The Evolution of German Cable-Stayed Bridges—An Overall Survey

ADOLF FEIGE

THE EVOLUTION OF BRIDGES with girders stayed by means of steel cables—referred to as "cable-stayed bridges" or "cable cantilever bridges"—has taken place in a relatively short period, namely, about fifteen years. In the domain of highway bridges the structural system in question fills the gap that once existed between the "deck" type bridge (with the girders installed under the bridge deck) and the suspension bridge. It has, however, also been successfully applied to the construction of footbridges.

As far back as 1950, more particularly for "deck" bridges, of medium span, the continuous solid-web superstructure with orthotropic steel deck plate functioning also as the top flange showed itself to be superior to other systems. For long spans, however, it necessitated considerable girder depths at the intermediate piers, e.g., as much as 33 ft for the world's biggest bridge of this type, the bridge over the River Save at Belgrade. The bridge with plate girders of constant depth which has been built over the Sill near Innsbruck has a superstructure with a depth of about 25 ft for a span length of 650 ft, i.e., a depth/span ratio of 1/26. Be that as it may, all the cable-stayed bridges that have been built in Germany in recent years are based on the structural system comprising an orthotropic deck plate and continuous girders. They are, generally speaking, considered to be economical for spans ranging from 330 ft to 1,150 ft. According to Homberg,[1] and provided that stay systems as indicated in Column 4 of Table 1 (multiple stays) are used, they are economically advantageous in comparison with suspension bridges for spans of as much as 1,640 ft to 2,600 ft. Besides the advantage of economy, the system in question has another advantage over "deck" bridges in that it has a superstructure of smaller depth, while it compares favorably with these bridges as well as with suspension bridges in having smaller deflections. Also, cable-stayed bridges exhibit better behavior than suspension bridges in that they have a less pronounced tendency to develop oscillations.

Besides, the cable-stayed bridge does not, as distinct from a suspension bridge, present the characteristic of giving lower values for the stresses and forces in the girders and cables if the deformations are taken into account in the calculations; on the contrary, higher values are obtained, as in the case of an arch bridge. In any case the influence of deformations is greatly reduced in cable-stayed bridges: for example, in the case of the Severin Bridge (Table 4, Case 6) it is, under the most unfavorable conditions, 6.4 percent for the girder and not even 1 percent for the cables[7]; for the bridge at Düsseldorf-North (Table 4, Case 8), again for the most unfavorable conditions, it is 12.4 percent for the girder.[8]

While it is true that from the aesthetic point of view the cable-stayed bridge cannot fully stand comparison with the plate-girder "deck" bridge nor with the suspension bridge, it nevertheless has a pleasing shape because it clearly reveals (even to the layman) the function of the cables and towers and because the cables, on account of their small diameter, are very unobtrusive in the overall appearance of the bridge, which is certainly not something that can be said of the chords and the web members (vertical and diagonal members) of a big lattice girder bridge, for example. From this point of view the axial girder bridge, with only a single load-bearing plane, provides a particularly successful solution, inasmuch as it obviates all cable intersections in the visual image of the bridge (Table 4, Cases 2, 4, 7, 11 and 12).

The idea of building a bridge in the form of a suspended structure similar to the present-day cable-stayed girder is not new: it was proposed as long ago as 1784 by C. J. Löscher (Fribourg) and around 1821 by Poyet (France). In 1817 an approximately 110-ft long footbridge with sloping suspension members

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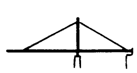
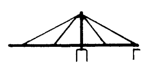
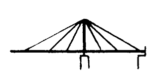
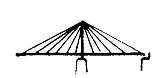
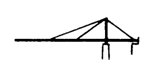
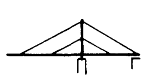
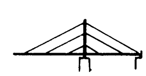
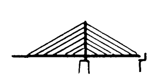
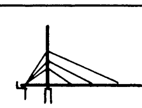
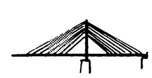
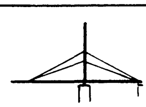
This paper is reprinted from Acier-Stahl-Steel, Brussels, Belgium, December, 1966.

was built in England. A 256-ft span bridge constructed over the River Saale near Nienburg in 1824 collapsed in the following year under overloading by a crowd of people. At the time, the knowledge necessary for successfully designing and constructing such bridges was still inadequate. The sloping members consisted of forged tie bars or of chain links made of looped wires. Around 1840 Hartley, an Englishman, built a bridge with a harp-shaped suspension system. The Albert Bridge over the Thames, with a main span of 400 ft and dating from 1873, affords an example of an even bigger bridge of this general type. In this structure the suspension system comprised tie members converging at the tops of the towers. There were three sloping tie members on each side of the center span and four on each side of the end spans.[2]

Recent developments in Germany, since 1950, have been characterized by the almost exclusive use of locked-coil cables for the stays. These must satisfy the same requirements as those applicable to the cables of suspension bridges. Hence it was possible to base analysis on the results of the tests performed with these latter cables and on the experience gained in the use thereof. In this connection the fatigue tests reported in References 7 and 10 call for special mention. There are—in Germany at any rate—no particular specifications for the cables used in cable-stayed bridges. The "Besondere technische Vorschriften für Stahlbrücken im Auftragsbereich des Bundesverkehrsministeriums" ("special technical specifications of steel bridges within the jurisdiction of the Federal Ministry of Transport") lay down more particularly in point 3.5 of the "Technische Bedingungen für Trag- und Hängeseile" ("technical requirements for supporting and suspension cables") that the factor of safety in relation to the calculated failure load should, for load-carrying cables, be 2.5. For round wires an ultimate strain of at least 3.5 percent and for wires of wedge-shaped cross-section an ultimate strain of at least 4.2 percent is specified. The elastic limit must not be less than 75 percent of the ultimate stress. For alternating stresses with an amplitude of at least 21,300 lb/in.^{2} (1,500 kg/cm^2) and for a load corresponding to 60 percent of the live load the cables must withstand two million load alternations, even in the presence of a transverse pressure of up to 5,600 lb/in. (1,000 kg/cm) per cable if this pressure acts directly upon the steel, and 14,000 lb/in. (2,500 kg/cm) if special bearing devices are provided. The nominal mechanical strength of round wires should not exceed 95 tons/in.^{2} (150 kg/mm^2); the strength of wedge-shaped or other special-section wires should, as far as possible, be of the same order of magnitude as that of round wires. This strength therefore corresponds to a permissible stress of 38 tons/in.^{2} (60 kg/mm^2). The German Standard DIN 1073 "Berechnungsgrundlage für stählerne Strassenbrücken" ("design principles for steel highway bridges") will, in its revised version (now in course of preparation), recast these specifications in a new form. The above-mentioned requirements apply to cables comprising wires in spiral arrangement. Under these specifications it is not permissible to use parallel-wire cables; they have, in fact, been used only once in Germany—in the construction of a footbridge. However, for very large bridges they present some advantages, as witness their use, for example, in the big American suspension bridges and recently also in Britain, more particularly in the construction of the Firth of Forth Bridge and the Severn Bridge.

Table 1. Stay Systems Used on Highway Bridges Built in Germany

	Single	Double	Triple	Multiple	Variable	
	1	2	3	4	5	
1						Bundles (converging)
2						Harp
3						Fan
4						Star

The various cable arrangements are summarized in Table 1. In the bridge types comprising from one to three cables, the arrangement adopted is in each case determined by the required span length of the girder. The multiple-cable systems have been found efficient —more particularly for long spans—in achieving a structurally simpler transmission of forces to the orthotropic deck plate and to the towers respectively.[1] Besides, if the harp-type cable arrangement is adopted (Row 2 in Table 1) with the cable attachments distributed over the entire height of the tower, the latter, too, can obviously be structurally simplified in comparison with the arrangement in which all the cables converge at the top of the tower. Also, the harp-type arrangement gives the bridge a good appearance. The star pattern (Row 4) is likewise an attractive cable arrangement from the aesthetic point of view and was entirely defensible in the case of a bridge with such dimensions as that at Hamburg (Table 4, Case 12). However, it is in contradiction with the principle that is generally acknowledged to be efficient, in view of what has been said above, for large bridges: for these it is considered that the points of attachment of the cables should be distributed as much as possible along the girder. As for the fanwise arrangement (Row 3), it offers the same advantages as the harp-type arrangement with regard to the attachment of the cables to the towers, besides constituting in many cases an entirely defensible variant from the aesthetic point of view.

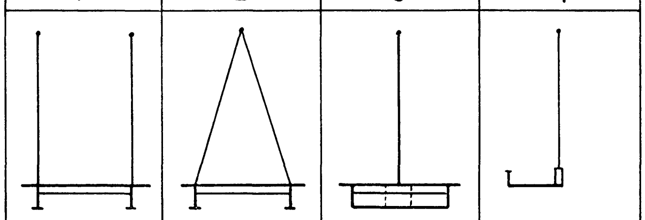
The attachments of the cables—or groups of cables combined in larger units—to the towers may either be fixed or movable bearings; in the latter case these take the form of appropriate hinges and/or roller devices. The structural interaction of all parts of the load-carrying system is thereby fundamentally affected. Examples of this are given in References 16 and 17. The rigidity of the system is a maximum if all the cables have fixed bearings. By introducing a certain prestress into the cables it is possible to reduce the bending moment peaks in the girder.

Table 2 shows the various positions that may be adopted for the planes in which the stays are located. First, there may be two vertical planes containing these load-bearing members; then, there may be two planes sloping toward each other, as is more particularly the case in the triple-chord triangular-section girder; finally, there may be only one load-bearing plane, with the girder positioned either axially or laterally in relation to it, the lateral girder system being a special case. The system embodying an axial girder, recommended by Haupt in 1948, has since come to be widely used. Of the twelve examples of bridges listed in Table 4, five have axial girders. This type of construction calls for a girder possessing a high degree of torsional rigidity, just as box-girder type "deck" bridges (i.e., with the girder disposed below deck level) must likewise be very rigid with regard to torsion.

As appears from Table 3, the towers may be of the trapezoidal portal-frame type (Column 1) or A-shaped (Column 5) and they may be pin-jointed ("hinged") in the longitudinal direction of the bridge or they may be fixed at the base. The arrangement in which the top cross-member is absent (Columns 2 and 3) presents no difficulties, because in the event of lateral displacement of the top of the tower—due to wind pressure, for example—the forces acting in the cables will provide a restoring component. Such single towers are fixed either to the pier (Column 2) or to the girder itself (Column 3). In the case of the axial-girder bridge the tower is generally fixed to the girder, whereas the tower of the lateral-girder bridge is fixed to the pier or to the foundation structure. For the design of towers which are fixed at the base and are provided with cables in the form of bundles converging at the top, a rational method has been developed by Klöppel, Esslinger and Kollmeier.[18]

Table 2. Positions of Planes in Which Stays Are Located

Double vertical	Double oblique	Single vertical	Vertical lateral
1	2	3	4
5	2	5	

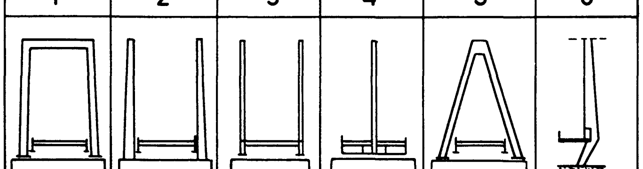


Number of cases among the twelve examples in Table IV

Table 3. Shapes of Towers

1. Portal-frame type with top cross-member.
2. Without top cross-member and fixed to the pier.
3. Without top cross-member and fixed to the superstructure.
4. Axial tower fixed to the superstructure.
5. A-shaped tower.
6. Lateral tower fixed to the pier.

1	2	3	4	5	6
1	1	3	5	2	



Number of cases among the twelve examples in Table IV.

Table 4. Cable-Stayed Bridges in the Federal Republic of Germany and in Sweden

1. Büchenauer crossing at Bruchsal (1956).
2. Jülicherstraße crossing at Düsseldorf (1964).
3. Bridge over the Strömsund in Sweden (1955).
4. Bridge over the Rhine near Maxau (1966).
5. Bridge on the elevated road at Ludwigshafen (1967).
6. Severin bridge at Cologne (1959).
7. Bridge over the Rhine near Leverkusen (1965).
8. North Bridge at Düsseldorf (1958).
9. "Kniebrücke" at Düsseldorf (1969).
10. Bridge over the Rhine at Rees (1967).
11. Bridge over the Rhine north of Bonn (1967).
12. Bridge over the Elbe at Hamburg (1962).

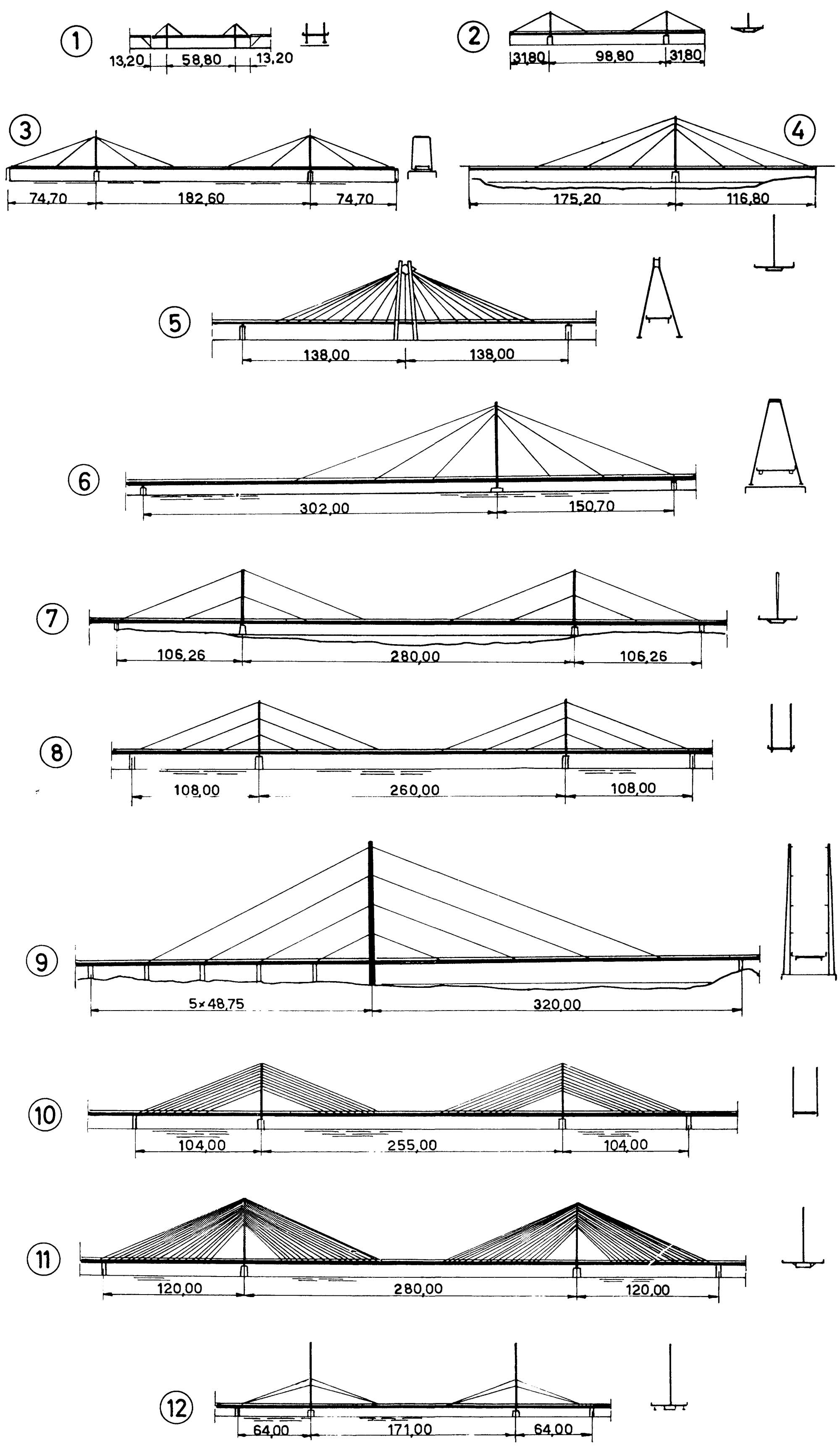


Table 4 gives a survey of German cable-stayed highway bridges, classified according to the stay system employed. For each case the actual stayed girder is schematically illustrated; any girders which are continuously connected to these and cross the side spans are not shown.

Case 1 in Table 4 shows one of the oldest bridges of this general type, dating from 1956, with a span of only 193 ft. It comprises a reinforced concrete carriageway slab which cooperates structurally with the four individual towers, the latter being fixed to the steelwork. The stay system is of the simple type (with one cable). This bridge crosses a number of railway lines at Bruchsal near Karlsruhe.[3] Depth of superstructure is 3 ft-7¼ in., i.e., 1/53 of the span.

The bridge shown as Case 2 also crosses railway lines, in the Jülicherstrasse at Düsseldorf, and was completed in 1964. It was built in accordance with the latest ideas and is an axial-girder bridge with an orthotropic deck plate, two towers, and a simple stay system.[4] Depth of superstructure is 5 ft-5 in., i.e., 1/60 of the span.

Case 3 represents the first German cable-stayed bridge in the sense that it was designed and fabricated in that country. It was, however, erected over the Strömsund in Sweden and was completed in 1955. It has a span of 600 ft. The stay system, in the form of converging bundles, in each case consists of two top and two bottom cables, immovably anchored together at the top of the tower. The towers are of trapezoidal frames hinged at the base to allow "rocking" movements in the longitudinal direction of the bridge. The deck structure consists of a reinforced concrete slab supported on steel longitudinal members and crossgirders[5] and has a depth of about 10 ft-6 in., i.e., 1/58 of the span.

All the cable-stayed bridges subsequently built have orthotropic deck plates which differ from one another only insofar as the cross-sections of the stringers (longitudinal ribs) and the spacing of the cross-girders are concerned. According to a report by Pelikan, a cross-girder spacing of more than about 6 ft-6 in. in the case of stringers having no significant amount of torsional rigidity, and of more than about 10 ft in the case of stringers with a high degree of torsional rigidity, is to be considered an economical value.

Case 4, the bridge over the Rhine near Maxau, is an axial-girder structure comprising a triple bundle of cables and two unequal spans, the longest of which measures 575 ft. It accordingly has only one tower, about 149 ft high. The attachments of the cables to the tower are as follows: at the top is a movable bearing, the central bearing is fixed, and the bottom cable bearing is movable. The width of the bridge between parapets is 114 ft. The cross-sectional shape of the bridge superstructure is that of a box girder, 39 ft-4 in. wide and possessing a high torsional rigidity, with 38 ft wide cantilevers on each side. The box girder has a depth of about 10 ft-6 in., corresponding to 1/62 of the length of the main span. The steelwork, including the cables, weighs 68 lbs/ft^2. The bridge was completed in 1966.

Case 5 is a bridge to be built on the elevated road at Ludwigshafen, which will have two bundles of multiple cables situated in oblique planes in relation to each other and will have an A-shaped tower rising to about 246 ft above the railway lines crossed by the bridge. The two symmetrical spans each have a length of 453 ft; the bridge is 54 ft-9 in. wide. The deck structure comprises two solid-web plate girders about 8 ft-2 in. in depth, corresponding to 1/55 of the span. Weight is 69.5 lb/ft^2. The bridge is scheduled for completion in 1967. Each bundle of cables is immovably attached to the tower.[6]

Case 6 is the Severin Bridge at Cologne. Its main span has the great length of 991 ft, including a length of 400 ft without intermediate support. Because of this it weighs 84.5 lbs/ft^2. The A-shaped tower is about 204 ft high, and all the cables are fixed directly to the top. The tower is rigidly connected to the pier with regard to the longitudinal direction of the bridge. The latter is 97 ft wide; its cross-section is shown in Table 6, Case 4. The two box-section main girders have a maximum depth of 15 ft-2 in. in the main span, this being equivalent to 1/66 of the length of the span. The bridge was completed in 1959.[7]

The bridge over the Rhine at Leverkusen, Case 7 in Table 4, is an axial-girder structure with a cable arrangement of the two-stringed harp type. The tower, about 147 ft high, is fixed to the box-section in three parts forming the girder. The top stay cables are attached to the tower by a movable bearing, whereas the bottom cables have fixed bearings. The bridge is 123 ft wide; the box girder is 8 ft-10½ in. wide, and each of the side cantilevers has a width of 38 ft. The box girder is 13 ft-9 in. deep, i.e., about 1/64 of the span. Weight is 70 lbs/ft^2. The bridge was completed in 1965.[2,8]

Case 8, the North Bridge over the Rhine at Düsseldorf, was completed in 1958. It was the first long-span cable-stayed bridge built in Germany. The center span is 853 ft long and 87 ft-6 in. wide. Its cross-section is similar to that of the Severin Bridge in that the two main girders are also box-section members. The carriageway deck is of special interest in that the top surface of the orthotropic plate is provided with a zigzag pattern of 1.1 in. x 0.24 in. flat bars set on edge and spaced 6 in. apart, their object being to hold the 2 in. thick asphalt surfacing in position. The actual deck plating has a minimum thickness of 0.55 in. Fatigue tests under alternating loads showed that this arrangement presented no hazard from the steel constructional point of view and, in particular, that the welds securing the flat bars involved no risk of fatigue failure. The girders are 10 ft-6 in. deep, which corresponds to 1/81 of the main span. The individual towers are fixed to these girders and are about 131 ft high. The stay system is of the three-stringed harp type; the middle cables are immovably fixed to the towers, whereas the upper and lower cables are attached to the latter by means of movable bearings.[9]

The "Kniebrücke" at Düsseldorf is represented as Case 9. This is another of the cable-stayed bridges with harp-type cable arrangement with which that city is equipping its central area. This process will be completed by the rebuilding of the Oberkassel Bridge on the same principle. The situation at Düsseldorf will then be as follows:

North Bridge: triple harp, with two towers on each side, these towers being fixed to the girder;

Oberkassel Bridge: quadruple harp, axial girder, with a tower on each side fixed to the girder;

Knie Bridge ("Kniebrücke"): quadruple harp, with two towers on each side fixed to the girder.

Construction work on the "Kniebrücke" started recently and completion is scheduled for 1969. With its span of 1,050 ft this bridge will, for the time being, be the world's longest-span cable-stayed bridge. The main girder depth is about 10 ft-6 in., i.e., 1/100 of the span. The cross-section of the deck structure with single-web main girders is shown in Table 6, Case 3. In accordance with the design that has been prepared for this bridge, the towers, which will rise to a height of 375 ft above the river bed, will be of reinforced concrete with dimensions of 28 ft x 21 ft-4 in. at the base and 10 ft-10 in. x 9 ft-2 in. at the top. Just as the projected Oberkassel Bridge, this bridge embodies the feature that the girder of the left-bank spans is supported on a row of piers, each of which is located at one of the points of attachment of the cables. The girder is anchored down on to its supports to obviate any lifting that might occur, so that the cables of that span, too, are connected to fixed points. The stiffness of the girder crossing the navigation channel is greatly increased. The very elaborate investigations that were carried out for the preparation of the preliminary design, as well as the experience gained in competitive designs for bridges over the Rhine in recent years, established the efficiency and superiority of this system beyond doubt, particularly as the comparison had also included continuous-girder "deck" bridges, arch bridges and suspension bridges.[10] The estimated weight of the "Kniebrücke" is 115 lbs/ft^2.[6]

Case 10, the bridge over the Rhine near Rees, has a stay system in the form of a multi-stringed harp, having ten stays, one above the other, on each side. This arrangement is the result of a desire to achieve structurally simpler transmission of the forces acting in the cables to the girder. Thus, instead of suspension at a few isolated points, this bridge had something very like continuous elastic support from the stay system, more or less similar to that provided by sleepers under railway lines. There are also two individual towers on each side, these being fixed to the girder. The main span has a length of 837 ft, and the girder is about 11 ft-6 in. deep, corresponding to 1/73 of the main span. The bridge is 62 ft wide. The two main girders are of the single-wet type. The bridge, with a weight of 74 lbs/ft^2 is scheduled for completion in 1967.[6]

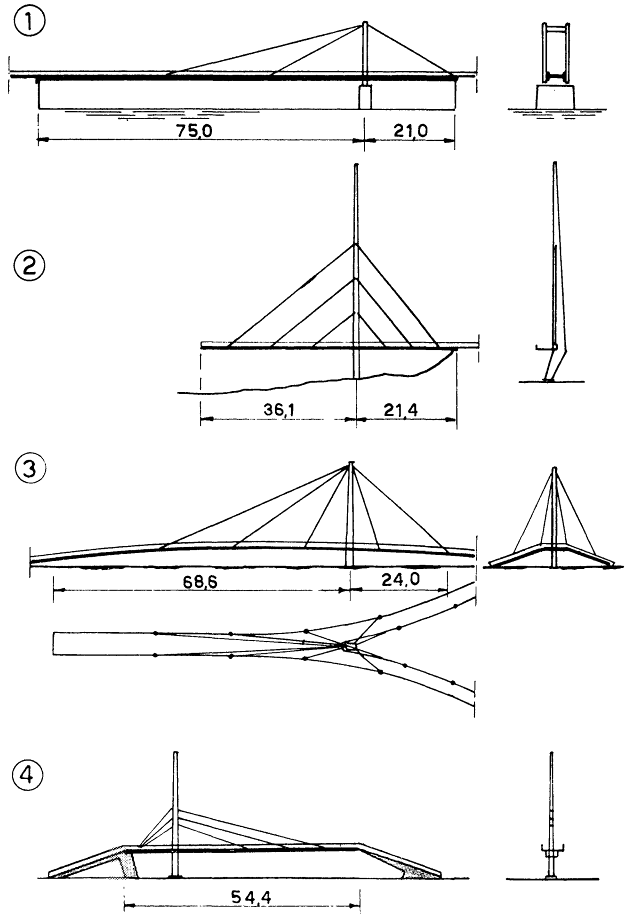
Case 11 represents the bridge over the Rhine at Bonn, in which the above-mentioned principle of suspending the girder at a large number of points has been further extended, for here the stay plane comprises twenty cables disposed one above the other. The points of suspension are about 14 ft-9 in. apart along the beam, while the points of attachment of the stay cables to the tower are spaced at intervals of 3 ft-3½ in. The steel towers, about 177 ft high, are fixed to the piers and function as an axial girder in conjunction with the stay system. Because of this the girder itself has been designed to have considerable torsional rigidity and comprises a 41 ft-3 in. wide box section provided, on each side, with a 39 ft wide cantilever. The cross-section is generally similar to that of Case 5 in Table 6. The main span is 837 ft long; the depth of the girder is 13 ft-9 in., i.e., 1/61 of the span. The bridge is 117 ft wide and weighs 69 lbs/ft^2. It is to be completed in 1967.[2,6]

Case 12 represents the motorway bridge over the Elbe at Hamburg, likewise designed as an axial-girder bridge. The judging committee appointed to examine the tenders considered that "the unique silhouette of the bridge with its well-defined load-carrying system and deck structure of constant depth, together with the upward-extended towers and the star-pattern of the stay system, constituted a design particularly pleasing to the eye and entirely in line with modern style". The main span is about 565 ft in length, and the girder is about 9 ft-10 in deep, i.e., 1/57 of the main span. The bridge is 101 ft wide. The deck structure consists of a grillage comprising a 26 ft-11 in. wide box girder (located axially) and two single-web lateral girders interconnected at intervals of about 70 ft by solid-web diaphragm-type cross-girders. The 175 ft high towers are fixed to the girder. The top cables are immovably fixed to the towers, whereas the bottom cables have movable bearings at their points of attachment to the towers. The weight of the bridge is about 66 lbs/ft^2. Each stay consists of ten 2.84-in. diameter cables.[11]

Table 5 gives some examples of the application of the cable-stayed girder to the construction of footbridges. The elegance and lightness of these structures is thereby enhanced and very attractive results can be obtained.

Case 1 shows the Volta footbridge over the Neckar at Stuttgart. It is 11 ft-10 in. wide, has a 246 ft long main span, and a 3 ft-9 in. deep girder, corresponding to 1/66

Table 5. Footbridges



of the span. This bridge was built in 1957. The portal-frame tower rises to a height of 39 ft above the top of the pier and can perform "rocking" movements in the longitudinal direction of the bridge. The total weight is 113 tons. On account of its short length, the side span could suitably be supported by a single cable, whereas two stays were provided for the main span. As a result, a particularly distinctive and pleasing form of the stay system was obtained.[12]

Case 2 shows the footbridge in the German section of the Universal Exhibition at Brussels in 1958. In view of the special character of that exhibition, this bridge was intentionally given an unusual appearance. It has a lateral girder with an approximately 118-ft long main span and an effective width of 9 ft-10 in. The deck is formed of boards resting on a torsionally rigid box girder 4 ft-3 in. deep and 2 ft-3½ in. wide. The tower is about 164 ft in height and is fixed to the foundation structure. The cables of the three-stringed harp pattern are immovably secured. The structure has a total weight of 88 tons.[13] After the exhibition had ended, the footbridge was dismantled and re-erected over a motorway near Duisburg.

Case 3, the footbridge over the Schillerstrasse at Stuttgart, was built in 1961. It is Y-shaped in plan, with a rocker-type tower, 79 ft high, installed at the bifurcation. The main span has a length of 225 ft, and the deck structure is 1 ft-8 in. in depth, corresponding to 1/33 of the span. The plan view of the bridge gives some idea of the arrangement of the stay system in the form of convergent bundles and affords an example of the great versatility and adaptability of such systems. The cables themselves are of a special type. This is the only example of a German cable-stayed bridge with parallel-wire cables. This form of cable was adopted on account of the more favorable modulus of elasticity (higher than for twisted-wire cables) and furthermore because it was thereby possible to achieve a shorter anchorage length for the cable than with the normally employed system. The cables consist of 0.236 in. wires of steel grade St 150/170 which, after being bundled, were provided with a wrapping of 0.1 in. diameter wire according to the procedure usually followed in suspension bridge construction in the United States. The final sheathing consists of polyethylene tubing. The space between the tubing and the actual cable was filled with cement grout. The total weight of the structure is 109 tons.[14]

Case 4, a footbridge which connected two sections of the International Horticultural Exhibition at Hamburg in 1963, is designed as an axial-girder structure with towers extended upwards for architectural reasons, so as to harmonize with the towers of the motorway bridge (Table 4, Case 12). The stay system is of the fan type, presenting a novel appearance, having regard to the purpose of this footbridge and yet perfectly rational from the technical point of view. The girder consists of a trapezoidal torsionally rigid box girder with a cantilever on each side. The longest span is about 130 ft.[15]

To the same group of structures belongs the Lodemann Bridge over the Ihme at Hanover, carrying a footway and a cycle track. It has a stay system in the form of triple convergent bundles forming an axial-girder structure, the girder being located centrally in the cross-section of the bridge. The stays are connected to the top of an A-shaped tower which has a needle-shaped upward extension, so that the tower as a whole looks like an inverted Y.

Figure 1 is a graphical representation of the weights mentioned in the foregoing description (insofar as these relate to comparable structures); for each bridge the weight has been plotted against the length of the main span. Although this span length varies between 453 ft and 920 ft, the maximum difference in weight per unit area is only about 13 percent.

The depth of the deck structure of these same bridges ranges from 8 ft-2 in. to 13 ft-10 in., with an average value of 11 ft-2 in.

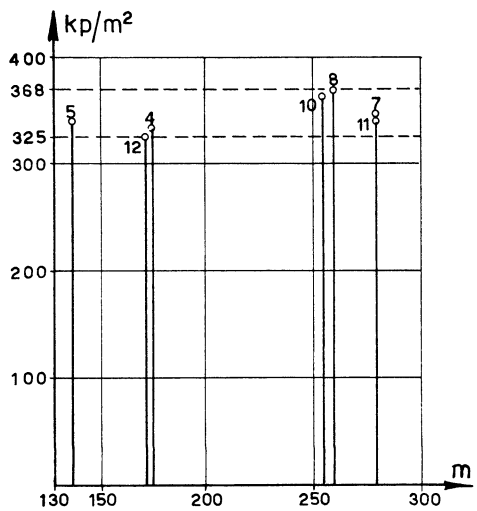


Fig. 7. Weight of steelwork in comparable bridges, per square meter of deck. (The numbers refer to Table IV.)

On considering the cross-sections of the bridges, with reference to Table 6, it can be seen that among the ten most recent bridges there are:

Three with single-web main girders;

Two with double-web (box-section) main girders;

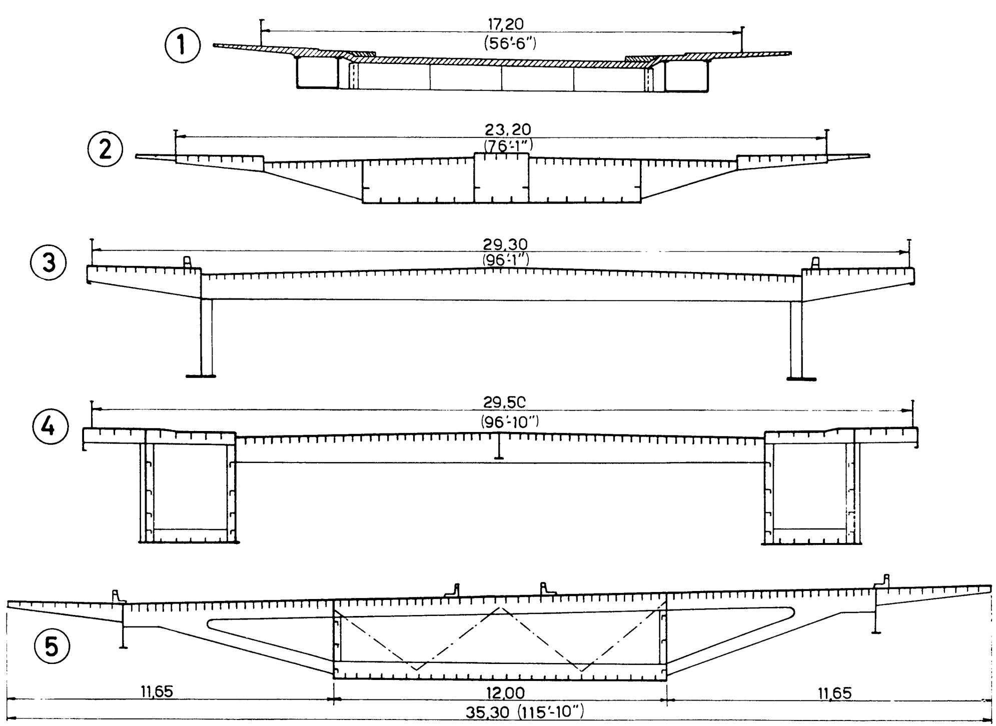
Five with torsionally rigid box girders positioned axially.

The structural design of the cable-stayed girder itself presents no unusual problems. On account of the co-operation with the deck structure consisting of beam grillages and members having a high torsional rigidity, the design calculations of course call for the application of appropriate methods or modern electronic computers, but they do not entail any special difficulties.

In the case of a stay system comprising convergent bundles, with the cables immovably fixed to the top of the tower (Table 7, Case A), the continuity of the girder in conjunction with the actual stay system presents a fourteen-times statically indeterminate problem. As explained in Reference 7, a statically determinate "main system" can be obtained by eliminating the bending moments in the girder at the points of attachment of the cables and at the section where the towers are fixed to the girder (Case B). In another case, where the top cable is immovably fixed to the tower, but the two lower cables are attached to it by means of movable bearings (Case C), the degree of indeterminacy is reduced to ten. As explained in Reference 8, it is, for example, possible in this case to form two symmetrically arranged statically indeterminate main systems by the introduction of hinges into the girder at **a** and **b**. Each of these "partial" systems will then be only four times statically indeterminate. The redundants (statically indeterminate quantities) X_a and X_b can suitably be calculated from the grouped live loads $Y = X_a + X_b$

Table 6. Characteristic Cross-Sections of Bridges

1. Büchenauer Bridge. Composite deck: reinforced concrete slab supported on two box-section main girders.
2. Jülicherstraße crossing. Orthotropic plate on torsionally rigid box girder comprising three parts with side cantilevers.
3. "Kniebrücke". Orthotropic plate on two solid-web girders.
4. Severin Bridge. Orthotropic plate on two box-section main girders.
5. Bridge near Maxau (similar to the bridge near Bonn). Orthotropic plate on torsionally rigid box girder, with two cantilevers.



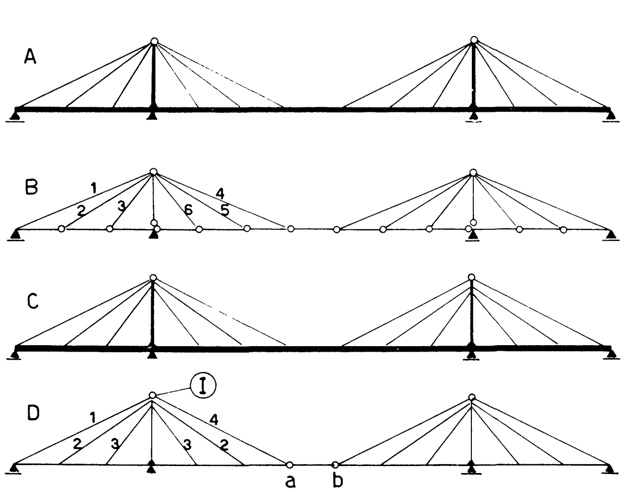
and $Z = X_a - X_b$ by applying a symmetrical and an antisymmetrical loading respectively. It sometimes occurs that other simply-supported girders are continuously connected to the girder of the stay system. In such cases the continuous girder itself has often been chosen as the "main system". For the design of cable-stayed systems Reference 18 should furthermore be consulted, as should the special publications that most of these bridges have had devoted to them; Reference 19 should be consulted for the design of the towers.

The analysis of the stress in accordance with the theory of second order, taking the deformations into account, may be carried out, for example, by the method explained in Reference 19 and illustrated by the calculations for the North Bridge at Düsseldorf.

In the structural design it is especially necessary to make a correct choice of the value for the modulus of elasticity. In the case of cables comprising wires twisted in spiral fashion, the modulus of elasticity will depend on the elasticity of the wires themselves, or on the internal deformation of the cable, or on the sag of the cable, or it may indeed depend on all these three factors at once. Hence the modulus is not a constant value, but is, instead, a function of the load acting in the cable. Having regard to the circumstances referred to above, the calculations are performed with an "ideal" modulus of elasticity, usually taken as 10,200 tons/in.^{2} for the live load and approximately 7,900 tons/in.^{2} for the various stages of erection. According to Reference 6 it is this lowering of the modulus of elasticity that practically determines the upper limit of the economic span length for cable-stayed bridges. Besides, a cable length of around 1,000 ft would appear to be the greatest economically acceptable length.

It should also be noted that in connection with the design of cable-stayed bridges in Germany the effect

Table 7. Examples of Structural Systems



1. Fixed or movable bearing.

of wind action and of oscillations has been investigated very thoroughly. For an example of such research, Reference 21—which reports on partial tests on models for the purpose of determining the aerodynamic behavior of certain bridges, including the Leverkusen Bridge—can advantageously be consulted, as well as Reference 22, which deals with stress and oscillation measurements on the bridge whereby the Federal motorway bypass to the south of Hamburg crosses the North Elbe.

In this article the author has, as was his intention, dealt only with cable-stayed bridges designed and/or built in Germany itself. In fact, it is particularly in this country that this bridge system has been greatly developed. This does not mean to say, however, that bridges embodying this system have not been built in other countries, too. In particular, mention should be made of the first "bridle-chord" bridge built in Britain, namely, the bridge over the Usk near Newport, dating from 1962 and having a main span of about 500 ft; also the bridge over the Wye, which was built in the following years and is of the axial-girder type, with a span of about 835 ft.

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Fig. 2. View of the Nordelbe Bridge K6 at Hamburg Germany