Cable-stayed bridges

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Cable-stayed bridges are being built increasingly for bridging medium and large spans. Although this concept of supporting a beam by stays from a tower is old, the evolution of modern cable-stayed bridges has taken place since 1950. India has yet to exploit this newly-developed bridge system to its full measure. The paper describes, in brief, the cable-stayed bridges built or proposed to be built in India, and recommends their wider adoption.

The cable-stayed bridge is the most modern and innovative of bridge systems. It found world-wide applications, especially in the countries of Europe during the last two decades. The concept of supporting a bridge deck by one or more inclined stays is by no means a new one and a number of such bridges were constructed in the past.

Nearly fifteen thousand bridges were destroyed in the Federal Republic of Germany in World War II. Reconstruction of these crossings in the post-war period provided bridge engineers an opportunity to develop a new concept of bridge design. Short supply of steel and the need to build bridges more economically brought the old concept of bridge design, namely the cable-stayed bridge concept, to the forefront. In addition to the potential economy the cable-stayed concept added a new dimension to the aesthetics of bridge design.

The rebirth of the new system must be credited to F. Dischinger, who published the results of his studies in 1949 and pointed out the advantages of high stresses in the stays of high-strength steel. The Stromsund Bridge, the first modern cable-stayed bridge, designed by Dischinger, was completed in Sweden in 1955. During the same period the Rhine Bridge at Dusseldorf, designed by Leonhardt, was erected and completed in 1958. The successful completion of these modern cable-stayed bridges heralded a new era of wide and successful application of the stayed-beam concept. Since then, the new system is very popular amongst German bridge engineers and is now increasingly applied by designers all over the world. Several cable-stayed bridges have been built throughout the world and have proved to be economical as compared to the conventional bridges for the same span, Table 1.

Progress in India

The potential of the cable-stayed system has yet to be fully exploited in India. So far, only a few cable-stayed bridges have been proposed or are being built in India. Their brief details are described below.

Bridge over Ganga Canal at Roorkee:

A small cablestayed pedestrian crossing was successfully constructed over the Ganga Canal at Roorkee in 1981. The bridge has a length of 73.0m and is supported by radiating bridge ropes in two planes to the portal frame type of steel tower, Figure 1. A 1.3-m deep steel truss is used as a deck for the cable-stayed foot bridge. It has a clear road width of 1.67m and tower height to main span ratio of 1/6.7. The design of the bridge was done in the Civil Engineering Department, University of Roorkee, Roorkee.

Hooghly Bridge at Calcutta:

A major six-lane bridge with radiating cables is under construction over Hooghly River at Calcutta. The main span is 457.2m, with side spans of 182.88m on each side. The bridge has a composite superstructure of reinforced concrete deck slab over steel girders. The general arrangement of the proposed Hooghly Bridge is shown in Figure 2.

Bridge over new supply channel at Hardwar:

A small two-lane highway bridge of 130-m span is under construction over the new supply channel at Hardwar. The cables radiate on two sides of the reinforced concrete deck from a diamond-shaped reinforced concrete tower. The main

Table 1. Brief details of various cable -stayed bridges in the world

Sr. No.	Name of the bridge and the country	Cables			Hight of tower m	Type of deck	Year of completion	Span length, m	
		Configuration	Type	No. of plan				Main	End
1.	Stromsund (Sweden)	Radiating	Locked coil	2	27	Concrete	1955	183	74
2.	North (W. Germany)	Harp	Locked coil	2	40	Steel	1958	260	108
3.	Severin (W. Germany)	Fan	Locked coil	2	65	Steel	1960	301	151
4.	North Elbe (W. Germany)	Star	Locked coil	1	53	Steel	1962	172	64
5.	General Ra fael Urdeneta (Venezuela)	Radiating/Harp	Locked coil	2	43	Concrete	1962	235	160
6.	Julicher-Str. (W. Germany)	Radiating/Harp	Locked coil	1	45	Steel	1963	99	32
7.	The George Street (England)	Fan	Locked coil	2	37	Concrete	1964	152	51
8.	Leverkusen (West Germany)	Harp	Locked coil	1	40	Steel	1964	280	106
9.	The Dnepr (USSR)	Radiating	Locked coil	2	27	Concrete	1964	144	66
10.	Maxau (W. Germany)	Fan	Locked coil	1	46	Steel	1965	175	117
11.	Bonn Nord (West Germany)	Fan	Locked coil	1	49	Steel	1966	280	120
12.	Mayer (Japan)	Fan	Locked coil	1	32	Steel	1966	140	69
13.	Rees (W. Germany)	Harp	Locked coil	2	43	Steel	1967	255	104
14.	Wye (England)	Radiating/Harp	Locked coil	1	29	Steel	1967	235	87
15.	Ansade Magliana (Italy)	Radiating/Harp	Locked coil	2	34	Concrete	1967	145	54
16.	Polcevera (Italy)	Radiating	Locked coil	2	45	Concrete	1967	210	140
17.	Ludwigschafen (W. Germany)	Radiating	Locked coil	2	72	Steel	1968	138	138
18.	Batman (Tasmania)	Radiating	Locked coil	1	96	Steel	1968	210	50
19.	Harmsen (Holland)	Combined Star & Fan	Locked coil	1	48	Steel	1968	108	47
20.	New Luangwa (Zambia)	-do-	Locked coil	2	15	Concrete	1968	222	40
21.	Knie (W. Germany)	Harp	Locked coil	2	114 above river bed	Steel	1969	320	195
22.	St. Florent (France)	Radiating	Br. Strands	2	35	Steel	1969	104	104
23.	Papineau (Canada)	Radiating	Br. Strands	1	39	Steel	1969	240	90
24.	Hawkshaw (nada)	Radiating/Harp	Br. strands	2	34	Steel	1969	220	58
25.	Duisburg-Neuenkatnp (W. Germany)	Fan	Locked coil	1	50	Steel	1970	350	165
26.	Onomichi (Japan)	Radiating	Locked coil	2	36	Steel	1970	215	85
27.	Yodo (Japan)	Fan	PPWS	1	36	Steel	1970	216	80
28.	Arakawa (Japan)	Harp	PPWS	1	34	Steel	1970	160	60
29.	Le Havre (France)	Radiating	Locked coil	2	31	Steel	1970	73	32
30.	Mannheim (W. Germany)	Fan	PPWS	2	70	Steel	1971	287	125
31.	Bratislava (Czechoslovakia)	Radiating	PPWS	2	88	Steel	1971	303	75
32.	Massena (France)	Fan	PPWS	1	34	Steel	1971	161.5	80.7
33.	Erskine (England)	Radiating/Harp	PPWS	1	88	Steel	1971	305	110
34.	Wadikuff (Libya)	Radiating/Harp	PPWS	2	54	Concrete	1971	287	95
35.	Oberkasseler (W. Germany)	Harp	PPWS	1	78	Steel	1972	258	258
36.	Sitka Harbor (US)	Radiating/Harp	Br. Strands	2	30	Concrete	1972	137	46
37.	Ishikari (Japan)	Fan	Locked coil	2	43	Steel	1972	250	110
38.	Mesopotamia (Argentinia)	Radiating/Harp	Locked coil	2	97	Concrete	1972	340	127
39.	River Waal (Holland)	Radiating	Locked coil	2	46	Concrete	1972	267	95
40.	River Parana (Argentina)	Radiating	Locked coil	2	48	Concrete	1972	245	132
41.	Hoechst (W. Germany)	Harp	HST Bar	2	172	Concrete	1972	148	111
42.	Linz (Austria)	Harp	Locked coil	1	66	Steel	1972	215	192
43.	Hainsburg (Austria)	Radiating	Locked coil	2	77	Steel	1973	228	138
44.	Kohlbrand (W. Germany)	Fan	Locked coil	2	98	Steel	1974	325	97.5
45.	Franklin (W. Germany)	Radiating/Harp	Locked coil	1	20	Steel	1974	125	42
46.	Speyer (W. Germany)	Radiating	Locked coil	2	76	Steel	1975	275	181
47.	Saint-Nazaire (France)	Radiating	PPWS	2	67	Steel	1975	404	158
48.	Deggenau (W. Germany)	Radiating	Locked coil	1	83	Steel	1975	290	145
49.	Daikaku (Japan)	Radiating	PPWS	2	41	Steel	1975	165	100
50.	Kamone (Japan)	Fan	PPWS	1	45	Steel	1975	240	100
51.	Suehiro Bridge (Japan)	Fan	PPWS	1	42.75	Steel	1975	250	110
52.	Albert Canal (Belgium)	Fan	Locked coil	1	48.50	Steel	1977	210.2	53.9
53.	Brotonne (France)	Fan	Br. strands	1	65	Concrete	1977	320	143
54.	Zarate (Argentina)	Radiating	PPWS	2	67	Steel	1977	330	110
55.	Pasco-Kennewick (US)	Radiating	PPWS	2	57	Concrete	1978	299	124
56.	West Gate (Australia)	Radiating	Br. Strands	2	46	Steel	1978	336	144
57.	Dusseldorf Flehe (W. Germany)	-	-	-	-	Steel	1978	367	-
58.	Strettoti Rande (Spain)	-	-	-	-	Steel	1978	400	-
59.	Roorkec (India)	Radiating Bridge	Ropes	2	11	Steel	1981	73.0	-
60.	Luling (US)	Radiating	PPWS	2	75	Stecl	UC	376	150
61.	I. Hutnigton (US)	Radiating	PPWS	2	77	Steel	UC	274	137
62.	Stavan ger Bridge (Norway)	Radiating	-	2	50.4	Con-Steel	UC	185	120
63.	Dames point (US)	Harp	HST Bar	2	92	Concrete	UC	396	198
64.	Weirton-Steubeaville (US)	Fan	Br. Strands	1	65	Steel	UC	250	167
65.	Yamatogawa (Japan)	Radiating	-	-	-	Steel	UC	355	-
66.	Hooghly (Calcutta)	Radiating	-	2	134.39	Steel-Con.	UC	457.2	182.9
67.	Posadas Encarnacu (Argentina)	Radiating	-	-	Concrete	UC	330	-	
68.	Hardwar (India)	Radiating	-	2	20	Concrete	UC	130	-
69.	Jogighopa (India)	Radiating	Parallel wire	2	50	Concrete	UC	5x286	-
70.	Akkar (India)	Radiating	-	2	56.11	Concrete	UC	152.4	-

Notes: 1. UC = Under construction or proposed
2. PPWS = Prefabricated parallel wire strands
3. HST Bar = High strength threaded bar

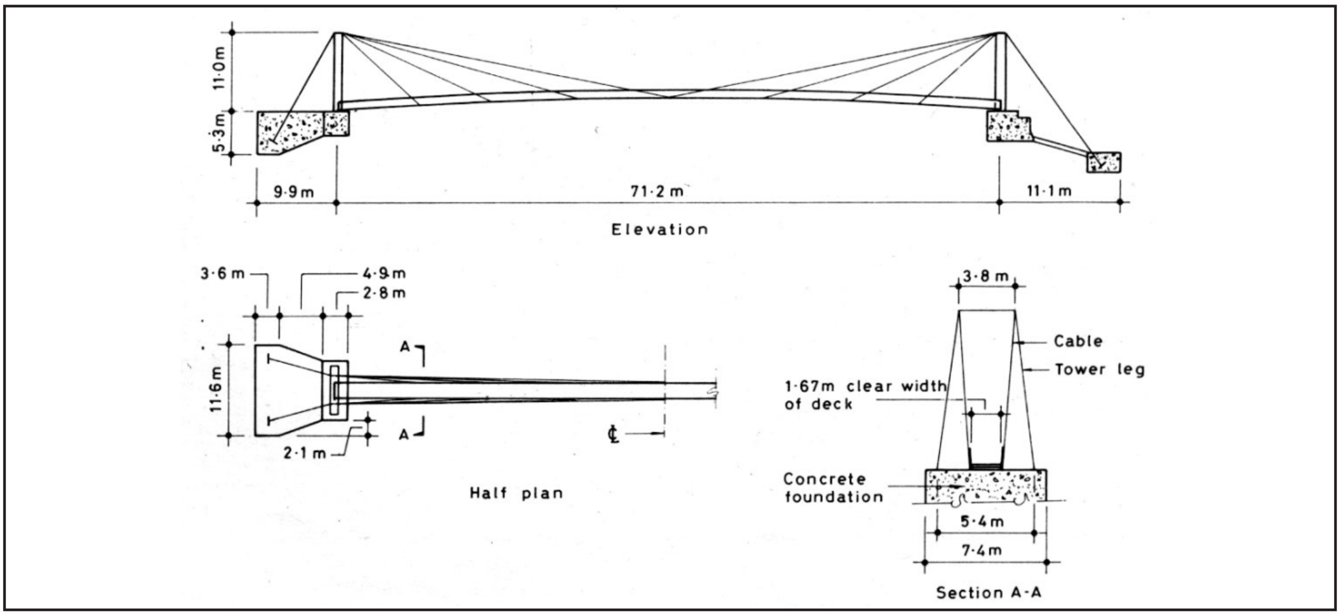

Figure 1. Bridge over Ganga Canal at Roorkee

features of the bridge are shown in Figure 3. The cables are spaced at 16.25m along the main girder and the tower height to main span ratio is 1/6.5. The bridge design was done at Civil Engineering Department, University of Roorkee, Roorkee. The allowable deflection limit assumed in the design was span/400.

Bridge across Brahmaputra at Jogighopa (Assam):

An interesting feasibility study was carried out by the Department of Civil and Earthquake Engineering, University of Roorkee, Roorkee, for the construction of a 2055-m long rail-cum-road bridge or alternatively, only a road bridge across Brahmaputra River at Jogighopa in Assam. The project was sponsored by Rail India Technical and Economic Services (RITES). Five modules, each 514-m long, with a three-span configuration of 114m-286m-114m were proposed for the highway bridge. A single-box prestressed concrete girder and A-type reinforced concrete tower were considered for the study. The general arrangement of the bridge is shown in Figure 4.

Bridge at Akkar (Sikkim):

A cable-stayed bridge of 152.40-m span with concrete deck and pylon is under construction at Akkar in Sikkim State. Figure 5 shows the broad details of the bridge.

Need for cable-stayed bridges

Utmost economy in material and an adequate carrying capacity are the main design features of the modern cable-stayed bridge system. These features are more or less successfully achieved, though no simple formula can be applied to evaluate the conditions in which the economy of the system can be guaranteed.

The conventional bridge designs are based on the premise that for the most economic design, the cost of superstructure and substructure should be nearly equal. In India, the major cost of any river bridge is due to the deep foundations. In the case of cable-stayed bridges, the number of foundations being invariably less, the cost of substructure is generally less than the cost of superstructure. However, there may be a range of spans for which the total cost of the cable-stayed bridges may be less than the total cost of conventional bridges.

Various studies carried out in European countries indicated that cable-stayed bridges are more economical for a span

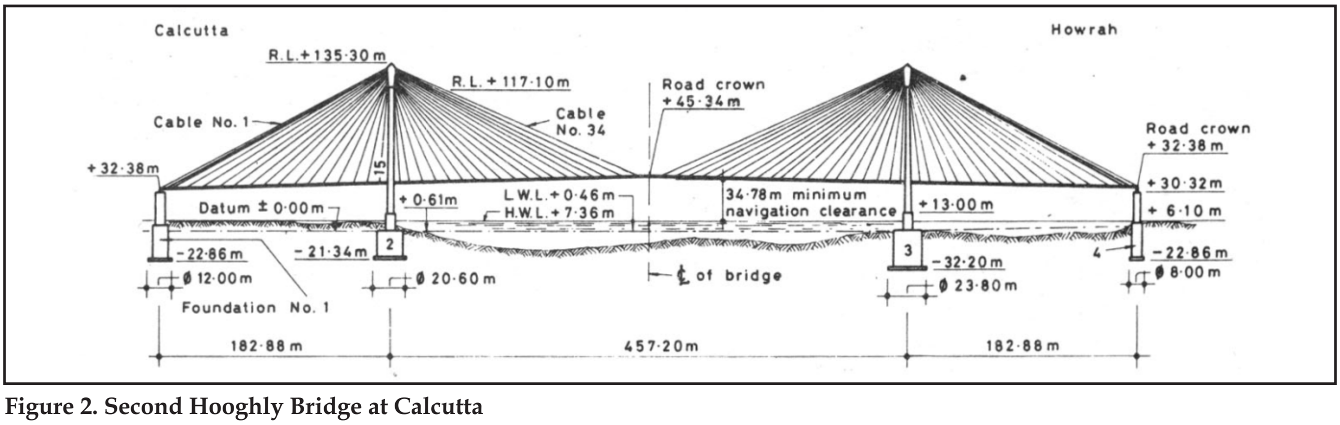

Figure 2. Second Hooghly Bridge at Calcutta

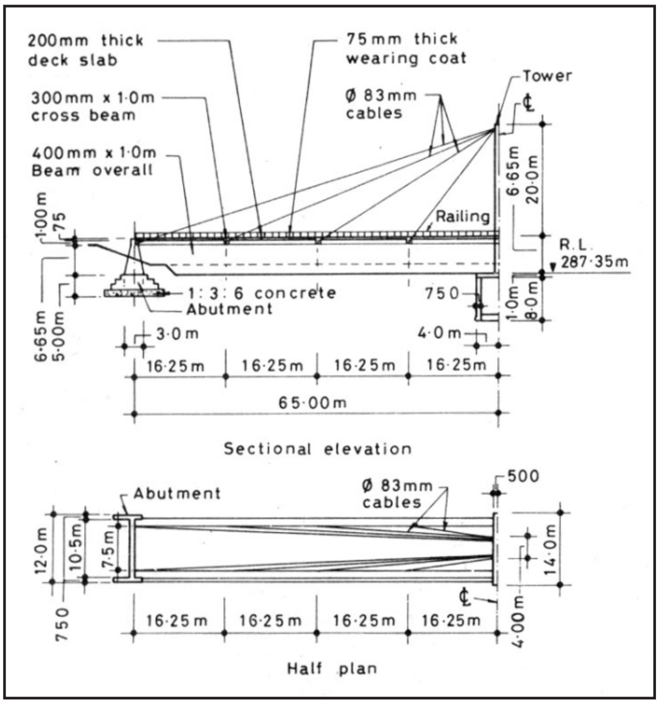

Figure 3. Bridge over new supply channel at Hardwar

length of about 300m. The cable-stayed Sitka Harbour Bridge in Alaska, U.S.A., and the PASCO, Washington Bridge in U.S.A. have proved to be more economical than the various conventional alternatives considered. Open design competitions held in Germany indicated that cable-stayed bridges are the most economical solution in that country for many highway bridges having a main span in the range of 150 to 370m.

In the field of cable-stayed bridge technology, only two studies have been reported in India so far, which indicate that cable-stayed bridges are most economical for a span length of 200 to 300m in Indian conditions[3, 6]. The feasibility study for Jogighopa Bridge in Assam has also proved that the cable-stayed bridge system is more economical. Thus, it would be opportune for bridge engineers in India to consider the potential of this newly developed bridge system favourably.

Ease of erection has made cable-stayed bridges more popular in the European countries because they can be built by the cantilever method and no temporary intermediate supports are needed during erection. This may be a decisive factor in some cases, if the bridge passes over a busy navigational channel, rail or highway. Also, all materials can be transported on the finished portion of the bridge as erection proceeds, thus eliminating the need for ancillary equipment.

The other important feature responsible for the popularity of the cable-stayed bridge system during the last two decades is its elegant form and capability to blend with the landscape. Cable-stayed bridges are truly representative of modern times. They are pleasing in outline, clean in their anatomical conception and free from ornamentation.

Analysis of cable-stayed bridges

A cable-stayed bridge is a statically indeterminate structure with a high degree of redundancy. Analysis of cable-stayed bridges considering three-dimensional space action is a relatively complex problem. But, if suitable assumptions are made, the problem may be solved by two-dimensional analysis and results can be obtained with reliable accuracy for practical design. Several investigators have used a two dimensional approach and many bridges have been designed on that basis and constructed.

Undoubtedly, the cable-stayed bridge displays a nonlinear behaviour due to large displacements, catenary action of cables and bending moment-axial force interaction in girders and towers. Various investigators have studied the non-linearity effect on cable-stayed bridges and found that non-linearity is not significant and linear analysis gives satisfactory results. However, for very large spans and important structures, non-linear analysis must be carried out and its

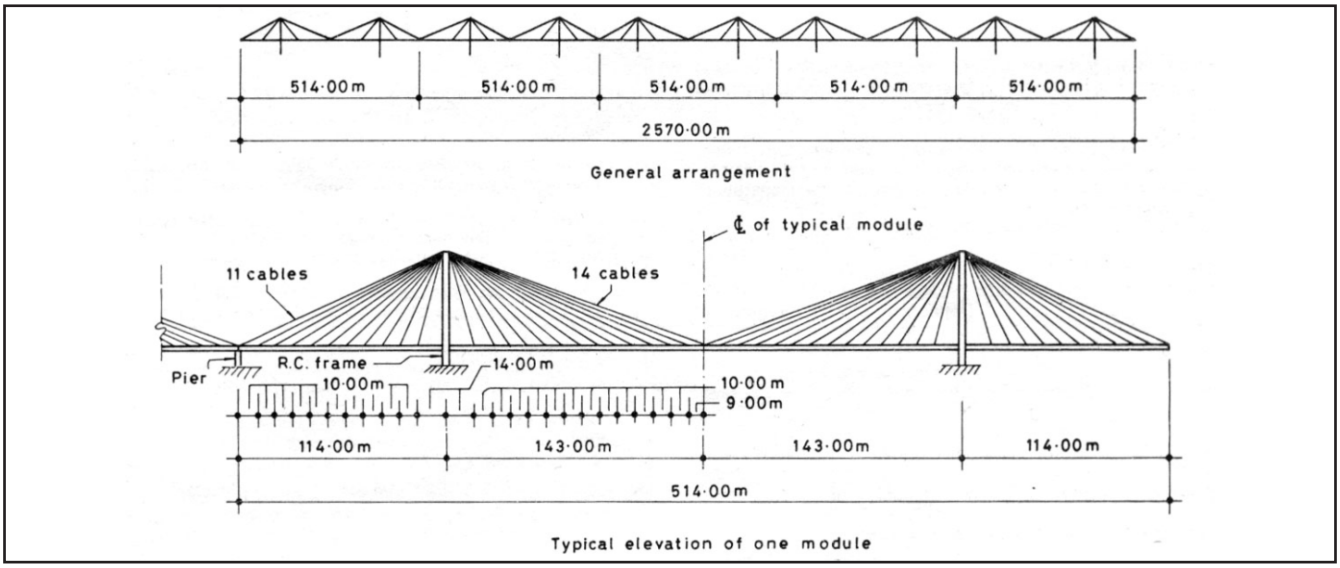

Figure 4. Bridge across Brahmaputra at Jogighopa, Assam

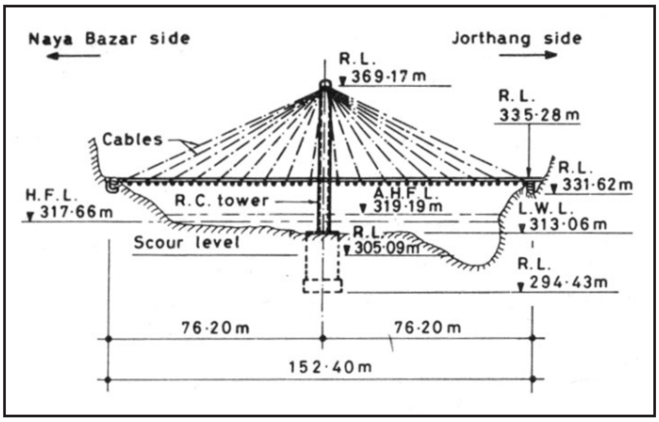

Figure 5. Akkar Bridge in Sikkim

effect studied. Analysis can be done by using stiffness or flexibility method, even a mixed method of analysis has been used by Podolony and Scalzi[13]. The load balancing method and finite element technique are the other methods used for the analysis of cable-stayed bridges[12,7].

Specifications

No specification exists for cable-stayed bridges in particular, or long-span bridges in general, in the Indian Roads Congress (IRC). The existing IRC code specifies that the deflection of the bridge should not exceed span/800, whereas in Germany the cable-stayed bridges are being designed with deflection limit ranging from 1/500 to 1/225 of the span length.

American Association of State Highway and Transportation Officials (AASHTO) recommends that until further experience is gained in this field, the 1/500 limit should be adopted for design of cable.stayed bridges. Thus, it is clear that existing IRC specifications are applicable to short and medium span bridges. If the same limit is insisted upon for cable-stayed bridges, which have long flexible spans, they may not always prove to be competitive in comparison to other conventional bridges. Thus, separate IRC codes stating clearly the type of loads, allowable deflection, etc. are essential for cable-stayed bridges.

Conclusion

A cable-stayed bridge is an indeterminate structure, in which the girder behaviour is similar to that of a continuous beam supported elastically at the points of cable attachment. A wide variety of geometric configurations can easily be selected to suit the numerous requirements of site conditions and aesthetics for rail, highway and foot bridges. Techniques required for the analysis of cable-stayed bridges have been developed by many researchers. Except for a very simple case, a computer is necessary for the solution of this type of structure. With today's developing technology and availability of faster computers, there seems to be an enormous scope for the adoption of cable-stayed bridges in India for important long-span structures or for small structures like footbridges. Thus, the time has come when Indian bridge designers must utilise the potential of this system.

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