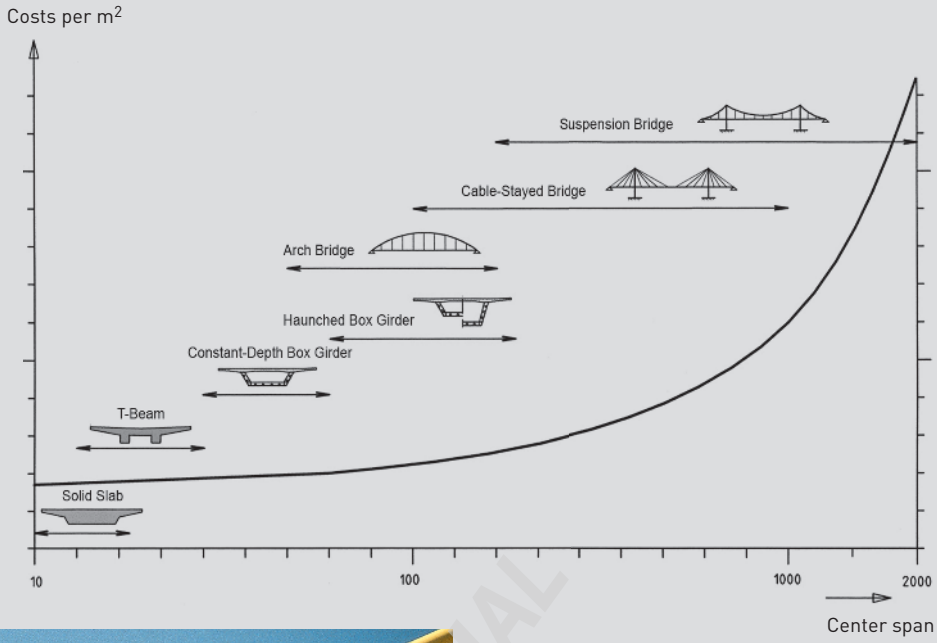
1 Introduction





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Cable-Stayed Bridges. 40 Years of Experience Worldwide. First Edition. Holger Svensson.
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Figure 1.1 (left side above) Relation between construction costs per m^2 and main span length

1.1 Design fundamentals

1.1.1 General

The position of cable-stayed bridges within all bridge systems is given in Fig. 1.1. Their spans range between continuous girders and arch bridges with shorter spans at one end, and suspension bridges with longer spans at the other.

The economic main span range of cable-stayed bridges thus lies between 100 m with one tower and 1100 m with two towers.

What are the special advantages of cable-stayed bridges?

First of all the bending moments are greatly reduced by the load transfer of the stay cables, Fig. 1.2. By installing the stay cables with their predetermined precise lengths the support conditions for a beam rigidly supported at the cable anchor points can be achieved and thus the moments from permanent loads are minimized, Fig. 1.3.

Even for live loads the bending moments of the beam elastically supported by the stay cables remain small.

Negative live load moments may occur over the vertical bearings at the towers. They can be avoided by supporting the beam by the stay cables only, including in the tower region. The biggest positive and negative moments occur in the side spans near the hold-down piers, which may require special measures. Shear forces remain small.

Large compression forces in the beam are caused by the horizontal components of the inclined stay cables. The normal forces in the main and side span equal one another so that only uplift forces have to be anchored in the abutments which act as hold-down piers.

The largest horizontal components belong to the backstay cables, Fig. 1.3. The beam compression forces thus increase quickly at the beam ends and increase less quickly near the towers where they reach a maximum. For concrete beams this compression force is beneficial. Only in the bridge center, where the compression forces from cables are small, is additional longitudinal post-tensioning required, which also has to overcome tension from friction, braking, etc.

The cross-section of steel beams requires only little additional material to cover the overall compression forces.

A second important advantage of cable-stayed bridges is their ease of construction, Fig. 1.4:

- Arch bridges with large spans are not stable during erection until the arch is closed and the horizontal support forces are anchored. They have to be temporarily supported, e. g. by auxiliary piers or temporary tie-backs.
- Self-anchored suspension bridges, which may be required when their horizontal cable component cannot economically be anchored due to bad soil conditions, need temporary supports of their beams until the main cables are installed.
- In cable-stayed bridges, however, the same flow of forces is present during free-cantilever construction stages as after completion. This is true for free cantilevering to both sides of the tower as well as for free cantilevering the main span only.

The third main advantage lies in the fact that cable-stayed bridges are inherently stiffer than suspension bridges. This is especially true

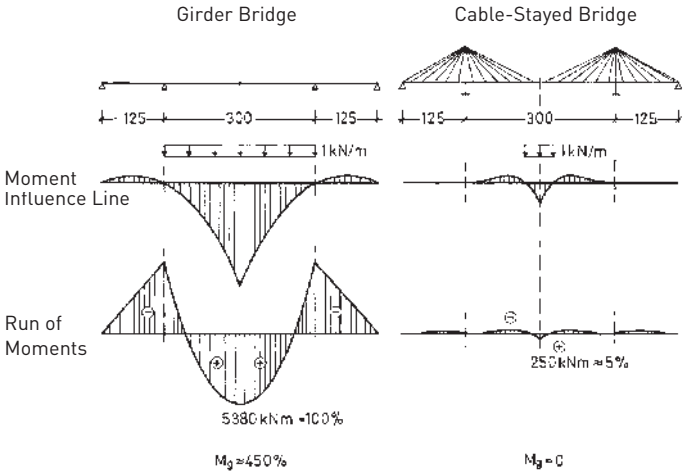


Figure 1.2 Comparison of beam moments

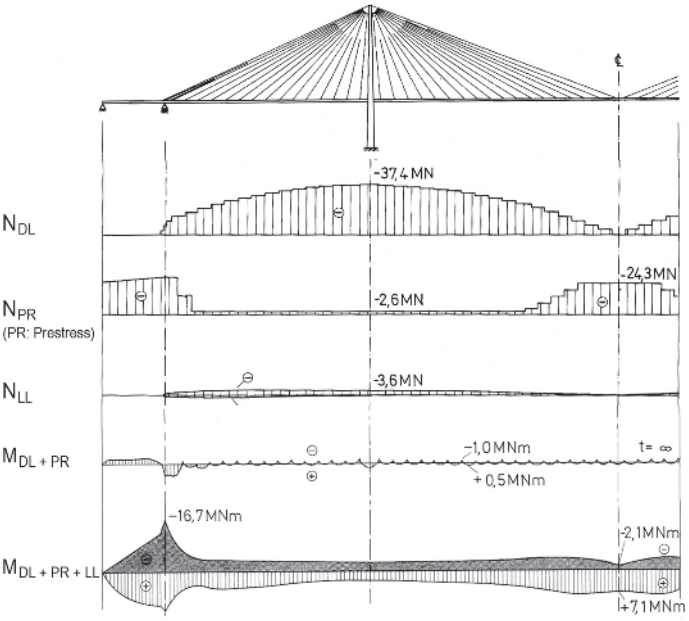


Figure 1.3 Bending moments and compression forces in beams of cable-stayed bridges

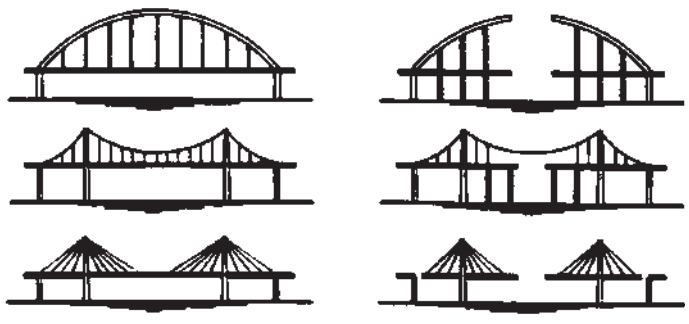


Figure 1.4 Erection systems for arches, self-anchored suspension bridges and cable-stayed bridges

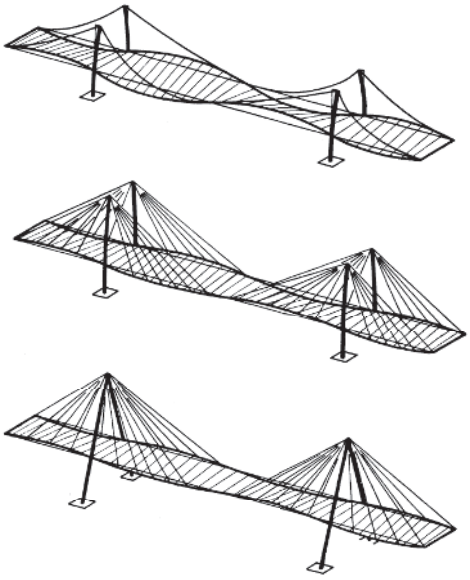


Figure 1.5 Eigenmodes of suspension bridges and cable-stayed bridges

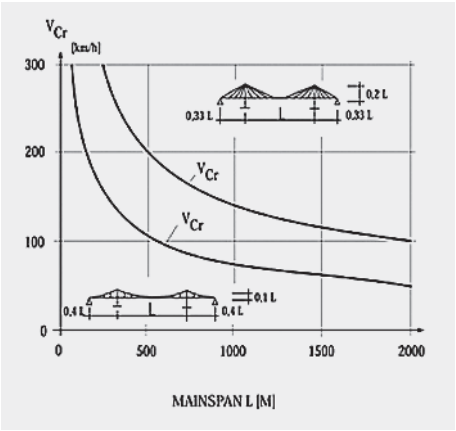


Figure 1.6 Critical wind speeds of suspension bridges and cable-stayed bridges

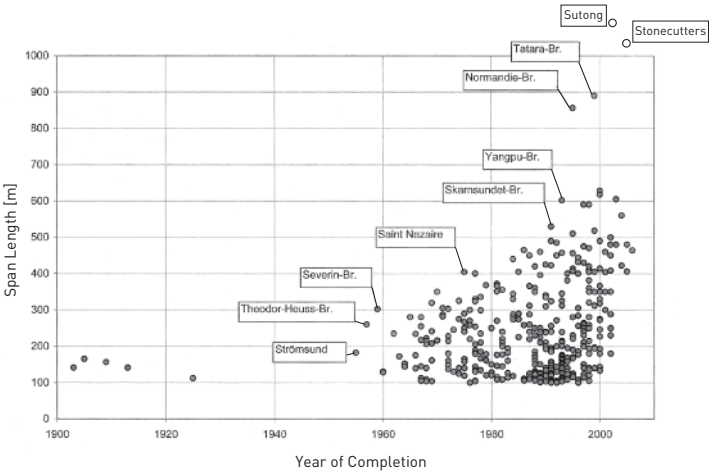


Figure 1.7 Development of main span lengths of cable-stayed bridges

for longitudinally eccentric loads, for which the main cables of a suspension bridge find a new equilibrium without increase of cable stresses (stressless deformations), whereas stay cables always have to be additionally stressed in order to carry any load.

Suspension bridges are thus generally not suitable for high railway loads: their deformations become too large.

The eigenfrequencies of cable-stayed bridges are significantly higher than those of suspension bridges. The torsional frequencies, which are especially important for the aerodynamic safety against flutter, can further be increased by using A-towers which omit the elasticity of the backstay cables, Fig. 1.5.

The critical wind speed for the onset of flutter is thus higher for cable-stayed bridges than for suspension bridges. The diagram in Fig. 1.6 shows that for a main span of 500 m the critical flutter wind speed for a typical cable-stayed bridge is about 200 km/h while for a corresponding suspension bridge it is only 100 km/h.

These advantages of cable-stayed bridges have become generally known worldwide since the 1970s, and since that time their number has increased strongly, Table 1.1. The total number of major cable-stayed bridges worldwide has currently reached about 1000.

The main span length of cable-stayed bridges has also increased dramatically, the longest currently being 1088 m, Fig. 1.7 [1.1].

Fritz Leonhardt and his collaborators have disseminated the above findings in lectures and publications all over the world since the 1970s, [1.2 – 1.9].

Table 1.1 Number of cable-stayed bridges until 2000

	1900 – 1950	1960	1970	1980	1990	2000	Σ
Japan				1	8	12	21
China						17	17
Germany		2	5	6	2		15
USA				2	7	4	13
Netherlands				2	1	2	5
France				2		2	4
USSR				1	1	2	4
Great Britain				1	1	2	4
other				3	9	21	33
Σ	0	2	5	18	29	62	116

1.1.2 Overall system

1.1.2.1 Cable arrangement

Cable-stayed bridges have at least one forestay and one backstay cable per tower. The forestays act like two piers omitted in the main span.

The first cable-stayed bridge across the River Rhine in the 1950s used relatively few stay cables, which comprised bundles of locked coil ropes, so that the distances between the cable anchorages at the beam were 40 to 60 m. Their anchorages and corrosion protection were difficult, and auxiliary tie-backs were required to overcome the large distances between the cables during construction.

The bridge designer, Hellmut Homberg (see Fig. 2.78), used many individual stay cables with distances of only 4.5 m for the Bonn North Bridge, which simplified decisively the structural detailing and the construction, Fig. 1.8. This design was trendsetting for the further development of cable-stayed bridges.

The number of stay cables is chosen advantageously in such way that for each stay only one cable is required so that the anchorages at the tower and at the beam become most simple.

With cable capacities now up to 20 MN, even for very wide bridges the distances between the cable anchorages at the beam can be 5 to 15 m, and even up to 20 m. Such small cable distances allow free cantilevering to be used without the need for auxiliary tie-backs during construction.

The reduction of cable distances at the beam over the years is shown in Fig. 1.9.

There are three basic cable arrangements in bridge elevation. With the fan arrangement, Fig. 1.10, all cables join at the tower head. With the harp arrangement, Fig. 1.11, all cables run parallel and are anchored over the height of the tower. The true fan arrangement can not be realized practically if the condition has been set that, in the case of damage, each individual cable must be able to be exchanged by reversing the installation procedure. This exchangeability requires individual cable anchorages to have certain minimum distances at the tower head.

In such way an intermediate cable arrangement between harp and fan is created, Fig. 1.12, which should be as close as possible to the fan arrangement due to its economical advantages. The harp arrangement, however, is aesthetically advantageous because there are no visual intersections of the stay cables, even for two cable planes in a skew view.

The arrangement of stay cables is also influenced by the relationship between side span and main span, and the location of the backstay anchorages, e. g. by connecting them directly above the piers in the side spans. The harmonic cable arrangement plays an important role in the aesthetic appearance of a cable-stayed bridge and has thus to be studied carefully from the very beginning of a design.

In addition to the basic arrangements mentioned above special configurations have been used.

The early South Elbe River Bridge used a star-shaped cable arrangement for which the few cables were separated at the towers in

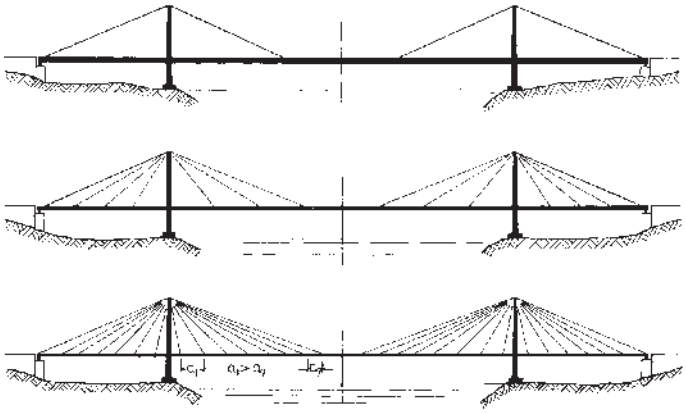


Figure 1.8 Development to multi-stay cable bridges

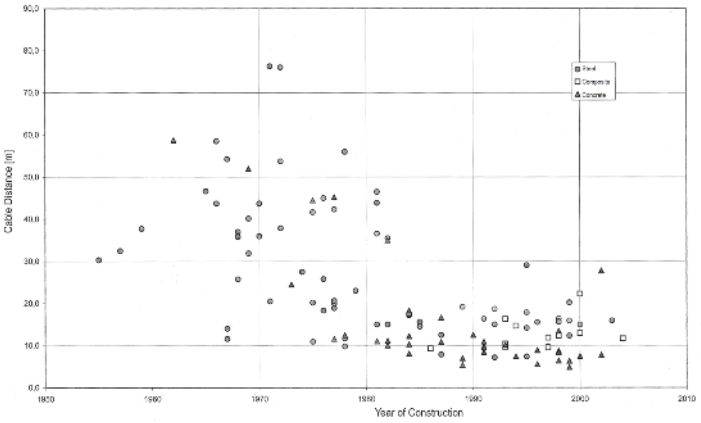


Figure 1.9 Development of cable distances at the beam



Figure 1.10 Fan system

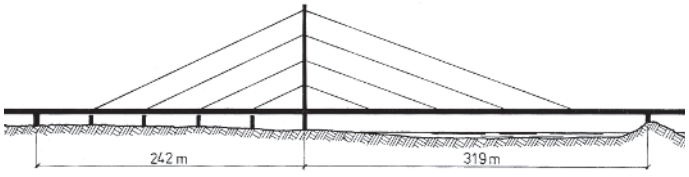


Figure 1.11 Harp system

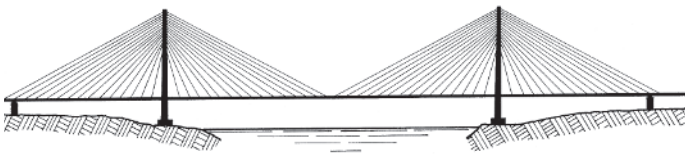


Figure 1.12 Intermediate system fan – harp

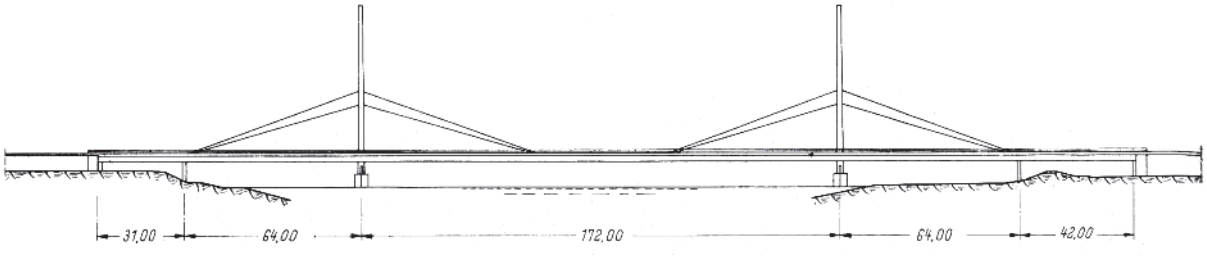


Figure 1.13 South Elbe River Bridge, star-shaped cable arrangement

order to simplify their anchorages, Fig. 1.13 [1.10]. Since the stays are still anchored together at the beam, this solution was not repeated.

For open cross-sections with low torsional stiffness two outer cable planes are required to carry eccentric live loads by a force couple. Hellmut Homberg (see Fig. 2.78) used mainly steel box girders for his designs. They have a high torsional rigidity and permit a central cable plane and also have a high bending stiffness so that a beam supported at the towers allows the removal of the first cables at both sides of the towers to some greater distance. This arrangement is called "Homberg's window", Fig. 1.14.

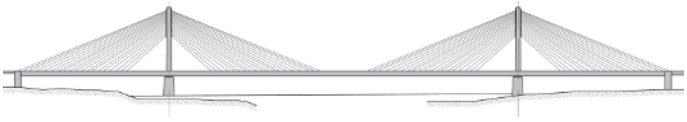


Figure 1.14 Bonn North Bridge, Homberg's window

The high negative bending moments above the tower piers can be carried by the box girder. This transfer of loads near the towers via shear and bending directly into the foundations is more economic than supporting the beam only by the cables.

The Rhine River Bridge at Ilverich is located in the vicinity of Düsseldorf airport. The normally required tower height of 110 m could thus not be realized because of air traffic safety requirements.

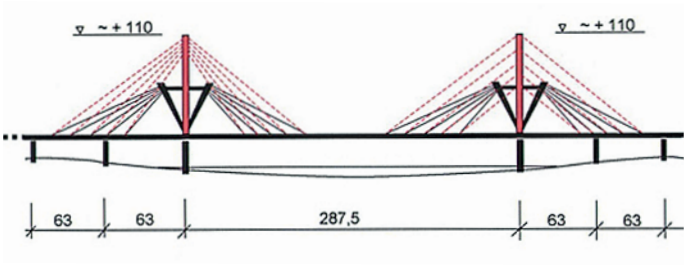


Figure 1.15 Rhine River Bridge at Ilverich, shortened towers

In order to avoid cables at too uneconomically flat an angle, each tower was split into two V-shaped legs and the backstay and forestay cable forces are carried by a tie, Fig. 1.15 [1.12].

1.1.2.2 Cable stiffness

The stiffness of cable-stayed bridges is governed by the stiffness of the stay cables, which is reduced by the cable sag, as given in the formula (1-1) by Ernst [1.13] (Fig. 1.16):

$$A_s E_{eff} = \frac{A_s E_0}{1 + \frac{\gamma^2 l_k^2 E_0}{12 \sigma^3}} \qquad (1\text{-}1)$$

A_s Cable Steel Area
E_0 Modulus of Elasticity for straight Cables
E_{eff} E-Modulus of Cable with Sag
γ Specific Weight of Cable including Corrosion Protection
l_k Horizontal Length of Cable
σ Tensile Stress in Cable

It gives the effective modulus of elasticity of a stay cable in relation to a straight vertical cable E_0, the specific weight of the cable γ, the horizontal projection of length l_k, and the steel stress σ. The steel stress is of major importance and occurs in the formula as the third power, Fig. 1.16.

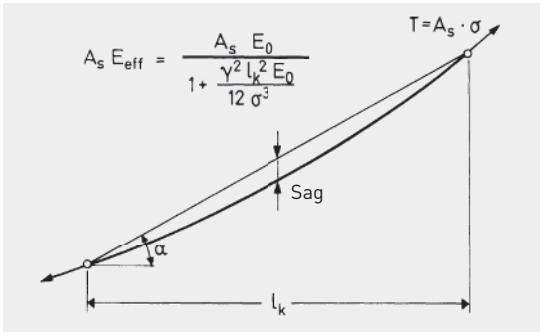


Figure 1.16 Effective stiffness of stay cables

The influence of the various parameters on the cable stiffness is shown in Fig. 1.17.

In order to achieve a high cable stiffness, a high cable stress is required. Therefore, high-strength steel as developed for prestressing tendons has to be used. The high dead weight of a concrete beam is advantageous in this respect. Assuming strands with a steel of 1660/1860 N/mm^2 and assuming a factor of safety for the ultimate limit state of 2.2, a service load stress of 845 N/mm^2 is reached. Assuming further a ratio of live load to dead load of 0.2, a cable stress of about 680 N/mm^2 can be used for the permanent load stage which governs the deflections of a cable-stayed bridge.

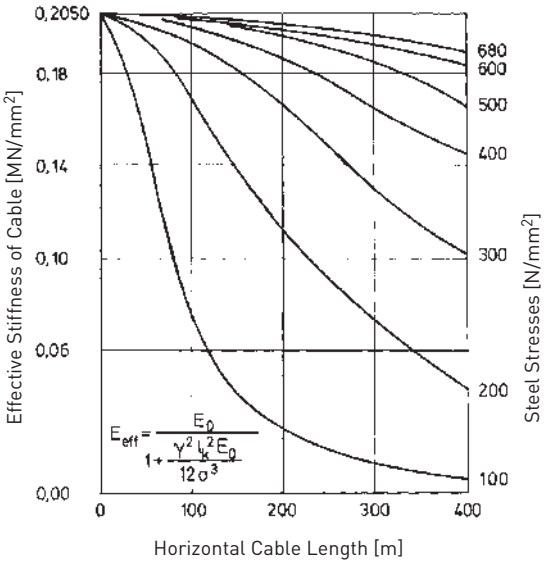


Figure 1.17 Relation between $E_{Effective}$ of cables, span lengths and steel stress

Fig. 1.17 shows that for such steel stresses the loss of cable stiffness is small.

1.1.2.3 Geometry

Main spans

In a first approximation the length of a side span comes to about 40 % of the main span for a concrete beam under road traffic loads. For a steel beam with railway loading this ratio may be reduced to 30 %.

The governing factor for the span ratio is the stress in the backstay cables. For the cable size required for the biggest backstay force with live load in the main span, the fatigue stress range for live load in the main and side span should not exceed the permissible range of, for example, 200 N/mm2, Fig. 1.18.

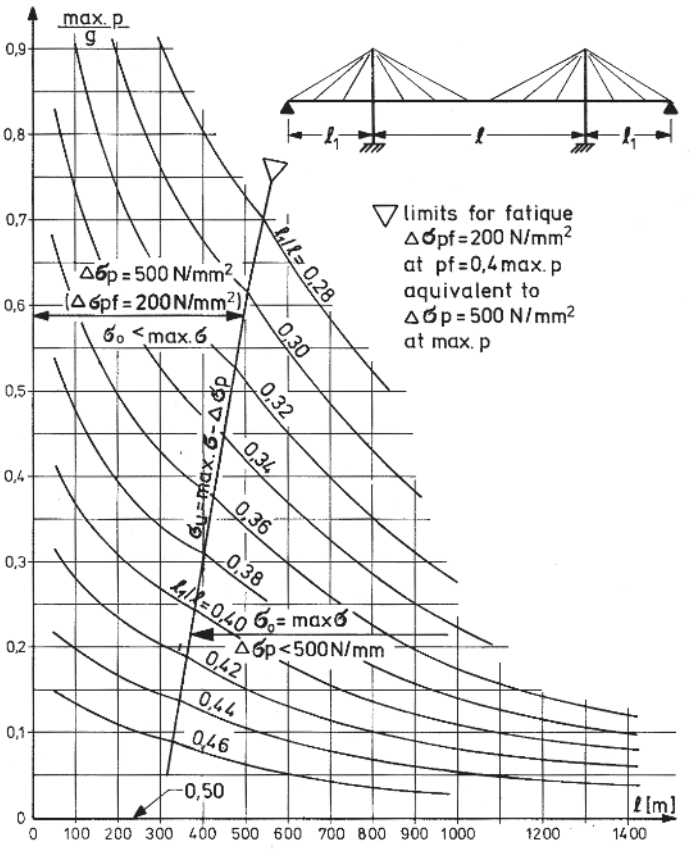


Figure 1.18 Relation between span ratios and backstay steel stresses

Tower heights

High towers reduce the required amount of cable steel and the compression forces in the bridge beam up to a cable inclination of 45°, but increase the costs for the towers themselves.

Optimizations indicate that tower heights of about 1/5 of the main span above deck achieve minimum costs for the whole bridge, Fig. 1.19.

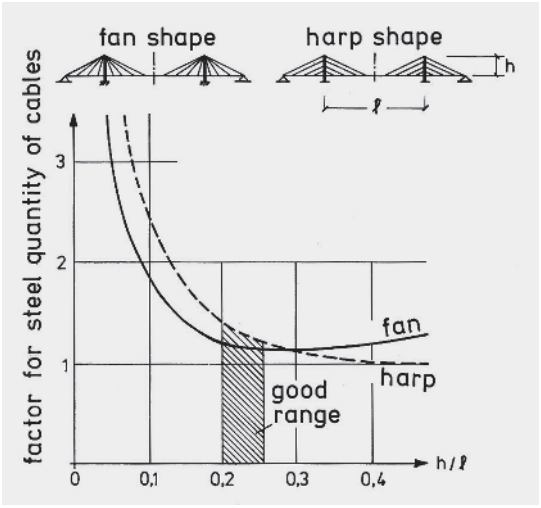


Figure 1.19 Relationship between tower height and amount of cable steel

Stiff towers

If the geometrical conditions require two equal spans with only one tower at the center, the tower height should be chosen so that the flattest cables have the usual inclination of about 27°. This gives a ratio of tower height to each main span of about 0.5.

Since there are no typical backstays, which restrain the tower head, the tower has to be stiff by itself. This is best achieved by towers that are A-shaped in the longitudinal direction, Fig. 1.20.

1.1.2.4 Support conditions

Longitudinal

The longitudinal support conditions for the beams of cable-stayed bridges are determined by the changes in lengths due to temperature, shrinkage and creep as well as longitudinal forces such as braking, wind and earthquake. A survey of the different support conditions with their advantages and disadvantages is given in Table 1.2 [1.14] for railway bridges which are especially sensitive in this regard.

For railway bridges high above ground the main problem is the high braking loads which are best distributed equally to both towers. A rigid connection to each tower, however, may create too high tower moments from the beam changes of lengths due to temperature and shrinkage and creep.

A compromise between these contradictory requirements are hydraulic buffers, which act as rigid connections between beam and towers for short-term loads such as braking or earthquake, but offer no resistance for slowly applied loads such as temperature, shrinkage and creep. Their disadvantage is that they require monitoring and

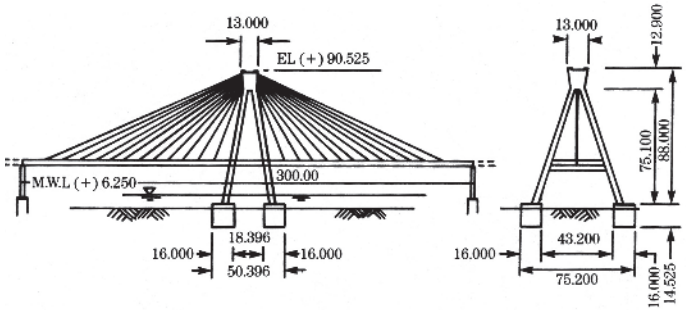


Figure 1.20 Olympic Grand Bridge, Seoul, Korea

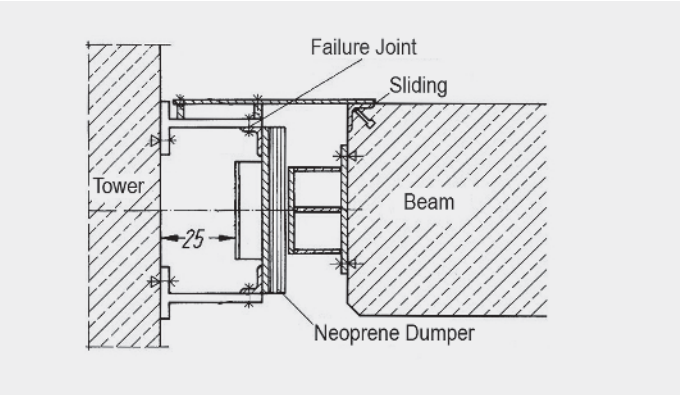


Figure 1.21 Transverse buffers at tower

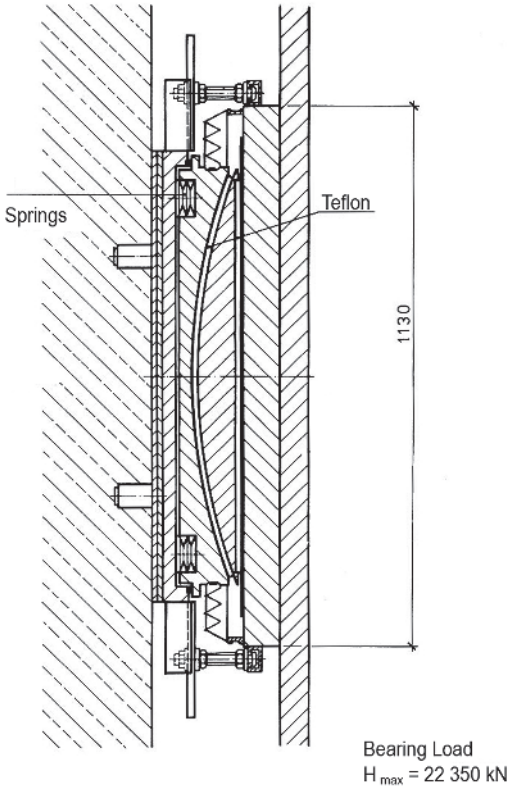


Figure 1.22 Post-tensioned transverse tower bearing

careful maintenance. A practical solution is to use high neoprene bearings which follow the beam deformations by inclination.

Another possibility, chosen in Japan, is to connect both towers with long cables to the beam so that the cables are elastically restrained by the beam deformations and thus both towers are equally loaded.

Transverse

The governing load for cable-stayed bridges in the transverse direction is wind on the cables, the towers and the beam. In many cases transverse buffers at the towers with little play can take the transverse beam loads, Fig. 1.21 [1.15].

Transversely post-tensioned bearings have been used where transverse movements are to be avoided, Fig. 1.22 [1.16].

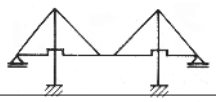
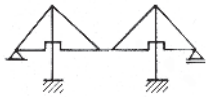
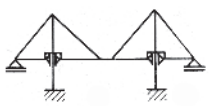
In order to cater for the horizontal bridge rotations at the abutments due to wind, a transversely fixed rotational bearing can be located in the center of the end cross girder. Should there be piers in the side span, their bearings can normally slide in the transverse direction in order to avoid undue restraints from the main span.

Anchor piers

At the anchor piers (hold-down piers) the uplift forces in the backstay cables from unbalanced loads in the main span have to be anchored. The simplest solution is to connect the beam directly to the anchor pier with the help of a rotational connection, Fig. 1.23. The anchor piers are stressed down into the foundations and have to be flexible enough to follow the longitudinal changes of length in the beam [1.17].

For a sliding support of the beam at stiff abutments pendulums have traditionally been used which extend deep into the abutments and are articulated at both ends. Especially with steel bridges it has to be taken into account that these pendulums may obtain both ten-

Table 1.2 Longitudinal support conditions

No.	System	Characteristics	Advantages	Disadvantages
1	Floating bridge beam 	Free deformations due to change of temperature Introduction of breaking forces into cables and towers	Same stresses and deformations for both halves of bridge	Large bending moments in towers and large horizontal movements of beam due to breaking and unsymmetrical live loads
2	One fixed bearing 	Free deformations due to change of temperature All horizontal forces act on one hold-down pier	Less deformations than in system 1	Strong forces on hold-down pier Longitudinally unsymmetric Large temperature movements in other hold-down pier
3	Hydraulic buffers at both towers 	Two fixed bearings for short-term loads Floating system for long-term loads	Small deformation of the symmetrical system Transfer of breaking forces onto both towers	System with variying support conditions depending on period of loading

sile and compression forces and thus have to be designed for fatigue. This is especially important for the end articulations.

The fatigue problem can be avoided if the beam is post-tensioned through the bearings against the anchor piers and thus a minimum compression force on the bearings is always ensured, Fig. 1.24 [1.18]. The longitudinal movements have again to be accounted for.

1.1.3 Tower shapes

The first cable-stayed bridges used steel towers. Since towers are mainly loaded by compression, concrete towers are more economical and, therefore, mainly used today. Only if extremely bad foundation conditions would require very long piles, are the lighter steel towers used today.

1.1.3.1 Two outer cable planes

The beams of cable-stayed bridges should normally be supported at the outsides in order to restrain the rotational deformations most effectively. This requires two cable planes, supported by two tower legs, Fig. 1.25. For small and medium spans vertical tower legs may be used. To stiffen them transversely they can be connected with cross beams. For longer spans the two tower legs should lean towards one another above deck in an A-shape, which provides increased torsional rigidity to the beam and stiffens the towers for transverse loads.

For bridge beams with a high clearance the two foundations for a straight A may be uneconomic. The two legs can then be pulled together underneath the beam to permit a common foundation.

1.1.3.2 One central cable plane

Only if one central cable plane is used, the cables for short and medium spans are anchored at one single tower at the bridge center



Figure 1.23 Articulated hold-down pier

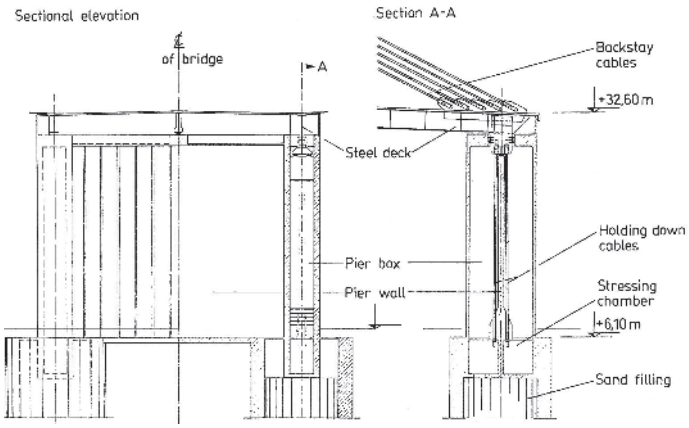


Figure 1.24 Prestressed pendulum

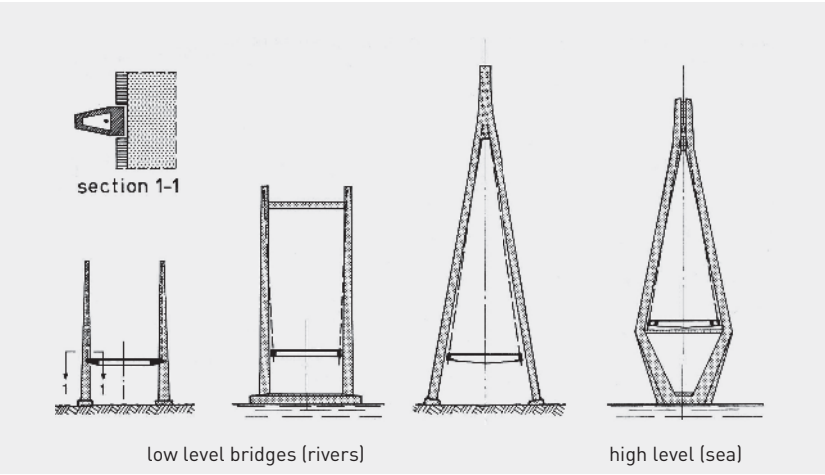


Figure 1.25 Towers for two cable planes

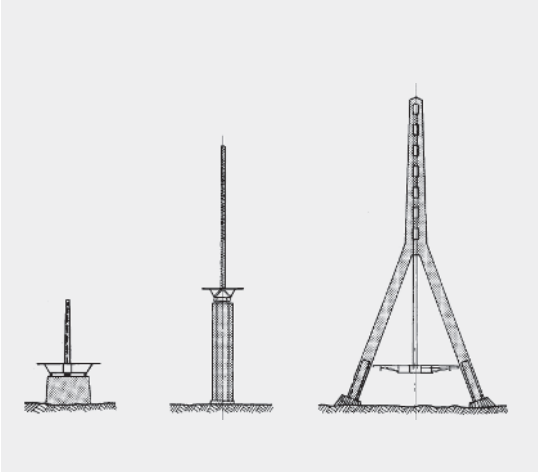


Figure 1.26 Towers for one cable plane

which is designed against lateral buckling, Fig. 1.26. For large spans the central plane can be anchored in the extended tip of an A-tower.

1.1.3.3 Spread central cable planes

If a cable-stayed bridge has to carry outer roadway lanes and central railway tracks it can be expedient to place the two tower legs in between the rail tracks and the roadway lanes. This results in partially spread tower legs, Fig. 1.27 [1.19]. The two cable planes are arranged parallel to the tower legs.

1.1.4 Beam cross-sections

Small cable distances result in small bending moments from the dead load in the beam. The live load moments are mostly restraint moments which decrease with the depth of the beam. Therefore, it is economic to choose a small depth for the beam, which is nearly independent of the span length. The limiting condition is the safety against buckling of the beam.

A further condition is to ascertain a minimum deflection radius under concentrated loads. This can easily be achieved for traffic loads even with slender beams, but railway bridges require larger beam depth.

1.1.4.1 Steel cross-sections

Steel cross-sections comprise an orthotropic deck supported by the main and cross girders. All beam members act together for the local and global loads.

Two outer cable planes

Open cross-sections: For short to medium spans the torsion from eccentric live loads can be carried by a couple in the outer cable planes. Open cross-sections with little torsional resistance can thus be used, Fig. 1.28 [1.20].

Box girders: Long spans may require the use of a box girder even with two outer cable planes in order to achieve the required torsional stiffness. An example is the current world record span holder, the Sutong Bridge in China, with a main span of 1088 m, Fig. 1.29 [1.21].

Separate beams: The Stonecutters Bridge in Hong Kong has a central tower with two outer cable planes. In order to provide the necessary space for the tower, two separate beams connected by cross girders are used, Fig. 1.30 [1.22].

One central cable plane

A central cable plane requires a box girder cross-section in order to carry the torsional moments. A typical example is the beam for the Rhine River Bridge at Ilverich, Fig. 1.31 [1.12].

Spread central cable planes

Open cross-sections: For the two spread central cable planes at the Rhine River Bridge Mannheim-Ludwigshafen two box girders provide the required torsional stiffness, and transverse bending is



Figure 1.27 Tower for partially spread central cable planes

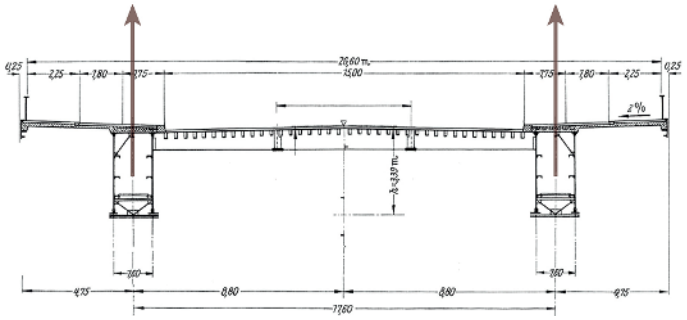


Figure 1.28 Open steel cross-section

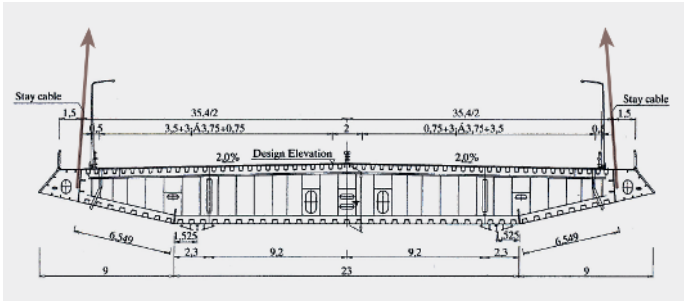


Figure 1.29 Steel box girder



Figure 1.30 Separate steel beams connected by cross girders

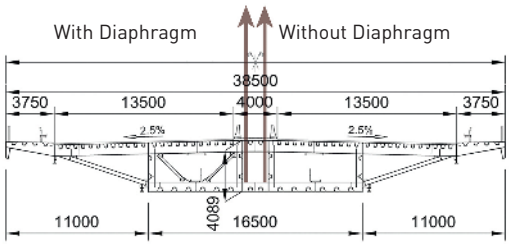


Figure 1.31 Steel box girder

carried by the cross girders, Fig. 1.32 [1.19]. The area between the two boxes is used by two tramway tracks which are lowered in one end region.

Box girders: The railway tracks in the center of the Sava River Bridge Ada Ciganlija, Fig. 1.33 [1.23], remain on top. The two spread central cable planes are anchored at the outside of the central box. For introduction of the cable forces into the 45 m wide beam additional webs are used.

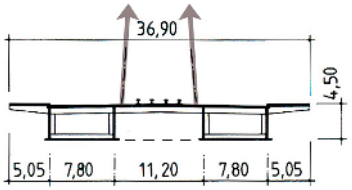


Figure 1.32 Separate steel boxes

1.1.4.2 Concrete cross-sections

The shape of concrete cross-sections is determined from similar considerations to steel cross-sections. It has, however, to be taken into account that concentrated tensile forces have to be carried by tendons.

Two outer cable planes

Open cross-sections: The open cross-section of the Pasco-Kennewick Bridge has triangular boxes at the outsides for aerodynamic reasons, Fig. 1.34 [1.15]. Transverse bending is carried by cross girders which are post-tensioned across the whole beam width. Additional short tendons transfer the cable forces via the inclined slabs into the main girders.

Box girders: For two cable planes and medium spans, box girders are generally not required.

For the Posadas-Encarnación Bridge in Argentina a box girder was selected due to the eccentric railway track, Fig. 1.35 [1.24]. The transverse stiffening of the box was achieved by individually post-tensioned transverse stiffeners from precast elements which carry tension and compression.

Solid cross-sections: The elastic support of the beam from the stay cables provides a good distribution of heavy single traffic loads. For smaller spans a solid slab may be used, Fig. 1.36 [1.25]. In this case the transverse slenderness ratio comes to 1 : 23.5.

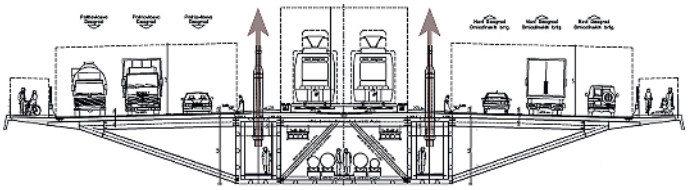


Figure 1.33 Steel box girder with wide cantilevers

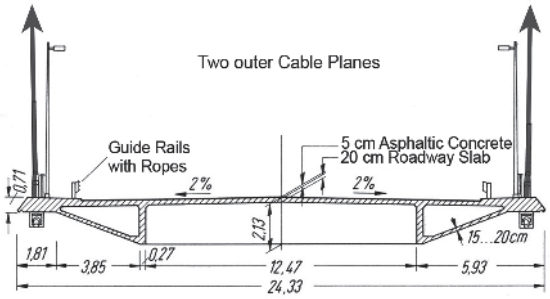


Figure 1.34 Open concrete cross-section

One central cable plane

A central cable plane also requires, for concrete beams, a box girder to carry the torsional moments from eccentric live loads.

For the Brotonne Bridge in France the cable forces are transmitted to the webs by post-tensioned diagonals, Fig. 1.37 [1.26].

The transverse distribution can also be achieved with cross girders, but larger quantities are required.

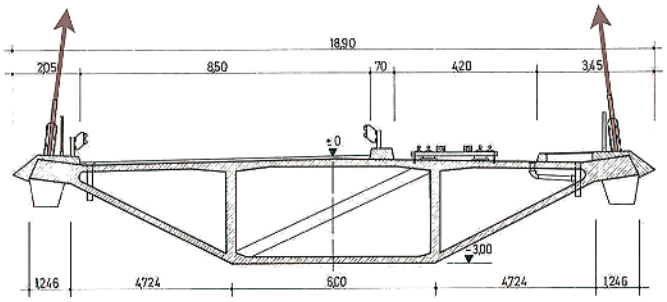


Figure 1.35 Concrete box girder

Spread central cable planes

The cables of the two spread central cable planes of the Second Main River Bridge at Hoechst are directly anchored to the webs of the central box girder, Fig. 1.38 [1.27].

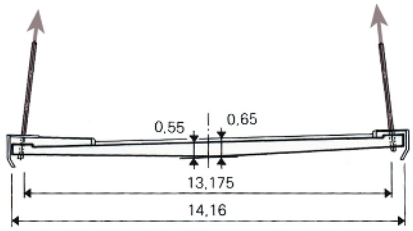


Figure 1.36 Solid cross-section

1.1.4.3 Composite cross-sections

Composite cross-sections use a concrete roadway slab as the top flange of the steel main and cross girders, connected by shear studs.

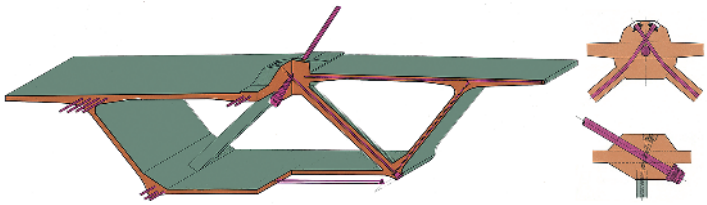


Figure 1.37 Concrete box girder

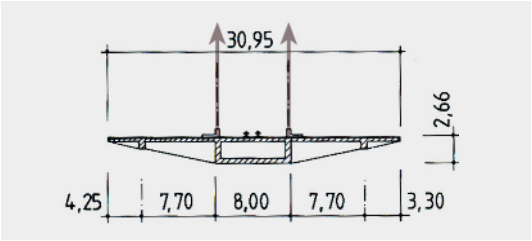


Figure 1.38 Concrete box girder

The concrete slab should always be under compression in both directions: longitudinally by the compression forces from the inclined cables, transversely as the top flange of a single-span girder between the two outer cable planes. Central cable planes should not be used for composite cross-sections.

The roadway slab can be built cast-in-place or from precast elements. The latter have the advantage that their shrinkage and creep is smaller after installation due to their advanced age. It has to be ascertained that the joints do not form weak spots during the life of the bridge. A typical composite cross-section is given in Figs 1.39 and 1.40 [1.28].

1.1.4.4 Hybrid beams (steel/concrete)

Hybrid cable-stayed bridges comprise a steel beam in the main span and a concrete beam in the side spans. The heavier concrete beam serves as a counterweight to the lighter steel main span. Both cross-sections are coupled at or near the tower with shear studs and tendons if the compression force from the cables is not sufficient to overcome local tensile forces from bending.

Two outer cable planes

The Normandy Bridge uses a flat steel box girder for aerodynamic stability in the main span of 856 m which is balanced by a similarly shaped concrete beam in the side spans, Fig. 1.41 [1.29]. The concrete beams extend some 100 m on both sides into the main span, Fig. 1.42.

One central cable plane

For the Rhine River Bridge, Flehe, steel and concrete box girders are used with a central cable plane, Figs 1.43 and 1.44 [1.16]. They join in the tower axis.

The side spans rest on outside piers. The support reactions are reduced by the central backstays in the cable anchorage region.

1.1.4.5 Double deck cross-section

If a multi-lane freeway has to be carried together with two railway tracks the railway may be placed on the lower level. This requires about an 8 m deep beam, for which a truss is often selected in order to permit a free view for the railway passengers during the long ride.

Two outer cable planes

For the Öresund Bridge in Denmark the cable forces are introduced by triangles into the lower and upper chord of the truss, Fig. 1.45 [1.30].

These are arranged as outriggers so that the beam can pass between the tower legs, Fig. 1.46.

One central cable plane

The third Orinoco Bridge carries only a single railway track on the lower chord. The truss can thus be supported by a single cable plane attached to the short upper cross girders between the directional traffic lanes, Fig. 1.47 [1.31].

The cable forces are transmitted by bending in the cross girders into the truss diagonals, the required torsional stiffness being provided naturally by the truss.

1.1.5 Stay cables

Stay cables are the characteristic structural components of cable-stayed bridges. Their performance governs the behavior of the complete bridge, not only in the final stage but also during construction. The durability of the stay cables determines the robustness of a cable-stayed bridge.

1.1.5.1 Systems

The currently used stay cable systems are locked coil ropes, parallel wire cables and parallel strand cables as outlined in Table 1.3.

For economic reasons parallel strand cables are mostly used worldwide today. Even in Germany, where until now mainly locked coil ropes have been used, the latest two cable-stayed bridges were provided with parallel strand cables. They are fabricated rather similarly by all major fabricators worldwide, Fig. 1.48 [1.32].

The strands are anchored with profiled wedges in anchor blocks. The depths of the wedge teeth increase gradually so that they anchor the strands safely, but reduce their fatigue strength only slightly.

The corrosion protection for every single strand comprises the following:

- galvanizing of every single wire in the strand
- filling the interstices between the single wires with grease
- surrounding each strand with a directly extruded PE-sheath.

Such strands are called monostrands.

A number of these monostrands are combined into a cable, for which all strands are covered additionally by a PE pipe, Fig. 1.48. At the transition from the free length to the anchorage region the strands spread out, the radial forces are contained by a clamp. A damper may be positioned at this location.

The installation of these stay cables takes place on site by assembling the individual components. The monostrands are pulled into the PE pipe. Each strand is individually stressed in such way that after complete cable assembly all strands have the same stress. It is possible to restress the complete cable with a large jack. Single strands may be exchanged later individually.

1.1.5.2 Cable anchorages

The stay cables typically run through a steel pipe to their anchor points. There split shims prevent sliding of the anchor heads. The lengths of the cables and thus their forces can be adjusted by changes in the thickness of the shims.

Support nuts around the anchor head can also be used for retaining the anchor head and adjustment of cable lengths.

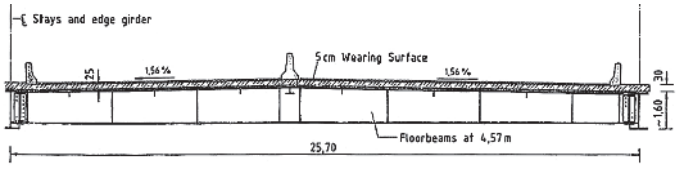


Figure 1.39 Typical open composite cross-section

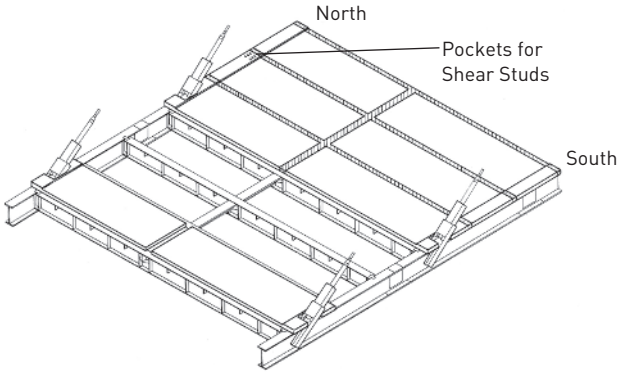


Figure 1.40 Typical composite beam

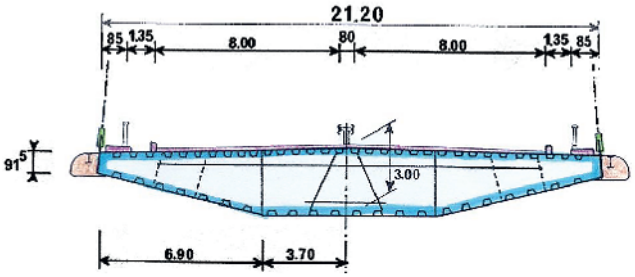


Figure 1.41 Main span steel cross-section of the Normandy Bridge, France

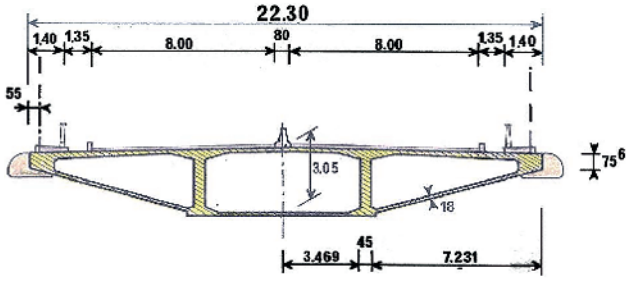


Figure 1.42 Side span concrete cross-section of the Normandy Bridge, France

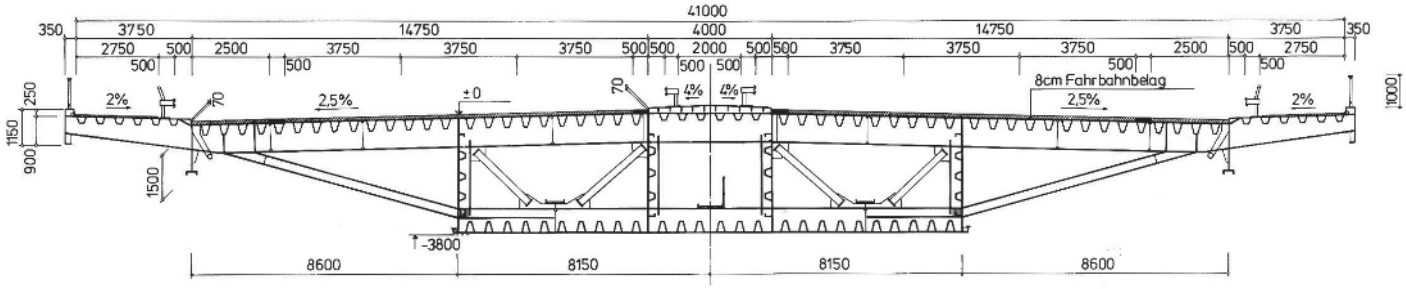


Figure 1.43 Main span steel cross-section for the Rhine River Bridge, Flehe, Germany

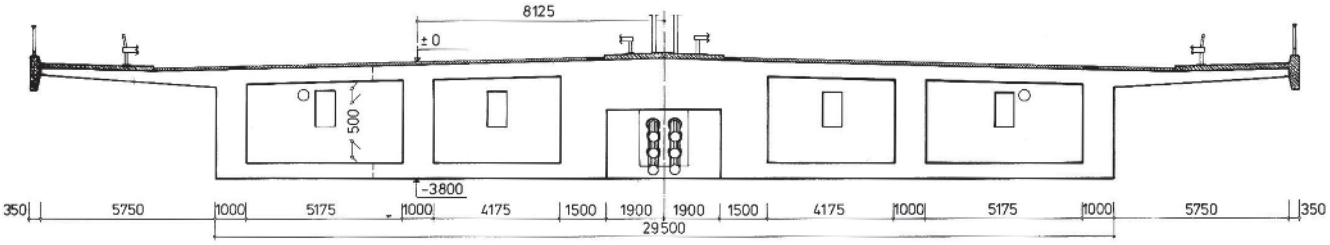


Figure 1.44 Side span concrete cross-section for the Rhine River Bridge, Flehe

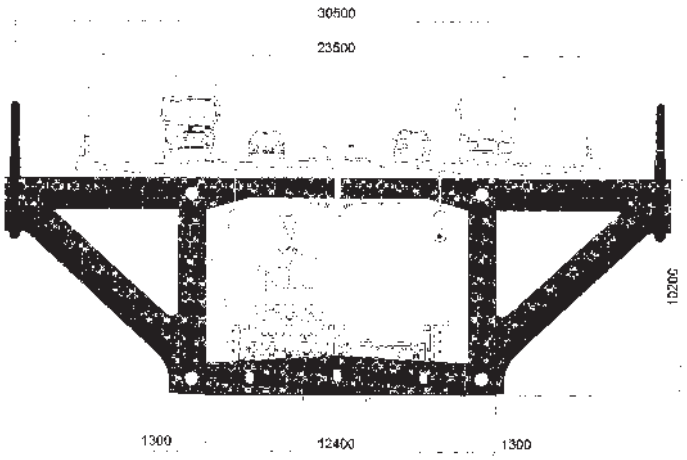


Figure 1.45 Truss beam of the Öresund Bridge, Denmark–Sweden



Figure 1.46 Cable anchorage of the Öresund Bridge

At beam

In concrete: A typical cable anchorage at a concrete beam is shown in Fig. 1.49 [1.15]. The cable forces are directly introduced into the main girder. The anchor head is supported by shims on pressure plates welded to the end of the steel pipe which transfer the cable forces either directly or via the steel pipe and shear rings into the concrete, where the tensile forces are covered by reinforcement.

At the tip of the steel pipe the cable is centered and possibly dampened by an elastomeric ring. The weather-resistant closure of the steel pipe is ensured by a neoprene boot clamped to the steel pipe and the stay cable.

In steel: A direct introduction of the cable forces into the main girder web is shown in Fig. 1.50 [1.33]. The web is extended with a butt weld through an opening in the top flange. A steel pipe is welded into this web extension to which the anchor head is attached with split shims or a support nut.

At the tower

In concrete: The simplest way to anchor individual cables at the tip of a concrete tower is to overlap them and thus to anchor them by compression, Fig. 1.51.

Usually the stay cables are anchored inside a tower box section, similar to that shown for a concrete beam. The tensile forces between forestays and backstays can be covered by short tendons, Fig. 1.52.

In steel: If the ideal fan shape of the cables is to be achieved they have to be split sideways into several planes. An example is the steel anchor head in Fig. 1.53, within which the cable forces are introduced into the longitudinal plates.

Usually the cables are spread vertically in their planes in order to obtain sufficient space for vertically aligned anchorages. This leads to a modified fan cable arrangement in elevation, Fig. 1.54. The tensile forces are also transferred into the longitudinal plates.

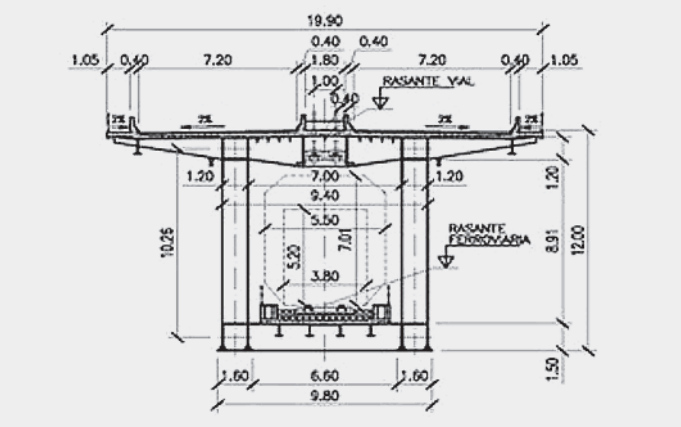
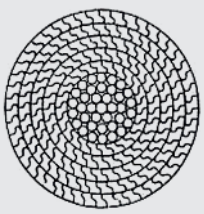
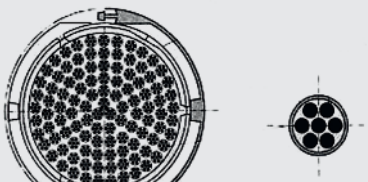


Figure 1.47 Truss for the third Orinoco Bridge, Venezuela

Table 1.3 Current stay cable systems

Characteristics		Modern locked coil rope	Parallel wire cable	Parallel strand cable
				
$E \cdot 10^{-6}$	[N/mm^2]	0.170	0.205	0.195
f_u	[N/mm^2]	1470	1670	1870
$\Delta\sigma$	[N/mm^2]	150	200	200

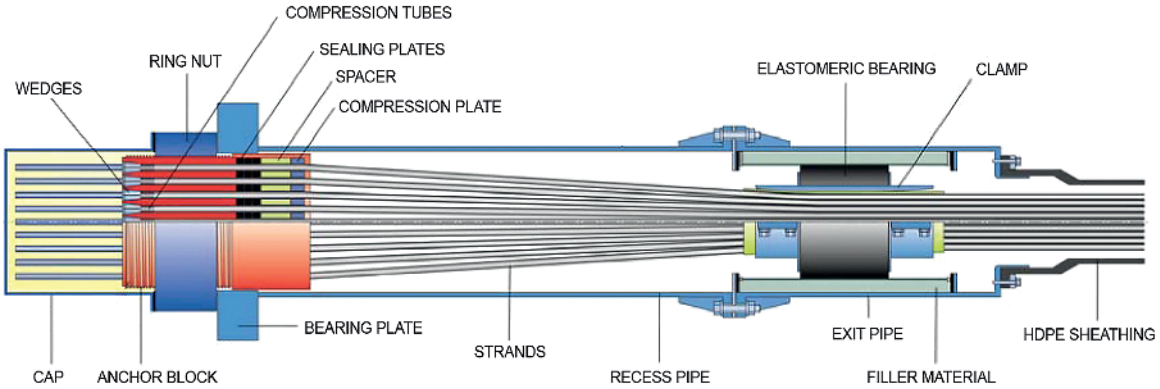


Figure 1.48 Typical parallel strand cable (DSI)

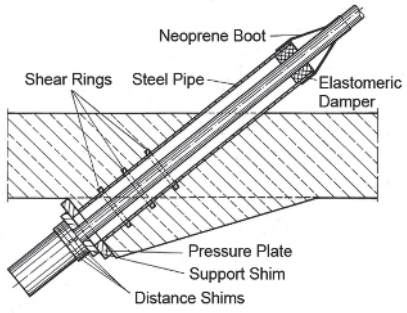


Figure 1.49 Typical cable anchorage in concrete

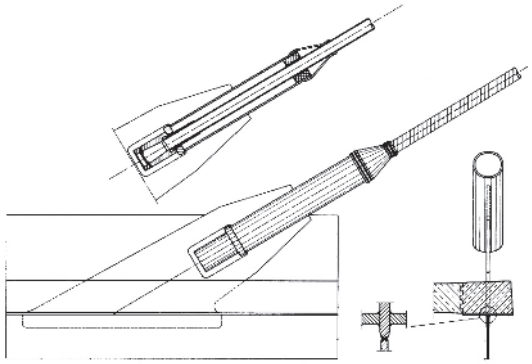


Figure 1.50 Typical cable anchorage in steel

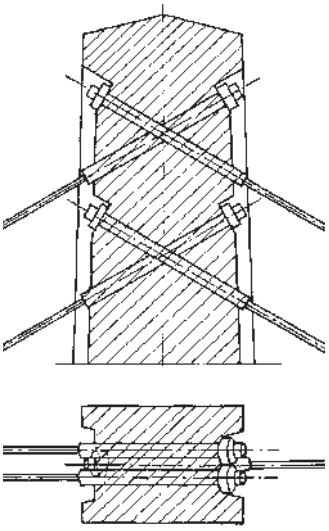


Figure 1.51 Cable anchorage by overlapping

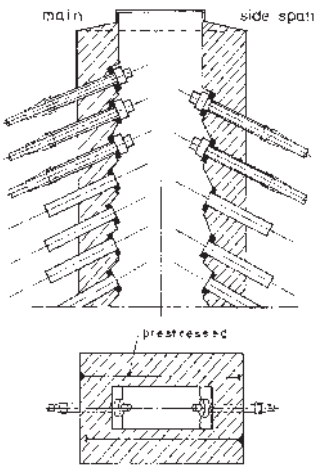


Figure 1.52 Cable anchorage inside a box

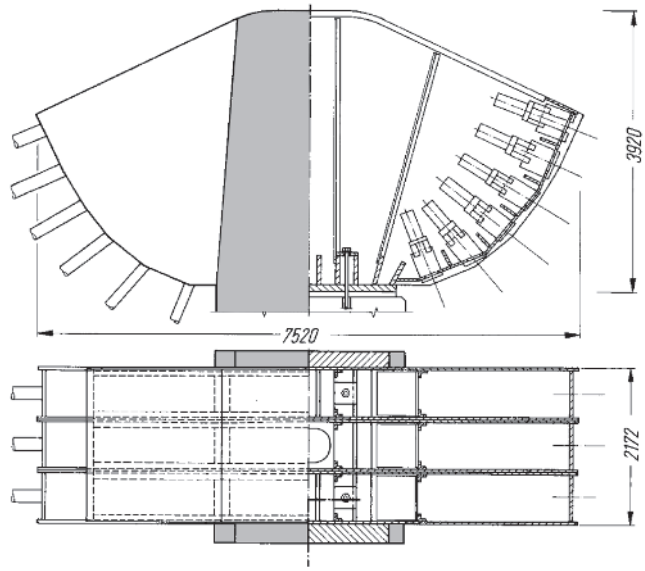


Figure 1.53 Steel tower head for fan arrangement

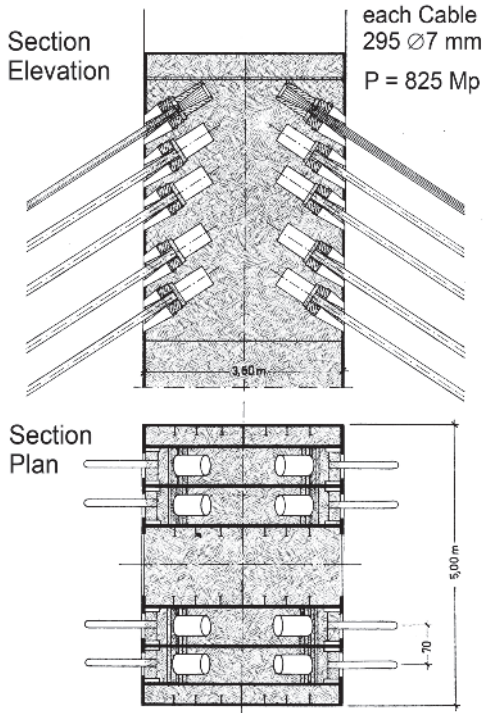


Figure 1.54 Modified fan arrangement

1.2 Aesthetic guidelines for bridge design

1.2.1 Introduction

In his ten books on architecture the Roman architect Marcus Vitruvius Pollio stated in Latin brevity and precision the three most important requirements for a structure as *firmitas*, *utilitas* and *venustas*. We will deal here with the *venustas*, the beauty.

There are no special aesthetic rules for cable-stayed bridges; they have to fulfill the same criteria as all other bridges. Their long spans, however, require stiff structures which can withstand, for example, heavy wind loads. Cable-stayed bridges, therefore, have to be designed taking carefully into account their aesthetics. A comparison with other types of bridges is interesting.

It is generally true that there are good-looking bridges which contribute favorably to the appearance of a city or a landscape and which are admired by most people, and there are ugly bridges which disturb the environment so that many people wish they had never been built or could be demolished. Why is one bridge considered beautiful and another one ugly?

It is true that the majority of people will judge one particular bridge in a group to be beautiful and another one to be ugly. Bridges have aesthetic characteristics which achieve the same reaction in different people. This effect depends on the individual's sensitivity and aesthetic education.

The competence of judging aesthetics develops only by repeated evaluation of consciously perceived values, and by training in visual appreciation. Aesthetic judgment thus has to be learned.

In his book *Bridges* [1.34], Fritz Leonhardt has pointed out that good-looking bridges are not designed by chance. There is no difficulty in defining 'feeling' which is particular only to a selected few, but there are aesthetic guidelines by which a design can consciously be reviewed.

Traditionally, there are two aesthetical points of view in structural engineering. The one, more technical point of view, is based on rational considerations and can be summarized with 'form follows function'. The history of bridges has, however, shown that a functionally rational design is not necessarily beautiful.

The other point of view refers to more intuitive impressions which are generally considered to be individually different. The catchwords are *'De gestibus non est disputandum'* – meaning 'Beauty lies in the eye of the beholder'. In his treatise *On Grace and Dignity* [1.35] the German poet Schiller has combined these two apparent contradictions at a higher level, so to say, dialectically. He shows that classical beauty fulfills rational, conscious requirements as well as intuitive subconscious requirements. In the following we will deal with the conscious requirements.

Ten guidelines for the aesthetic design of bridges are introduced. But these guidelines should not limit the freedom of intuition and fantasy. Good designs always depend on the talent of the designer, their sensitivity for aesthetics and their training in evaluation of the appearance. The guidelines can, however, support the rational evaluation of designs. Good designs are normally the result of such critical analysis, which, step by step, may lead to improvements.

In the following, cable-stayed bridges are shown as examples for each aesthetic guideline, but their relevance for other bridge types is also demonstrated.

1.2.2 Aesthetic guidelines

1.2.2.1 Guideline 1: Clear structural system

'Choice of a convincing and simple load-bearing system'

A bridge must look trustworthy and stable.

A mixture of different statical systems often leads to a bad appearance. The number of different load-bearing elements should be reduced to a minimum. A statically correct system, on the other hand, is not necessarily beautiful.

The Caroni River Bridge for road and rail near Ciudad Guyana in Venezuela has the remarkable main span of 214 m, Fig. 1.55. Although the girder requires a structural depth of 14 m above the piers, the bridge does not appear clumsy due to the dynamic run of its strongly curved underside.

This is possible because road and rail are both located on the deck and the railway does not run inside the box as often done elsewhere. Therefore, a structural depth of 4.8 m in the center is sufficient. The beam depth corresponds to the run of moments for a continuous three-span girder. Only two load-bearing structural members are used, the beam and the piers, both strong and trustworthy.

The Weitingen Bridge, Fig. 1.56, crosses the Neckar Valley high above ground as a multi-span continuous girder. The constant beam depth underlines its continuity. In addition to the two main load-bearing structural members, the beam and the piers, the 216 m long side spans are stayed from underneath with an air strut. This emphasizes the high moments at these locations.

Prof. Hans Kammerer acted as architectural advisor to the bridge engineer Fritz Leonhardt.

The competitive design for an arch bridge across the Svinesund between Norway and Sweden has a convincing structural system. The arch is fixed to the rock slopes at both sides of the valley, its structural depth increasing with the run of moments from the center to the outsides, Fig. 1.57.

The roadway is hung from the arch. Its slenderness offers a contrast to the strong arch. The hangers are visually intersecting although they are vertical. This is due to the inclined arches – a definite disadvantage of inclined arches.

The competitive design for the Stonecutters Bridge in Hong Kong shows how transparently a cable-stayed bridge can be designed, even for a record span of 1007 m, Fig. 1.58.

A suspension bridge with a main span of 1210 m like the Höga Kusten Bridge in Sweden, Fig. 1.59, cannot be outclassed in clarity, simplicity and elegance. This aesthetic advantage of suspension bridges over cable-stayed bridges is undeniable.

The main cables carry the loads from the slender beam via the hangers and the concrete towers to the abutments. Four structural elements are used: Beam, hangers, main cables and towers.

1.2.2.2 Guideline 2: Good proportions

'*Good proportions in all three dimensions between the structural members or between lengths and heights of the bridge spans*'

A balanced ratio must exist between the structural elements, the lengths and heights of the spans, between the lit and shadowed areas as well as the masses of beam, piers and abutments.

Good proportions between span lengths and heights of the piers are important. They have to be distinctly different, resulting in lying or standing rectangles – squares appear dull.

For a bridge across a valley the ratio between span lengths and heights should be approximately kept constant.

One example is the spans for the Mosel Valley Bridge at Winningen, Fig. 1.60. Their span lengths and height above ground increase from the outside to the center. The main span rectangle with 240 m span and 120 m height has the aesthetically attractive ratio of 2 : 1.

The up to 180 m high piers of the Kocher Valley Bridge with spans of 130 m have a parabolic shape in the transverse direction. This outline provides an elegant appearance, Fig. 1.61. In spite of the large dimensions a monumental impression is avoided because the bridge fits the deep valley.

The attractive appearance of the haunched three-span girder of the Cologne-Deutz Bridge, Fig. 1.62, results from the good ratio of beam depths over the piers and in the bridge center of 2 : 1. This is also because, at the bridge ends, the beam depths are equal to those in the bridge center, and because the undersides of the beam run parallel to the bridge deck. Adhering to these rules will nearly always result in a good-looking bridge.

This is also apparent for the bridge across the Severn River in the USA, Fig. 1.63. For its 90 m main span a haunched continuous girder was also selected with a depth ratio of about 2 : 1 and a continuous transition from main span to side spans. The beam depth in the bridge center is equal to those of the side spans. This clear system underlines the main span and provides the otherwise tranquil bridge with a certain dynamic.

V-piers require a roadway gradient with just the right height above ground to achieve good-looking triangles, Fig. 1.64. The beam of the railway bridge across the Main River as part of the new high-speed railway line between Hannover and Würzburg is slightly haunched in order to emphasize the 130 m main span.

Arch bridges require distinctly different depths between the arch proper and the beam, at least in a ratio of 2 : 1 or 1 : 2. Equal structural depths between beam and arch appear dull. For the tied arch of the Elbe River Bridge at Tangermünde the bending stiffness is provided by the composite beam, Fig. 1.65, which carries the beam depths of the long approaches across the main span. The steel arches can thus be slender.



Figure 1.55 Third Caroni River Bridge for road and rail, Venezuela



Figure 1.56 Weitingen Bridge across Neckar Valley, Germany



Figure 1.57 Competitive design (LAP) for the Svinesund Bridge between Norway and Sweden



Figure 1.58 Runner-up design for the Stonecutters Bridge, Hong Kong (LAP)



Figure 1.59 Höga Kusten Bridge, Sweden



Figure 1.63 Annapolis Bridge, USA



Figure 1.60 Mosel Valley Bridge at Winningen, Germany



Figure 1.64 Railway Bridge Gemünden across the Main River at Würzburg



Figure 1.61 Kocher Valley Bridge, Germany

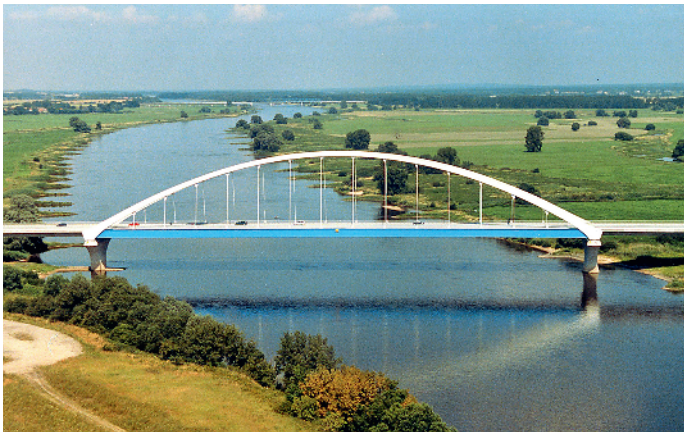


Figure 1.65 Elbe River Bridge at Tangermünde, Germany



Figure 1.62 Rhine River Bridge, Cologne-Deutz, Germany



Figure 1.66 Bridge across Roosevelt Dam, Arizona, USA

The fixed arch across the Roosevelt Dam in Arizona carries the bending stiffness in the strong, haunched arches proper. The roadway slab can thus be very slender, Fig. 1.66.

The beam of the Pasco-Kennewick Bridge has a depth of only 2.1 m for a main span of 300 m and thus appears slender, Fig. 1.67. This impression is heightened by the only 40 cm deep white-colored edge girder. The actual beam depth nearly disappears behind the shadowed inclined underside. The impression of a ribbon spanning the river is created.

1.2.2.3 Guideline 3: Good order

'Good order of all lines and edges of a structure which determine the appearance – the number of directions should be minimized.'

The number and directions of the structural elements should be minimized, especially for trusses. Symmetry and repetition of equal elements should lead to good order as long as monotony does not prevail.

The truss for the Hammerbrook Railway Bridge in Hamburg comprises only rising and falling diagonals which create an orderly impression even for a skew view, Fig. 1.68.

The railway bridge across the Main River near Nantenbach, Fig. 1.69, comprises only rising and falling diagonals as well, but with no cross frames in order to reduce the member directions to the minimum of two. The inclination of the diagonals remains nearly constant in spite of the changing depth of the girder so that no glancing intersections are present.

Although this is the railway bridge with the longest span in Germany, 207 m, it appears light.

In contrast typical 19th century trusses give a bewildering impression with a multitude of truss members in all directions. An example is the Howrah Bridge across the Hooghly River in Calcutta, Fig. 1.70.

The new Hooghly River Bridge in Calcutta, Fig. 1.71, by contrast, is designed as a cable-stayed bridge with clear lines. Even the regular arrangement of the longitudinal and transverse girders shows good order in a view from underneath, and this is continuously repeated without creating monotony.

The shape of the towers and the cable arrangements determine the appearance of a cable-stayed bridge. Visual intersections of the stay cables play an important role.

A parallel arrangement of the stay cables in a harp shape shows the best order as demonstrated by the Oberkassel Bridge, Fig. 1.72. One cable plane naturally does not provide intersections. During the initial design phase of the Düsseldorf Bridge Family in the early 1950s the city architect Friedrich Tamms insisted that all three bridges have stay cables in harp arrangements. Although the structural systems of the bridges are quite different, the common harp-shaped cable arrangement visually unites them into a bridge family.

Even two harp-shaped cable planes do not show intersections, Fig. 1.73, independent of whether the planes are vertical or inclined.



Figure 1.67 Pasco-Kennewick Bridge across the Columbia River, WA, USA



Figure 1.68 Hammerbrook Railway Bridge, Hamburg, Germany



Figure 1.69 Railway Bridge across Main River at Nantenbach, Germany



Figure 1.70 Howrah Bridge, Calcutta, India

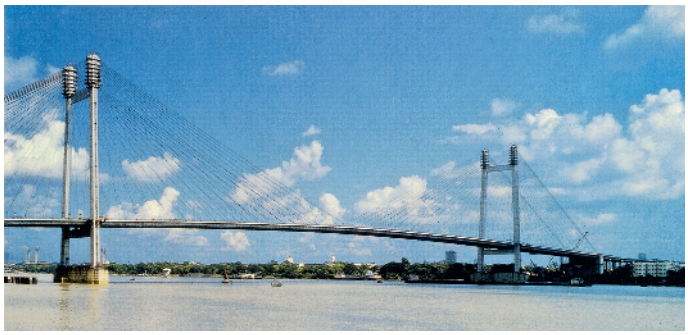


Figure 1.71 Hooghly Bridge, Calcutta, India



Figure 1.72 Rhine River Bridge Oberkassel, Germany



Figure 1.73 Heinola Bridge, Finland



Figure 1.74 Stonecutters Bridge, Hong Kong, China

If the stay cables are arranged with changing inclinations in a fan shape, visual intersections can only be avoided if a single central plane of cables is used, as for example for the Stonecutters Bridge in Hong Kong, Fig. 1.74. Dissing and Weitling from Denmark were the architectural advisors to the bridge engineer, Ian Firth.

With two fan-shaped cable planes visual intersections can be mitigated by the use of an A-tower with inclined cable planes, Fig. 1.75.

This disadvantage of intersections can further be reduced if the number of cables becomes very large, Fig. 1.76, and the impression of a veil is created.

The bridge across the Houston Ship Channel in Texas, Fig. 1.77, requires eight lanes with full shoulders. The most economic system comprises two independent cable-stayed bridges with two diamond shaped towers, interconnected at beam level. This results in good order for the bridge with four cable planes. The many cables also approach the appearance of a veil and the visual cable intersections are somewhat mitigated.

1.2.2.4 Guideline 4: Integration into the environment

'Harmonic integration of the bridge into its environment'

The material and the scale of the bridge in comparison to its immediate surroundings are the subject of this guideline.

An impressive example is the Upper Havel River South Bridge, Fig. 1.78. The piers extend upwards on both sides of the bridge and use the same brownstones as the surrounding residential buildings. Prof. Walter Nöbel from Berlin was the architectural advisor for this project.

A further example for adapting a bridge design to its immediate urban surroundings is the Humboldt Harbor Bridge in Berlin, Fig. 1.79. The deviation from the normal use of materials – concrete for compression members and steel for tension and bending – was chosen here to adjust the bridge appearance to the adjacent steel-glass structure of the new Main Railway Station. Both bridge and station have been jointly designed by the architect Volkwin Marg and the engineer Jörg Schlaich.

The second freeway bridge across the Oder River near Frankfurt was built for aesthetic reasons as a series of arches similar to the existing arch bridge.

Although this bridge system is not economic today, it fits the beautiful undisturbed landscape along the Oder River, Fig. 1.80.

The bridge across the Severn River in front of the famous Annapolis Naval Academy won a US nationwide design competition, Fig. 1.81. The bridge was designed attractively curved but rather subdued in order not to compete visually with the historic buildings of the academy in the background. Due to its simple shape the bridge won the competition against more involved bridge designs with structures above the deck such as arches and stay cables.

The Dittenbrunn Bridge of the German Railways follows the natural contours and seems to grow out of the slope and thus fits in with the surroundings, Fig. 1.82.

The Schillersteg pedestrian bridge in Stuttgart connects the upper and the middle public Schloßpark. The very slender steel beam is bifurcated at one end in order to follow the natural footpaths, Fig. 1.83.

Finally, the purely technical design of the Glebe Island Bridge seems to blend in with the industrial surroundings of Sydney Harbour, Fig. 1.84.

1.2.2.5 Guideline 5: Choice of material

'Correct selection of materials in regard to their load-bearing capacity and appearance'

In general, concrete should be selected for struts, and steel for ties. A lining of large areas of piers and abutments with natural stones can be advantageous; large concrete surfaces can receive a texture from the forms or by chiseling. Large surfaces should generally be roughened, while for small areas smooth surfaces are appropriate.

In accordance with the only building material available at that time the Ilm River Bridge near Oberroßla, Fig. 1.85, was built from natural stones in 1848. Since no tensile forces can be carried by these stones, arches were selected which carry their loads in compression. After an in-depth rehabilitation and replacement of the top slab the bridge serves today for the modern high-speed railway.

Timber appears to be the natural material for the pedestrian bridge, Fig. 1.86, with the remarkable span of 60 m. The design aims at lightness and transparency. The end frames, which have to carry the transverse wind loads, would have required heavy timber sections. In order to avoid the impression of heaviness there, slender steel sections were used. The difference in material is made apparent by using different colors for steel and timber.

The 800 m long freeway bridge across the Warnow valley lies only 10 m above ground, Fig. 1.87. Concrete is the appropriate material for the relatively short spans.

The Annapolis Bridge in the USA was designed with slender octagonal concrete piers without cross girders in order to emphasize the lightness of the bridge, Fig. 1.88. These slender haunched twin piers rest on common granite clad foundations. The floating impression of the superstructure is supported by the upwards striving piers and the strong foundations.

The modern tied three-span arch bridge across the Elbe River near Pirna uses concrete for the arches in compression and steel for the girder as tie and bending member, Fig. 1.89. The concrete roadway slab distributes the local wheel loads.

The governing characteristic of the beam for the Helgeland Bridge in Norway is its compression resistance, Fig. 1.90. It was, therefore, built in concrete. A depth of 1.2 m for the main span of 425 m is sufficient to carry the bending moments and to ensure safety against buckling. This results in a record slenderness of 1 : 355. It becomes evident that concrete bridge girders are not necessarily clumsy.

The Rhine River Bridge at Flehe uses a good combination of materials with steel for the main span beam and concrete for the approach beam as counterweight for the main span, Fig. 1.91.



Figure 1.75 East Huntington Bridge across the Ohio River, WV, USA



Figure 1.76 Yang Pu Bridge, Shanghai, China



Figure 1.77 Houston Ship Channel Crossing, USA



Figure 1.78 Upper Havel River South Bridge, Berlin, Germany



Figure 1.79 Railway bridge across Humboldt Harbor, Berlin, Germany



Figure 1.80 Oder River Bridge, Frankfurt, Germany

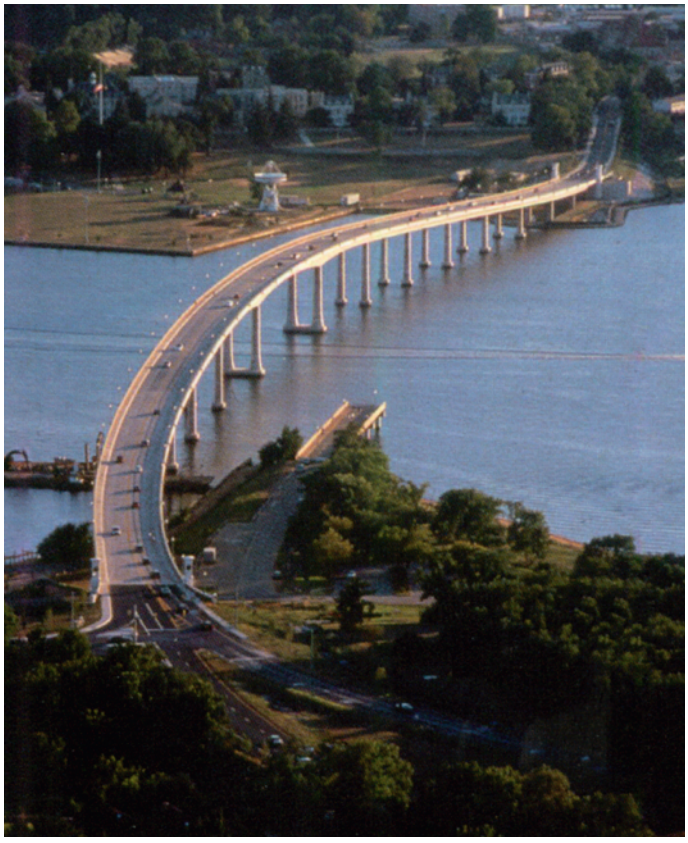


Figure 1.81 Annapolis Bridge, USA



Figure 1.82 Dittenbrunn Railway Bridge along slope, Germany

The delicate appearance of the once record span Normandy Bridge confirms the use of steel as material for the very long spans, Fig. 1.92.

1.2.2.6 Guideline 6: Coloring

'An important element for pleasing appearance is the color.'

Not only steel bridges but also concrete bridges should occasionally be provided with color so that they fit their surroundings. For large areas loud colors should be avoided.

For the concrete Schatten Bridge in Stuttgart a light green was selected for the beam and a dark green for the piers in accordance with the surrounding forest, Fig. 1.93.

The assembly for the open tunnel in Ravensburg is an example how to use a strong red for slender members such as the truss diagonals. The same color was chosen for the truss of the open tunnel, for the towers of the pedestrian cable-stayed bridge, Fig. 1.94, and the curved pedestrian truss bridge, Fig. 1.95. The uniform color combines the different structures into a unit.

For the Elbe River Bridge at Tangermünde, Fig. 1.96, the coloring emphasizes the load-bearing function of the different bridge members. The bending stiffness is provided by the relatively deep beam which is provided with a strong, light blue. The arch slenderness is underlined by its light gray color.

The two nearly identical bridges across the Paraná River between the cities of Zárate and Brazo Largo near Buenos Aires in Argentina with main spans of 330 m were the first major cable-stayed bridges for road and rail, Fig. 1.97. Their unique coloring comprises the red steel diagonals at the tower tops and the white cables. Both emphasize the main span of the long bridge which is otherwise provided with uniform grey concrete color.

For the Burlington Bridge across the Mississippi off-white cables were selected, Fig. 1.98, similar to many other cable-stayed bridges. The light color underlines the floating impression of a cable-supported structure.

A special white concrete from precast elements was selected for the Dee River Bridge in Wales which gives the whole bridge an ethereal appearance, Fig. 1.99.

The yellow stay cables of the Houston Ship Channel Bridge seem to fit the strong sun and the dark blue sky in Texas, Figs 1.100 and 1.101. These yellow cables give a strong impression to the bridge users.

For the stay cables of the Rhine River Bridge at Flehe a red lead coloring was selected, Fig. 1.102.

Air traffic control requested that the towers of the Loire River Bridge at St. Nazaire be provided with a striped hazard coloring, Fig. 1.103. This unsuitable solution has nowhere else been repeated, normally hazard beacons at the tower tops are considered sufficient.



Figure 1.83 Schillersteg pedestrian bridge, Stuttgart, Germany



Figure 1.84 Glebe Island Bridge, Sydney, Australia



Figure 1.85 Ilm River railway bridge, Oberroßla, Germany



Figure 1.86 Pedestrian bridge across Dahme River near Berlin, Germany



Figure 1.87 Freeway bridge across the Warnow Valley, Rostock, Germany

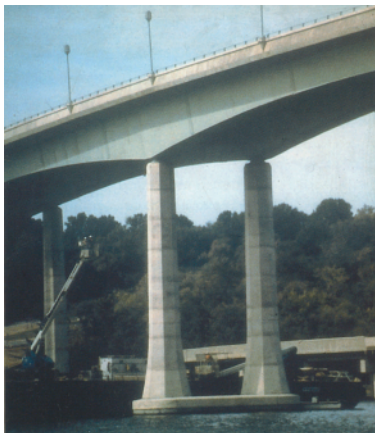


Figure 1.88 Annapolis Bridge, USA



Figure 1.89 Elbe River Bridge, Pirna, Germany



Figure 1.90 Helgeland Bridge, Norway



Figure 1.91 Rhine River Bridge, Flehe, Germany



Figure 1.92 Normandy Bridge, France



Figure 1.93 Schatten Bridge, Stuttgart, Germany



Figure 1.94 Open tunnel and cable-stayed bridge, Ravensburg, Germany



Figure 1.95 Pedestrian truss bridge, Ravensburg, Germany

1.2.2.7 Guideline 7: Space above the bridge

'The space above the bridge should be shaped in such way that the driver experiences the bridge and gets a comfortable feeling.'

It is a good idea to show the beginning and the end of a bridge, if no bridge members extend above the bridge deck.

Old bridges have traditionally been decorated with columns or statues of saints as with the Karls Bridge in Prague which shows St Nepomuk, the patron saint of bridges, Fig. 1.104.

In this tradition the piers of the Upper Havel River South Bridge, protrude on both sides of the bridge above deck, Fig. 1.105. They support a special lighting system for this bridge, which is mainly used by pedestrians.

The Broad Street Bridge in Columbus, Ohio, was consciously designed as a slow inner city bridge, for example, by marking the ends of the bridge with columns, Fig. 1.106. This solution was found in workshops that received strong public participation.

The two cable planes of cable-stayed bridges with A-towers form a tent-like roof which provides users with a feeling of safety. A typical example is the slender Helgeland Bridge, Fig. 1.107.

The Paraná River Bridge between the cities of Posadas and Encarnación in Argentina, with one eccentric railway track, also has two cable planes with A-towers, Fig. 1.108.

From this point of view cable-stayed bridges with just one central cable plane are aesthetically questionable, as shown by the not-realized design for the Kocher Valley Bridge. Whereas the bird's eye view appears quite attractive, Fig. 1.109, a driver's view on the bridge ahead is inadequate, Fig. 1.110. The driver only sees a mast in front, whose meaning is not immediately apparent. This creates a feeling of uncertainty.

1.2.2.8 Guideline 8: Recognizable flow of forces

'A bridge must be designed in such way that the flow of forces is evident even for a casual observer.'

Even an uninitiated observer has an instinctive feeling whether the transfer of forces in a bridge appears plausible. This rule has recently been frequently violated by spectacular designs under the catchwords 'signature bridge' or 'icon bridge' which have been developed for appearance only, without regard to the efficient flow of forces. Very often in these cases the design was created by architects against whom the engineers could not or did not want to succeed.

The haunches of a bridge should rest optically secure on strong piers, and the pier heads should be wider than the underside of the beam.

The Elbe River Bridge at Torgau uses a single haunch only, the concentration of forces at this location being emphasized by a single strong pier with granite cladding which has the opposite side inclination to the other piers ('A' instead of 'V'), Fig. 1.111.

The tower of the Leven River Bridge in Scotland is transversely slightly unsymmetrical and thus reflects the curvature of the bridge beam, Fig. 1.112.



Figure 1.96 Elbe River Bridge, Tangermünde, Germany



Figure 1.97 One Zárate-Brazo Largo Bridge, Argentina; for road and rail



Figure 1.98 Mississippi Bridge, Burlington, USA



Figure 1.99 Dee River Bridge, Wales, GB



Figures 1.100 and 1.101 Houston Ship Channel Crossing, USA; stay cables



Figure 1.102 Rhine River Bridge, Flehe, Germany



Figure 1.103 St. Nazaire Bridge, France



Figure 1.104 Karls Bridge, Prague, Czech Republic



Figure 1.105 Upper Havel River South Bridge, Berlin, Germany



Figure 1.106 Broad Street Bridge, Columbus, Ohio, USA



Figure 1.107 Helgeland Bridge, Norway



Figure 1.108 Posadas-Encarnación Bridge, Argentina; for road and rail

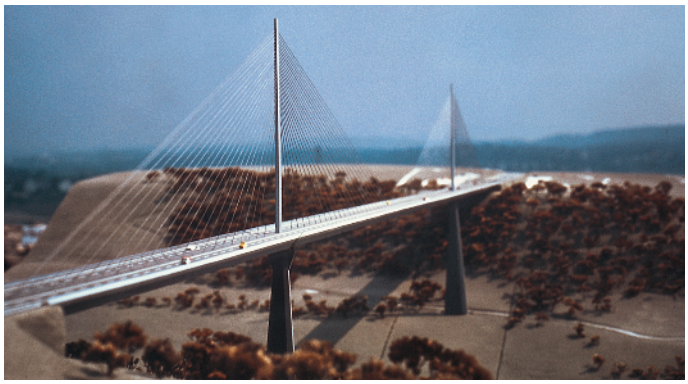


Figure 1.109 Design Kocher Valley Bridge, Germany – bird's eye view

The towers of a cable-stayed bridge have to transfer loads from the cables into the foundations. The simplest and most effective shape is the already mentioned straight A-towers, e. g. Fig. 1.112.

If, due to the overall geometry of the bridge, the distance between the tower legs becomes too big for ship traffic or if the required two independent foundations are too expensive, the tower legs can be pulled together again underneath the deck. This leads to a diamond shape.

An early example is the alternative steel design for the Sunshine Skyway Bridge near Tampa, Florida, Fig. 1.113. The flow of forces is apparent from the widths of the tower legs in the transverse direction. The governing load is transverse wind on the stay cables which is carried in truss action by tension and compression above the beam, the tower legs above deck thus have constant widths. The deviation forces at the kink below deck create tension in the cross beam and are carried by post-tensioning. The pulled-in V-shaped tower legs further down have to carry the transverse forces in bending. Their widths thus increases downwards. The hold-down piers have similar V-shape.

The Houston Ship Channel Crossing at Baytown, Texas, USA, requires two separate beams. The most effective flow of forces is given by two diamond-shaped towers connected at beam level, Fig. 1.114. These now form a truss over their full height so that the transverse wind forces are carried by tension and compression only, also underneath the beam. The slender tower legs can thus have a constant width of only 2.1 m.

The nearby Düsseldorf airport required a height limitation for the towers of the Rhine River Bridge Ilverich to less than the usual 1/5 of the main span. In order to achieve the economic inclination of the stay cables, the towers were formed V-shaped in the longitudinal direction, Fig. 1.115. The tensile forces between the forestay and backstay cables are directly connected with a strong tie, so the flow of forces is clearly apparent.

The transfer of loads for the Rama 8 Bridge, Fig. 1.116, is quite apparent: the loads from the main span are concentrated in a large concrete counterweight at the end of the bridge.

In order to show the force transfer from the stay cables into the beam, the cables in Fig. 1.117 are led through a concrete beam and are supported on corbels underneath. The clearly visible cable anchor heads show the force transition.

The concentrated backstay cables carry the biggest loads in a cable-stayed bridge. Their load transfer should, therefore, be highlighted. In Fig. 1.118 the stiffeners parallel to the stay cables indicate the force introduction from the stay cables into the main girder web. The uplift forces are then transferred from the beam into the hold-down piers with the help of a strong 30 cm diameter pin.

The vertical anchorage of the backstays is shown very clearly as an architectural feature in Fig. 1.119.

For series of cable-stayed bridges with more than one main opening the main design problem is how to stabilize the tips of the towers, because the usual concentrated backstay cables are missing.

The center tower of the Ting Kau Bridge in Hong Kong is stayed to both outside towers at beam level, Fig. 1.120. The strong tieback cables are distinguished by their larger sag against the regular cables and thus show the flow of forces. Visual intersections between the different types of cables have been accepted.

Another solution with a more direct flow of forces was possible for the Second Orinoco River Bridge. Two main spans of 300 m each with a distance in between were required for navigational clearance. Two regular cable-stayed bridges back to back were the solution, Fig. 1.121. The hold-down pier in the center is designed as an A-frame in order to also carry the important breaking forces of the railway over the full length of the bridge.

The Alamillo Bridge in Spain by Calatrava shows an unusual flow of forces, Fig. 1.122. The permanent loads of the main span are balanced by the inclined tower. Transient loads in the main span have to be carried by bending in the tower because the usual backstay cables are missing.

1.2.2.9 Guideline 9: Lighting

'Aesthetic lighting can enhance the appearance of a bridge at night.'

The modern way of lighting a bridge uses floodlights which cover whole areas instead of using individual lights which only follow the contours.

The Kap Shui Mun Bridge in Hong Kong is lit in a pale blue, Fig. 1.123. Interesting coloring effects are achieved by the transition from strong lighting at beam level to darker colors higher up.

The Nan Pu Bridge in Shanghai uses a warm yellow light above the beam and a pale blue underneath, Fig. 1.124.

The Houston Ship Channel Bridge, USA, uses a warm yellow floodlight for the towers and the cables, located at the beam, Fig. 1.125.

The competitive design for the Stonecutters Bridge in Hong Kong uses white floodlighting for cables and towers as shown in the visualization, Fig. 1.126.

An interesting combination of colors during sunset is shown for the Heinola Bridge, Fig. 1.127. In front of the reddish sky the tower, floodlit in a pale yellow, can be clearly seen in front of a series of street lights in the main span. The individual lights at the tower are required for navigational safety.

1.2.2.10 Guideline 10: Simplicity

'Above all: simplicity'

Simplicity and refinement to the pure structural shape is most important. All additions, such as ornaments, decorations or architectural extras, should only be used as an exception. The shape of a bridge is mature if nothing can be left out.



Figure 1.110 Design Kocher Valley Bridge, Germany – driver's view



Figure 1.111 Elbe River Bridge, Torgau, Germany



Figure 1.112 Leven River Bridge, Scotland, GB



Figure 1.113 Alternative design for the Sunshine Skyway Bridge, Tampa, USA



Figure 1.114 Baytown Bridge, Houston, Texas, USA



Figure 1.115 Rhine River Bridge, Ilverich, Germany



Figure 1.116 Rama 8 Bridge, Bangkok, Thailand



Figure 1.117 Cable anchorage at the beam of the Pasco Bridge, USA

The Stöbnitz Valley Bridge is an integral post-tensioned railway bridge, Fig. 1.128. The beam has a solid cross section and rests on cylindrical concrete piers. This bridge convinces by its simplicity.

The single central piers of the Weitingen Bridge have octagonal cross-sections and a taper of 1 : 70, Fig. 1.129. These 120 m high single piers carry a 30 m wide freeway beam, Fig. 1.130. Piers cannot be designed more simply.

The bracing between the arches of the Tangermünde Bridge is reduced to a minimum, Fig. 1.131. Instead of the usual truss with members in different directions, only steel pipes rectangular to the arches were used.

An even simpler solution is shown for the Harbor Bridge Riesa, Fig. 1.132. The two arches are spaced widely and protrude only a little above the roadway. A bracing at their top would have led to a horizontal rectangle which would look unfavorable. Therefore, no bracing at all was used but the individual arches were stiffened against lateral buckling.

From the pedestrian bridge at Villingen-Schwenningen also nothing can be taken away, Fig. 1.133. Four forestays in a central plane support the main span and are anchored in parallel to the abutment. The slender tower is fixed to the beam, which indicates its high bending forces at this location by a haunch.

The Enz River pedestrian bridge at Mühlacker, designed by Leonhardt himself, comprises only one load-bearing element, a concrete arch, embellished with a light red railing, Fig. 1.134. The bridge shows an absolute minimum of structural elements and is of striking beauty.

1.2.3 Collaboration

Finally some remarks on the collaboration between architects and engineers.

For the planning of buildings the architect is in charge of the design and the engineer advises on technical issues. The collaboration between the architect Volkwin Marg and the engineer Jörg Schlaich in Germany shows how a congenial work can be created, [1.37].

For the design of bridges the engineer is in charge and the architect advises him on questions of shape. This collaboration for bridges can also be fruitful. The lead should always remain with the engineer because a bridge is primarily a technical structure. To design a bridge requires special knowledge and experience. Therefore, not every architect is suited to being an advisor for bridges, but experienced architects with an understanding for the flow of forces are required. The key for a successful collaboration is that each side listens carefully to the arguments of the other and tries to understand them.

The famous architect Prof. Tamms has commented [1.38] that the architectural advisor for engineering structures is well advised to hold back in all questions of the basic layout, the construction and the material, in order to attain to his intrinsical task of influencing the shape of the structure.



Figure 1.118 Anchorage of the backstays at the Baytown Bridge



Figure 1.119 Tie-downs of the backstays



Figure 1.120 Ting Kau Bridge, Hong Kong, China



Figure 1.121 Second Orinoco River Bridge, Venezuela; for road and rail



Figure 1.122 Alamillo Bridge, Spain



Figure 1.123 Kap Shui Mun Bridge, Hong Kong, China



Figure 1.124 Nan Pu Bridge, Shanghai, China



Figure 1.125 Houston Ship Channel Crossing, USA



Figure 1.126 Visual rendering of the Stonecutters Bridge at night, China



Figure 1.127 Heinola Bridge, Finland



Figure 1.128 Stöbnitz Valley railway bridge, Germany





Figures 1.129 and 1.130 Weitingen Bridge, Germany; overview and center tower



Figure 1.131 Elbe River Bridge, Tangermünde, Germany



Figure 1.132 Harbor Bridge, Riesa, Germany



Figure 1.133 Pedestrian bridge at Villingen-Schwenningen, Germany



Figure 1.134 Enz River pedestrian bridge at Mühlacker, Germany

Prof. Leonhardt always appreciated the collaboration with specially qualified architects, including Prof. Tamms, Prof. Bonatz and his successor Gerd Lohmer, and Prof. Kammerer, to name only a few.

The author has also successfully collaborated with architects for bridges – Tom Piotrowski from H2L2 in the USA, Ronald Yee in the UK, Prof. Burghardt from Hamburg and Prof. Nöbel from Berlin. The Danish consulting architects Dissing & Weitling with Poul Ove Jensen have advised on outstanding cable-stayed bridge designs worldwide.

The jury for design competitions should always contain a majority of engineers in order to avoid the winning design not being realized for technical or economic problems.

As a result of the above considerations it can be stated that a well-designed bridge has a clear structural system, has harmonic proportions in good order, fits the surroundings and is as simple as possible.

For such a well-designed bridge technical and economical requirements are not contradictory to beauty. Contrary to widespread belief, a beautiful bridge is not necessarily more expensive than an ugly one. A bridge becomes, however, more expensive if the flow of forces is wrong. A beautiful bridge requires only an additional effort of technical and architectural creativity.