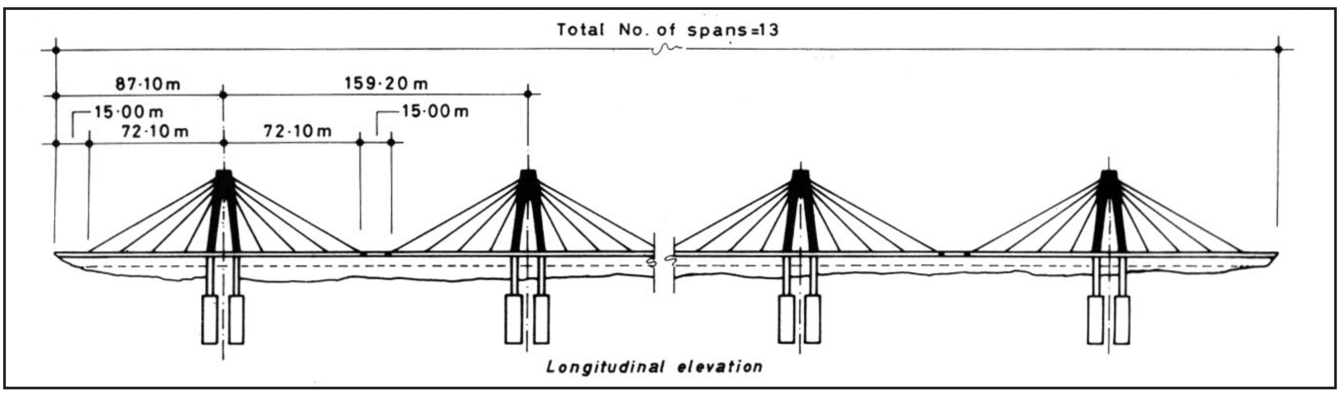

Figure 6 Proposed Ganga Bridge at Allahabad, which could not be constructed

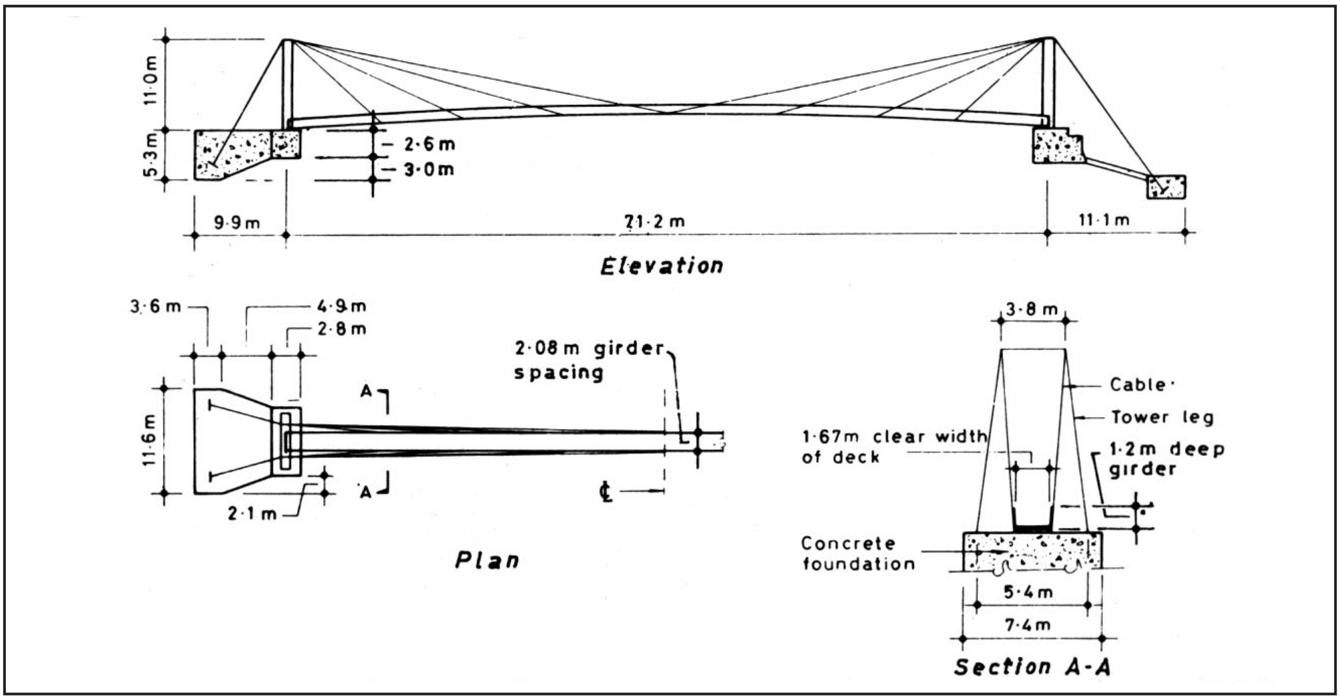

Figure 7 General arrangement for cable-stayed foot-bridge over Ganga Canal at Roorkee

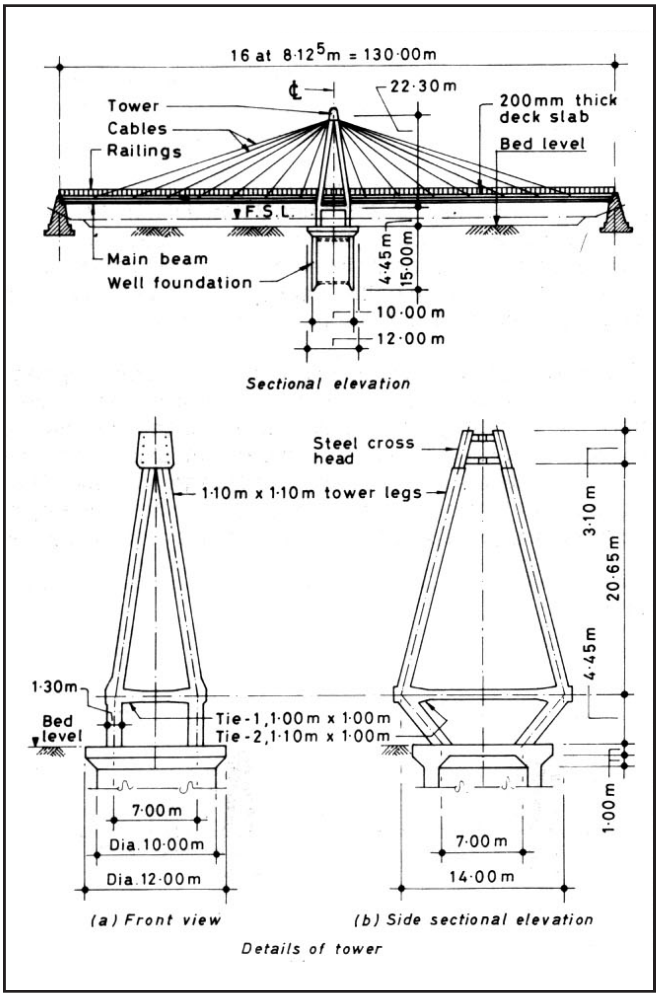

Figure 8 General arrangement of cable-stayed bridge at Hardwar

skills and maintenance efforts. The study on 3-span systems was extended to include an orthotropic steel plate deck also, besides the prestressed concrete box girder[7,8]. It was conclusively established that the prestressed concrete deck is cheaper than the steel deck for main spans up to 400m. The preliminary study for the Jogighopa Bridge also showed conclusively that a prestressed concrete box girder deck was more competitive than a steel orthotropic plate deck for 514-m long 3-span highway bridge module with anchored girder tips, though the reverse was true for a similar arrangement with 685-m modules for a rail-cum-road bridge 9. The study further showed the concrete pylons to be cheaper than the steel ones. Therefore, considering all the factors mentioned above, it is possible to say that, in the present Indian context, concrete has an edge over steel.

Bridges in India

Engineers in India were first exposed to the idea of using cable-stayed bridges in the 1960s. An earnest attempt was made to construct a cable-stayed multi-span bridge of concrete across the Ganga River at Allahabad. Several bridges have since been considered and have progressed to different stages, starting from a feasibility study to completion. Those Indian bridges, which are within the knowledge of the author, are briefly described below with a view to present an overall status of cable-stayed bridges in the country.

Bridge across river Ganga at Allahabad

The Ganga Bridge at Allahabad was designed for two traffic lanes with a clear roadway width of 7.5m[10]. Triangle-shaped towers in the longitudinal elevation were spaced at 159.2m with the deck cantilevering on either side by 72.1 m. The cantilever tips carried a suspended span of 15-m length. Cables supported the cantilevers at a spacing of about 14m, Figure 6.

The cable-stayed design was, however, not implemented due to some problems faced by the construction agency.

Besides being the first cable-stayed bridge perceived for construction in India, it gave an opportunity for further study and research on the subject and led to the design of several such bridges. Dynamic analysis of the proposed bridge was carried out by the Department of Earthquake Engineering at the University of Roorkee during 1968-69. Model studies were carried out on a 1/40 scale model of perspex. An earthquake of maximum intensity equal to 2/3 of that of EI Centro was estimated to occur at Allahabad, for which the design was checked.

Second Hooghly Bridge at Calcutta

A major six-lane cable-stayed bridge with a radiating cable arrangement is under construction over the Hooghly River at Calcutta[11]. Its completion will be a major step forward for India in the design and construction of these technologically advanced bridge systems. General structural arrangement of the bridge is given elsewhere*. The bridge has a main span of 457.2m with side spans of 182.9m on either side. It has a composite superstructure of reinforced concrete deck slab over steel girders. Cables have been provided at a spacing of about 13m. A comprehensive seismic study for the initial design of the bridge was undertaken by the University of Roorkee. The study included the determination of design accelerograms and the response spectra, tests on a 1/200 scale perspex model as well as an aluminium alloy model, and a detailed static and seismic analysis of the two models as also the prototype[12,13].

* *See Fig 6 on page 458*

Foot-bridge over Ganga Canal at Roorkee

It is the first cable-stayed pedestrian crossing in India[14]. This bridge was designed at the Department of Civil Engineering, University of Roorkee, for the U.P. Irrigation Department and constructed by a local contractor with lithe experience in steel bridge superstructure erection. The bridge was completed in 1981. The bridge is supported from a tower at either bank. In this form, the back-stays cannot be utilised for supporting the deck but merely act as anchor cables to support the tower. Although the span of this bridge did not lie in the economical range for cable-stayed bridges, the choice was based on aesthetic considerations and on the necessity for eliminating an intermediate supporting pier. The selection also offered an opportunity to try and develop indigenous know-how and technology for cable-stayed bridge systems. General structural arrangement of the bridge is shown in Figure 7.

A radiating cable arrangement was adopted for greater stiffness and construction convenience. Tower height to main span ratio of 1/6.7 has been provided to achieve a balance between inclinations of back-stays (60°) and fore-stays (minimum 16°). The towers are fixed at the base. Girder depth is 1/60 of span. With a rather narrow walkway width, the lateral wind causes high forces in the bottom chords of the trusses which resist these loads. To minimise these forces, the girder has been partially fixed against rotation at either end in the horizontal plane; 35-mm diameter stranded cables were used for the bridge, each back-stay consisting of 5 such cables. Since the manufacturers did not have prestretching facilities at the time the bridge was constructed, cables had to be prestretched at site. Cables were anchored into end sockets with hot molten zinc. Bearing capacity at the site was low due

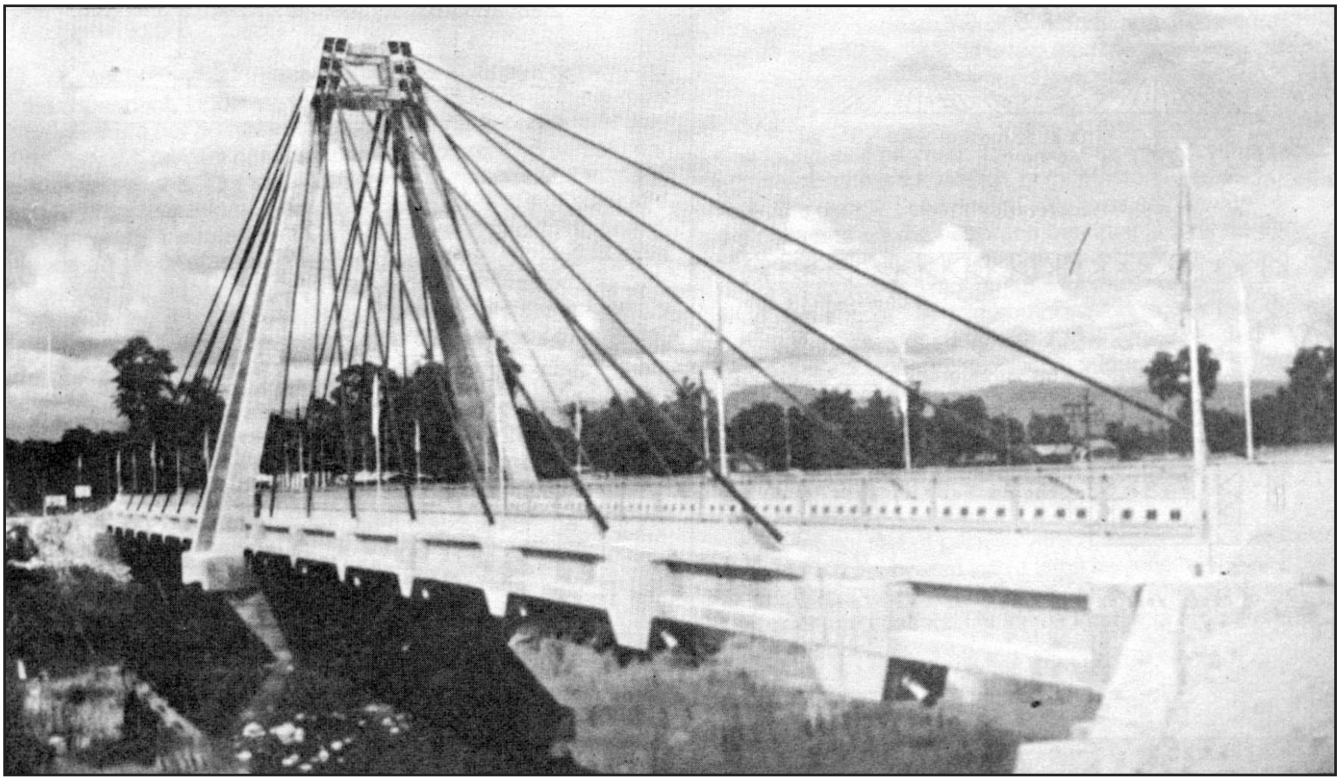

Figure 9 A view of the cable-stayed bridge at Hardwar

to poor soils and closeness of the embankment slope. Piles were, therefore, provided to achieve stability as well as to overcome strength problems for the back-stay anchor foundations. Introduction of piles also helped in stiffening the foundations and reducing deformations, not only in the foundations but also in the superstructure.

Bridge over new supply channel at Hardwar

A two-lane cable-stayed reinforced concrete gii'cler bridge has been constructed at Hardwar by the U.P. State Bridge Corporation[15]. The bridge has been designed at the Department of Civil Engineering, University of Roorkee. The general layout of the bridge is shown in Figure 8. The span of 130m may just touch the lower fringe of the economic span range for such bridges. However, the cable-stayed system was chosen from the point of view of aesthetics and to gain firsthand experience in constructing such bridges.

A tower height to the bridge span ratio of 1/6.5 was used for this bridge. It gives cable inclinations within an appropriate range of values. The tower, supported on a single well, has an A-frame configuration in the longitudinal elevation and is diamond-shaped in the transverse view. Abutments are made to rest on open foundations as they have to carry very small loads, and there is no scouring action of water near the abutments. The tower cross-head is made of steel.

A multiple cable system with a close spacing of 8.125m was finally adopted for economy in girder size. The deck system consists of two main girders, two secondary longitudinal beams, and cross beams at every cable point supporting the reinforced concrete deck. The erection procedure is so chosen as to ensure that, under the 'dead load' condition, the cables, acting as non-yielding supports for the main girders, will carry the total deck load. The girders are continuous over the central support and placed on rollers at the abutments. The main girders are 1.4-m deep— approximately 1/50th of the free span.

The bridge is designed for two lanes of I RC class A or for one lane of class AA/70R loading with a seismic coefficient of 0.1g. In most parts of the bridge structure, high-strength concrete has been used with deformed reinforcement steel. The deflection limit is placed at span/400. For the first time in India, this bridge has used parallel wire strands with the BBR anchorage system which is being manufactured by Usha Martin Industries at Ranchi. Purely as a precautionary measure for a first experience, the design is based on the assumption that any cable can snap at a time, and for this condition a higher permissible stress is allowed. Figure 9 shows a view of the bridge.

Bridge across Brahmaputra at Jogighopa in Assam

The preliminary design of this multimodule rail-cum-road double deck bridge with a cable-stayed system was assigned to the University of Roorkee by Rail India Technical and Economic Services (RITES) who were carrying out a technoeconomic feasibility study for the bridge 9. An alternative road bridge was also investigated. This is the first rail-cum-road cable-stayed bridge to be contemplated in India.

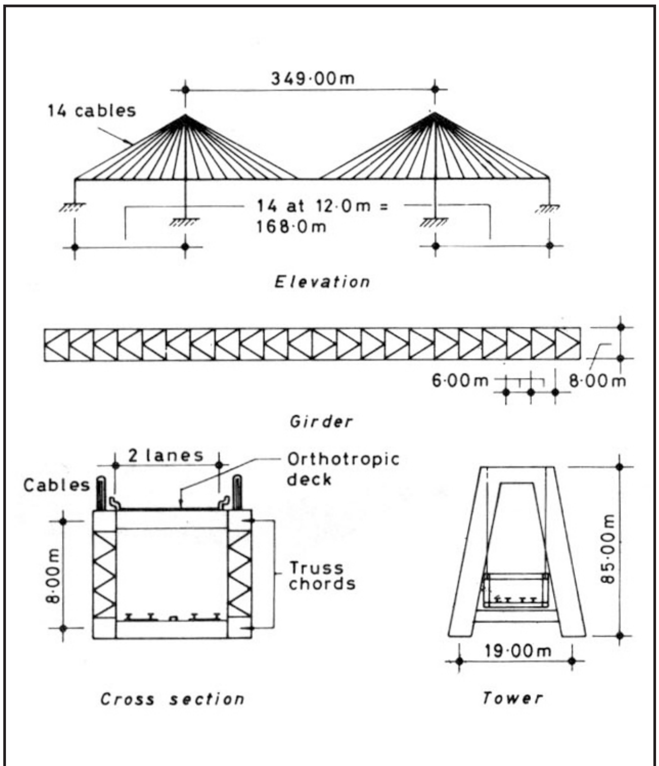

Figure 10 Rail-cum-road bridge at Jogighopa, Assam

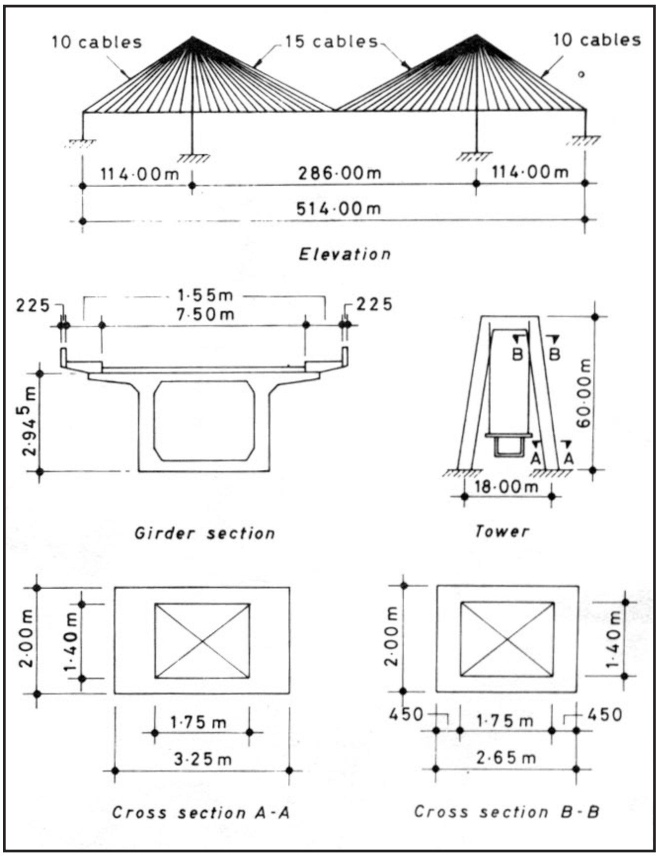

Figure 11 Alternative highway bridge at Jogighopa, Assam

The general arrangement for the two cases is shown in Figures 10 and 11, respectively. Following the submission of the preliminary design report by the University in 1981, RITES engaged the famous US firm, Steinman, Boynton, Gronquist and Birdsall, to improve upon this preliminary work.

A long-span bridge system with lesser number of foundations was considered for reasons of economy, since 70-m to 90-m deep foundations were indicated by the scour data at the bridge site. It would not only be expensive but also time-consuming to construct larger number of such deep foundations. The bridge has to carry two lanes of I RC class A or one lane of class AA/70R highway loading and two tracks of BGML railway loading.

Both the highway as well as the railway bridge loading codes and the corresponding design specifications, apparently do not envisage application to longer spans. Much initial efforts were, therefore, needed to extrapolate the given information for this preliminary exercise. A major issue was the deflection and slope limitations. It was obvious that the upper deflection limit of span/800 will preclude an economical stayed solution.

The various cable-stayed systems investigated for this bridge included:

1. double-cantilever arrangement

2. balanced-cantilever arrangement

3. balanced cantilever with a suspended span which was further supported by cables

4. three-span continuous girder system in each module.

Only the alternative mentioned at (4) above satisfied the restrictions on deflections.

Various alternatives were considered for the bridge spans. A module of 685-m length with three different arrangements of end and central span lengths, namely, 156m-373m-156m, 168m-349m-168m, and 180m-325m-180m were studied in detail. The live load deflection was limited to span/600. The 168m-349m-168m arrangement was found to consume the least amount of cable weight, which constitutes the most expensive item, and was, therefore, adopted for the bridge. Three such modules would cover the bridge length of 2055m and require 10 foundations-6 for the towers, 2 for anchor piers and 2 for abutments which are considerably less than those in the conventional girder bridge design.

The bridge has rail tracks on the lower deck and highway on the upper deck. Under various conditions of loading, the vertical curves were not permitted to exceed the rate of change of gradient by 0.1 percent per 30m for summits and 0.05 percent per 30m for troughs. The towers are of A-frame type and made in high-strength reinforced concrete, the girders are of steel and the highway is carried by an orthotropic steel deck. The girders are made in steel to minimise the dead load which would have been excessive for the 685-m long double deck, built in concrete. In the first stage analysis, steel was chosen for towers also, but was found to be much costlier than reinforced concrete.

For the alternative proposal of a road bridge module, with a smaller span of 514m (114m-286m-114m), and much lighter traffic loading compared to the rail-cum-road bridge, a prestressed concrete box girder was found to be more economical. A cable spacing' of 10m was adopted (against 12m in the rail-cum-road bridge) and a smaller deflection limit of span/800 was attained in the design. For this bridge, there would be 8 tower foundations, 3 anchor piers and 2 abutments.

An A-type concrete tower was also used for the road bridge. No support was provided for the girder at the tower as it was found that providing this support does not appreciably change the deflections, moments and axial forces in the girder. However, the girder was supported laterally at the tower as well as at the anchor piers.

Main conclusions drawn from these design exercises for the two bridges are as follows:

1. In cable-stayed bridges, deflection and slope limits often become the overriding design criteria for deciding the required sections of cables and girders.

2. In a multi-span arrangement it becomes essential to introduce anchor piers at the junctions of the modules in order to meet the deformation limits, particularly if the spans are long and live loads are heavy.

3. For minimising the cost of cables and foundations, which will reduce the overall cost of the bridge, it is desirable to cut down the dead weight of the decking and girders. Therefore, steel deck, though costlier compared to a concrete deck with the present cost ratios for the materials involved, becomes economical for long spans and heavy traffic loading (as in the case of the longer span rail-cum-road bridge).

The current status of this bridge is that one cable-stayed module, 138m-348m-138m, is to be combined with smaller conventional girder spans for this railroad double-deck bridge. The cable-stayed module is being designed by Steinman and Company.

Bridge at Akkar in Sikkim

This two-lane 11.1-m wide, cable-stayed concrete highway bridge is being constructed by Gammon India Ltd. in Sikkim. It is the first all-concrete cable-stayed bridge to have been undertaken in India. It has a central tower with two symmetric spans of 77m each. The deck structure of the bridge consists of a thin 18-cm concrete slab spanning 3m longitudinally between cross girders which are supported by two main girders. The general features of the bridge are shown elsewhere in this issue *. The radiating cables support the main girders every 6m, and only towards the bridge ends where cable forces are higher and more stiffness is required the spacing is reduced to 3m. Only one cable diameter is used for this bridge.

The two pylon legs are hollow boxes placed on a common well foundation and pier. The deck has no direct support at the pylon legs, either for vertical, or for horizontal loads. Longitudinally, the deck is "swimming", ie., gaps are provided between the deck and elastic neoprene bearings in order to avoid any temperature restraints. But, the deck is allowed to rest on the bearings after small movements for the transfer of longitudinal wind, braking or seismic compression forces into the abutments.

Vertical deck loads are mainly suspended from the pylon; the abutments get only minor loads under assymmetric live loads. The bridge has been designed for the IRC Class A, Class AA/70R loading, whichever produces the worst effects. Horizontal seismic loads have been applied as 10 percent of dead and live loads in the final stage and as 5 percent during erection.

Cables consist of parallel wire bundles of 7-mm diameter wires, which are twisted with a large lay-length. The wire bundle is protected against corrosion by a 1-mm to 2-mm thick polyurethane coating. The cable interior is also filled with the same material.

Current status and scope

Most cable-stayed bridges are large projects and in order that the system can be adopted with confidence in situations where its use will be appropriate, an adequate backup of technology and infrastructure is needed. The information given in the previous section will show that experience in the analysis, design and construction is being gained in India, though slowly. That the merits of the system are being realised is clear from the fact that many such bridges are being contemplated. An attempt is made to describe the status as understood by the author, vis -a - vis many facets of the problem.

Analysis

Theoretical aspects of the problem appear to be reasonably well-understood and considerable effort towards this end has been made in India [7-13, 17-19]. Good facilities exist for model studies as necessary for static, dynamic as well as aerodynamic effects. The experience in aerodynamic testing is, as yet, quite limited.

Design

Valuable design and detailing experience is being gained through the cable-stayed bridges designed and those being implemented. In some of these cases, the rich experience of designers abroad has been utilised. Much more effort is, however, needed on this aspect to create confidence and selfsufficiency. In respect of the latter, though the Indian engineers should be readily willing to learn from experience gained abroad, there can be no substitute for self-indulgence. A further need is to critically examine and share the experience being gained through contact with experts outside or efforts within.

Materials

A cable-stayed bridge employs conventional construction materials, except for the stays where high tensile steel wire strands are used. Till a few years ago, only twisted wire strands were being produced. Recently, however, facilities to prestretch strand/rope, as well as to produce parallel wire strands, have been developed by Usha Martin Industries at Ranchi in collaboration with BBR of Switzerland. Parallel wire strands produced by them have been used for the first time in India for Hardwar Bridge and will be used for the Second Hooghly Bridge. This is an important step forward.

Specifications

Design specifications for loads and other design factors for both highway and railway bridges in India neither cover cablestayed bridges in particular nor the range of spans in which these bridges are normally employed. It would not be fair to expect such a coverage either since, by and large, the status of bridge specificaions the world over is similar. Experience in the use of the cable-stayed system is needed to formulate specifications for such bridges. Nevertheless, a beginning needs to be made without delay on the basis of existing data and information, so that the absence of specifications will not inhibit use of the system.

Construction and management

The construction of a cable-stayed bridge involves some precision engineering, needing a specialised effort. It should not be difficult to believe that large consulting and contracting (construction) companies in this country have the necessary skill and competence to take up cable-stayed bridge projects and to deliver the kind of engineering involved. Firsthand experience is lacking and perhaps the first few projects will not be commercially as fruitful as the more conventional ones, but with greater experience this should not remain a problem.

Analysis, design and construction (or the lack of it) do not, therefore, appear to be the impediment in taking up cablestayed bridge projects. There have been delays and cost escalations in the first few projects in hand. This is not unusual, even under the best circumstances. However, a more coordinated effort between the designer, construction contractor, the agency manufacturing and erecting cables, the user, and the appropriate government agency will go a long way in reducing such delays.

A systematic and speedy approach on the part of all the agencies involved is necessary to economise on time and effort, and achieve success in a project of this nature. In the author's opinion it is probable that a consortium combining the specialised capability of analysis, design and construction and taking complete responsibility for such bridge projects will make coordination with the user agencies much easier and raise their confidence. This may also save effort and avoid delays.

In a country of India's size, with large rivers and extensive hilly tracks, there is a need to construct a large number of bridges and that too with good speed. The cable-stayed bridge system has proved its merit for both rail and highway bridges, all over the developed world. A number of cable-stayed bridge projects are being contemplated in the country, though the ushering in has not been smooth. The author, however, believes that, once the initial problems are overcome, the cable-stayed system will find an appropriate place on the Indian bridging scene with wide-ranging applications in the years to follow.

Acknowledgement
The paper has generously drawn upon references 20 and 21.

References

1. PODOLNY. W. and SCALZI. J.B. Construction and Design of Cable Stayed Bridges. John Wiley and Sons. 1976.
2. LEONHAROT. F. and ZELLER. W. Vergteiche Zhichen Hangebrucken and Schragekabel-brucken Fur Spannweiten Uber 600m. International Association for Bridge and Structural Engineering, Vol. 32, 1972.
3. GIMSING. N.J. Anchored and partially-anchored stayed bridges. Proceedings of the International Symposium on Suspension Bridges (IABSE), Lisbon, 1966.
4. PODOLNY. W.Jr. Economic comparisons of stayed girder bridges. Highway Focus, August 1973, Vol. 5, No.2.
5. DUBROVA. E. Economic effectiveness of application of precast reinforced concrete and steel bridges, USSR, IABSE Bulletin 28, 1972.
6. KEALEY. T.R. Feasibility Study of Mississippi River Crossings Interstate 410. Meeting Preprint 2003. ASCE National Structural Engineering Meeting, San Francisco, 1973.
7. KRISHNA. P., GUPTA. S.P. and CHALISGAONKAR, R. Studies on cost economics of cable-stayed bridges in India. Bridge and Structural Engineer, December 1984, Vol.14, No.4.
8. CHALISGAONKAR. R., GOYAL, S.K., KRISHNA, P. and GUPTA. S.P. Cost economics of cable-stayed bridge in India. Proceedings of the Second International Conference on Computer Aided Analysis and Design in Civil Engineering, University of Roorkee, Roorkee, 1985, pp. III 100 to 106.
9. KRISHNA. P., ARYA, A.S., KUMAR. K., GUPTA. S.P. and PRAKASH, R. Preliminary Design for Superstructure of 2055-m Long Cable Stayed Bridges across Brahmaputra at Jogighopa, Report of the Departments of Civil and Earthquake Engineering, University of Roorkee, Roorkee, 1982.
10. KRISHNA. J., ARYA, A.S. and THAKKAR, S.K. Dynamic Analysis and Model Studies of Ganga Bridge at Allahabad for Earthquake Motions., Report of the SRTEE (now Department of Earthquake Engineering), University of Roorkee, Roorkee, 1969.
11. ARYA. A.S., KRISHNA. P.. and others. Third Report on Seismic Investigations of Second Hooghly Bridge. Earthquake Engineering Studies No. EQ. 79.1, Department of Earthquake Engineering. University of Roorkee. Roorkee, 1979.
12. SETHIA. M.R. Static and Dynamic Study of Cable-stayed Bridges. PhD thesis, University of Roorkee. 1979.
13. AGARWAL. T.P. Cable-stayed Bridges-A Study, PhD thesis, University of Roorkee, 1979.
14. KUMAR. K. Cable-stayed Pedestrian Bridge across the Ganga Canal at Roorkee- A Case Study, Specialist Course No 403-SPL, Continuing Education Department, University of Roorkee, 1983.
15. KRISHNA, P., JAIN. S.C. and JAIN. P.C. Cable-stayed bridge towers. Proceedings of Workshop on Detailing of Reinforced Concrete Structures, University of Roorkee. April 1986, Vol. I, pp. 228-241.
16. BERGERMANN. R. and HARIDAS. G.R. The first cable-stayed concrete bridge in India, Proceedings of the Tenth International Congress of the EIP, New Delhi, February 1986, pp. 97-104.
17. SAWHNEV. P.S. Influence Lines for Cable-stayed Bridges. ME thesis, University of Roorkee, 1977.
18. SONDH B.S. Beam-column Effects in Cable-stayed Bridges, ME thesis, University of Roorkee, 1977.
19. KRISHNA. P., ARYA. A.S.. and AGARWAL. T.P. Effect of cable stiffness on cable-stayed bridges. ASCE Journal of Structural Engineering, September 1985, Vol. III, No. 9. pp. 2008-2020.
20. KRISHNA P. and KRISHEN. KUMAR. Cable-stayed bridges in India - Problems and prospects. Seminar on Recent Advances in Concrete Construction, March 1987, Indian Institute of Technology. Madras.
21. KRISHNA. P. and KRISHEN. KUMAR. Cable-stayed bridges in India. International Conference on Cable-stayed Bridges, November 1987, Bangkok.

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