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Review paper

Cable-stayed bridges. Basic static schemes

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Abstract: The paper presents an overview of shaping of cable-stayed bridges. Historical background, basic static sketches and overview of selected bridges are included. Selected natural solutions and interesting unrealized projects were presented. Basic ideas and most important principals are discussed. The examples and sketches were given an author's comment. Static diagrams of two pylon structures with three variants of the arrangement of cables are presented. The details important for the structure were discussed and the consequences of choosing the variant were indicated. Mono-pylon structures in asymmetric and symmetrical arrangements are shown. the solutions are discussed and the details important for the structure are indicated. An overview of multi-pylon structures is also presented, paying attention to important details. All the discussed static diagrams were enriched with realized examples. The advantages and disadvantages of individual structural solutions are presented. The main ideas allowing to achieve the goal in the implementation of non-standard suspended structures were also indicated.

Keywords: cable-stayed bridge, static schema, structure shaping

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1. Beginning

In the past, bridges were built naturally as a result of the inventiveness of builders. A good example are the bamboo bridges in Java (Fig. 1).

Fig. 1. Bridge constructed of bamboo, Java, 1930 (photo: digitalcommons.brockport.edu)

Many concepts of cable-stayed bridges have been invented in Europe. However, most of them ended at the design stage. Anyway, it was probably an inspiration for the successors. A good example is the design of the French architect Poyet, developed later by Navier (Fig. 2). One of the first documented and constructed cable-stayed bridges, dating back to 1784, was built entirely of wood by the German carpenter Löscher in the Swiss city of Friborg. Its span was 32 m (Fig. 3)

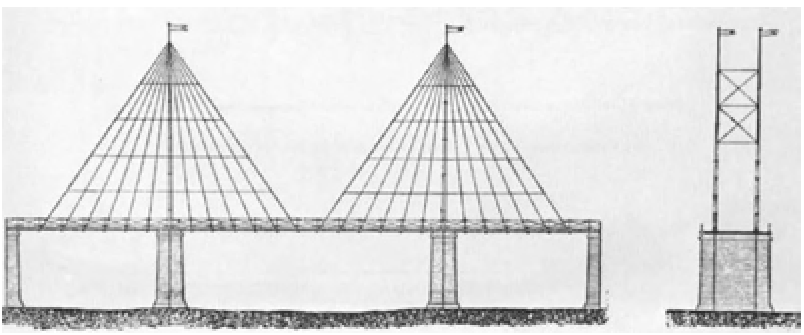

Fig. 2. Fan type cable-stayed bridge – Poyet. 1821 [1–3]

In 1817, a suspension bridge was built across the River Tweed, next to Dryburgh Abbey (Fig. 4). The bridge was sensitive to the dynamic activities of pedestrians and six months after

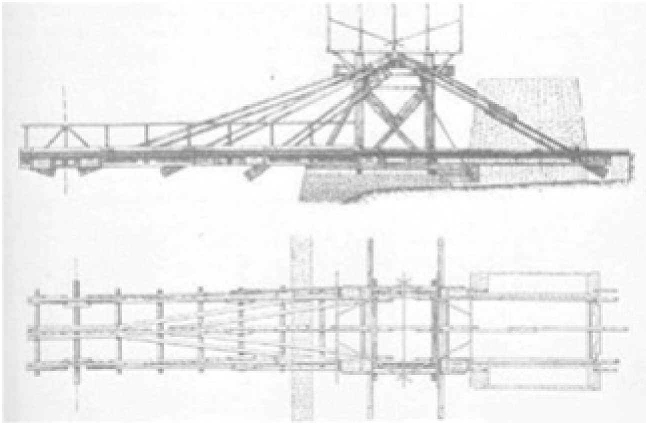

Fig. 3. Wooden bridge by Löscher. Fryburg (1784) [1–3]

completion it was destroyed by strong wind. This fact prompted C.L. Navier in 1823 to write a dissertation entitled: Report et Memoires sur les Ponts Suspendus [2] in which he proposed the systems shown in Fig. 5.

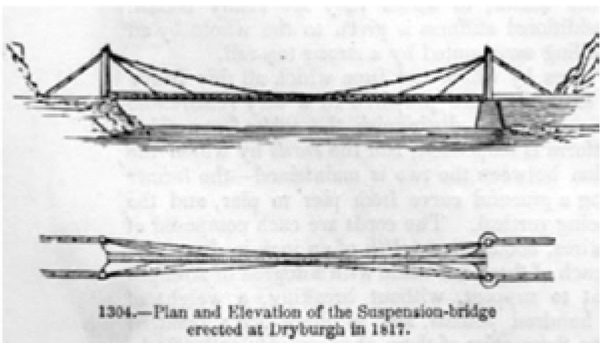

Fig. 4. Bridge near Dryburgh Abbey

In 1824, a 78-meter-long bridge [3] was built over the Saale River in Saxony (Fig. 6), which was excessively deflected. The structure showed no load-carrying capacity from the very beginning and was eventually destroyed.

The modern cable-stayed bridge system was designed in 1899 by Albert Gisclard [5]. He mixed the cable-stayed idea with the elements of the suspension bridge (Fig. 7). Several bridges were built according to this idea (Fig. 8, Fig. 9).

Gisclard's bridges had no pre-tensioned stayes. Spanish engineer Eduardo Torroja was the first who introduce controlled tension in the construction of a reinforced concrete aqueduct [5]. The cable-stayed system was pretensioned by the controlled lifting of the pylon head. In order to protect against corrosion, the tendons of its structure have been concreted (Fig. 10).

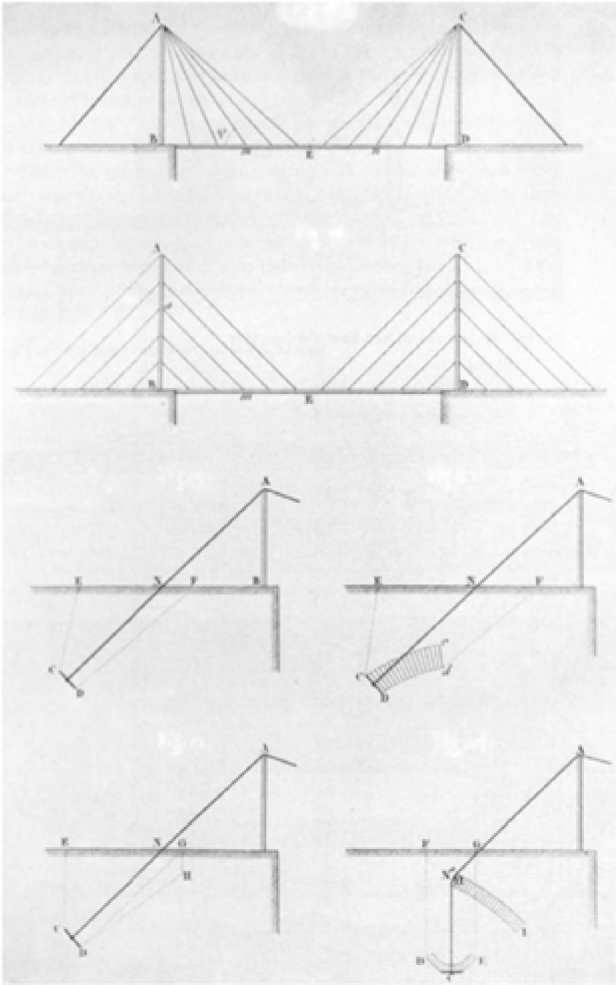

Fig. 5. Static schema of cable-stayed bridge developed by Navier, 1823 [1–3]

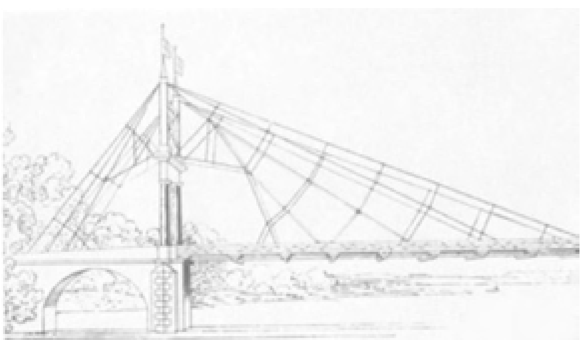

Fig. 6. Bridge over Saale River [2, 3]

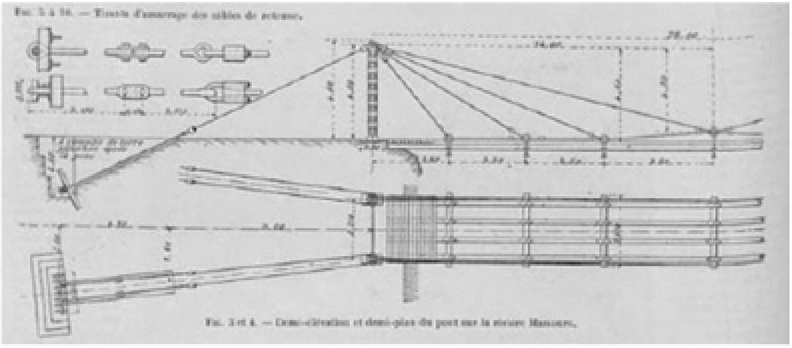

Fig. 7. WBridge developed by Albert Gisclard (www.timbresponts.fr)

Fig. 8. Multi span bridge developed by Albert Gisclard (www.timbresponts.fr)

Fig. 9. Pont de Lezardrieux, 1925, (wikipedia)

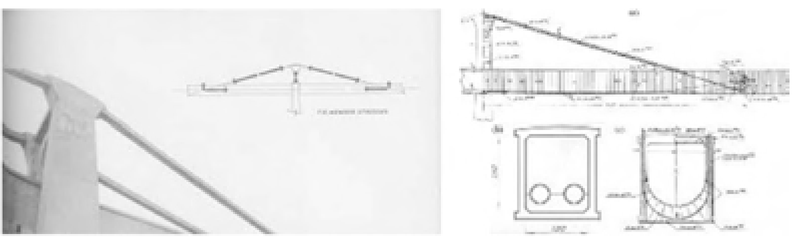

Fig. 10. Aqueduct designed by Eduardo Torroja, 1929

2. Modern cable-stayed bridges

In the 1940s, after the spectacular disaster of the Tacoma Narrows Bridge, the search began for the economic construction of bridges with a span of more than 200 m. Additionally, the development of the production technology of high strength ropes convinced designers to use the concept of cable-stays spans in practice. As a result, in the 1950s, construction of cable-stayed road bridges began.

2.1. Two-pylon bridges

The evolution of the structural concept of suspension bridges was shown by Leonhard in his monograph [4], Fig. 11. This drawing shows the base assumptions applied by designers of the cable-stayed bridges. The first cable-stayed bridges (Fig. 11.1) are beam structures were the cable-stay played the role of an additional elastic support. These bridges were characterized by a small number of cables and a relatively high bending stiffness of the spans. The next stages of evolution (Fig. 11.2–5) are structures in which the suspension concept does not differ significantly from the concept of truss structures. In trusses, the global bending moment and shear forces are transferred by tension and compression bar systems. The bending elements are kept to the necessary minimum. This concept is shown below in Fig. 12. A system of cable-stays called according to [4] fan-shaped was used here. The main bending moments are realized here, just like in trusses, by pairs of normal forces of opposite directions.

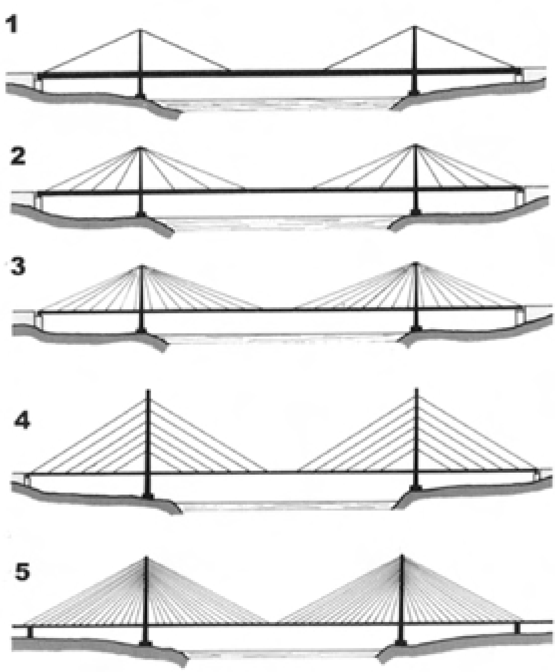

Fig. 11. Evolution of the static system of the classic suspension bridge. Based on [4]

The diagram shown in Fig. 12 illustrates the operation of a properly designed cable-stayed bridge. The most important features of a static schema can be distinguished here:

– the system is three-span,
– the side parts have span smaller than the half of the middle span,
– pylons are stabilized by anchoring the last cables to the abutments or the pilar of the side spans,
– the side spans must usually be anchored in the abutment (this can be omitted in the case when the outer spans are much heavier than the middle one),
– all cables are anchored in the pylon as close to each other as possible.

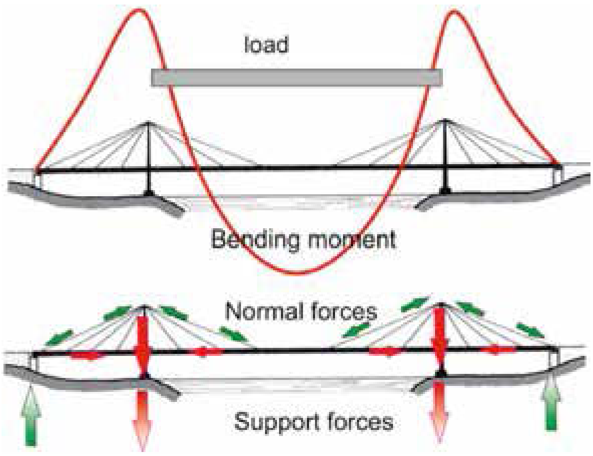

Fig. 12. Main forces in the classical scheme of a fan-shaped cable-stayed bridge

This scheme has been implemented many times. Good examples are the Strömsund Bridge in Sweden (Fig. 13) and the Hooghly River Bridge in Calcutta (Fig. 14).

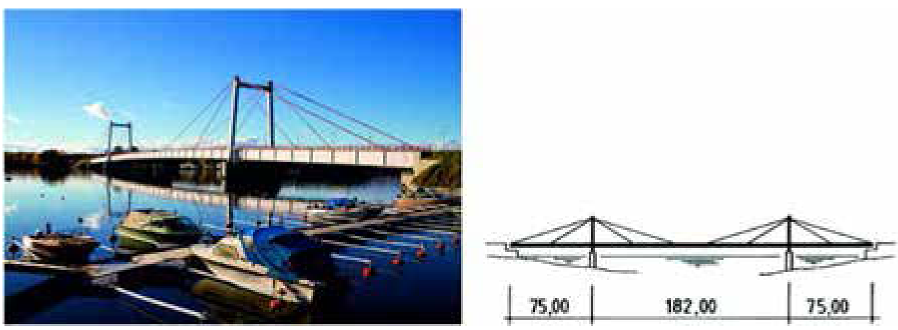

Fig. 13. Strömsund Bridge, Sweden, 1956 [5] (photo: wikipedia.com)

An alternative to the fan system is the harp arrangement (Fig. 15) according to [4]. It is characterized by the parallel arrangement of the cables. This arrangement can be attractive for aesthetic reasons. From an engineering point of view, it is inferior to a fan system for

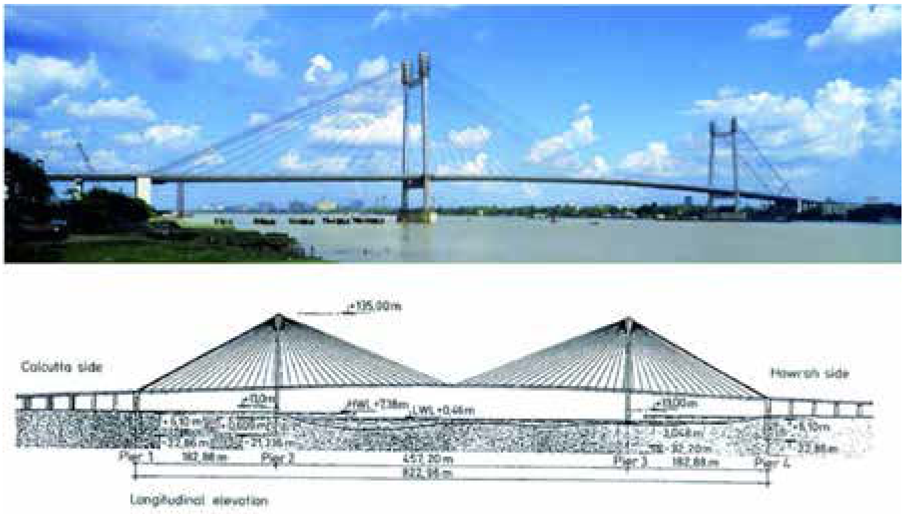

Fig. 14. Hooghly River Bridge, Kalkuta, India, 1994 [5], (photo: wikipedia.com)

two reasons. The individual cables act on a smaller lever to the compressed deck and are therefore less effective in transferring the global bending moment. Additionally, local bending of pylons occurs, which introduces an unfavorable state of stress on them. That is why the harp arrangements are usually supplemented with additional supports for anchoring the side spans. Such a procedure significantly improves the work of the structure thanks to better stabilization of the pylon.

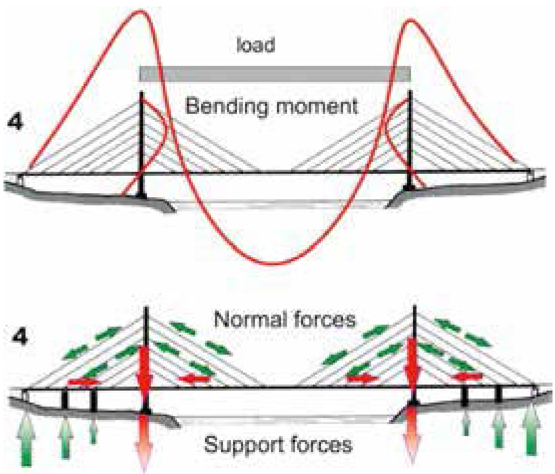

Fig. 15. The distribution of internal forces in the harp arrangement

The advantage of the harp arrangement may be the incremental vertical loading on the pylon, unlike the fan arrangement where all force is applied to the top. The harp arrangement has been used in many bridges around the world [1–6]. Representative examples are the Rhine River Bridge in Duisburg (Fig. 16) and the Solidarity Bridge in Plock (Fig. 17).

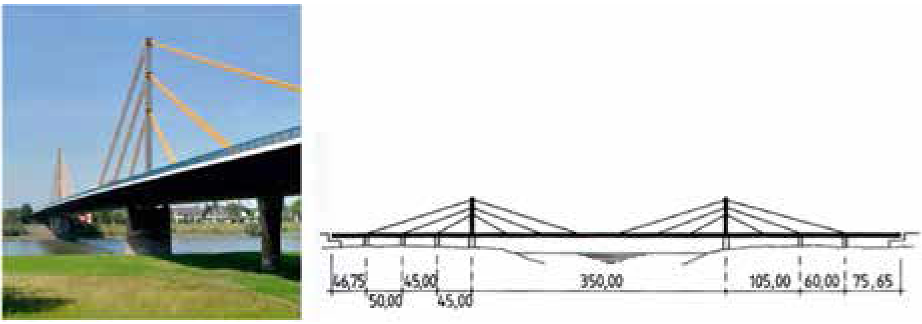

Fig. 16. Rhine River Bridge in Duisburg, Germany [5], 1970 (photo: wikipedia)

Fig. 17. Solidarity Bridge in Plock, Poland (2002) (photo: wikipedia)

It should be noted that both above examples are structures where the pylons are rigidly connected to the deck and are supported on the pillars by bearings arranged in a continuous beam schema.

Structural difficulties in the implementation of the fan arrangements of cables (no place to arrange anchor) resulted in the creation of the third cable-stayed system, known as the fan-harp (Fig. 18) according to [4]. This system takes the advantages of the fan idea and is directly determined by the space for anchoring the cables in the pylon. Due to the above-described stabilization of the pylon, the static system of most fan-harp bridges was supplemented with additional supports in the side spans.

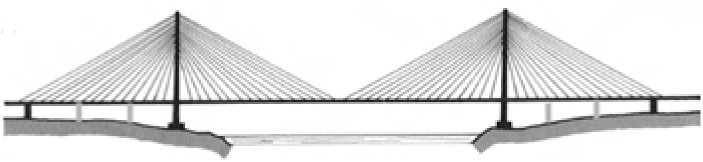

Fig. 18. Fan-harp suspension system with anchoring supports in the side spans

The system works similarly to the harp (Fig. 15) but is more effective due to the larger lever of normal forces acting to the deck and due to the limitation of the local bending of the pylons. The largest bridges in the world have been constructed in this form. Representative examples are the Normandie Bridge, France, 1975 (Fig. 19) and the Stonecutter Bridge, Hong Kong, 2009 (Fig. 20).

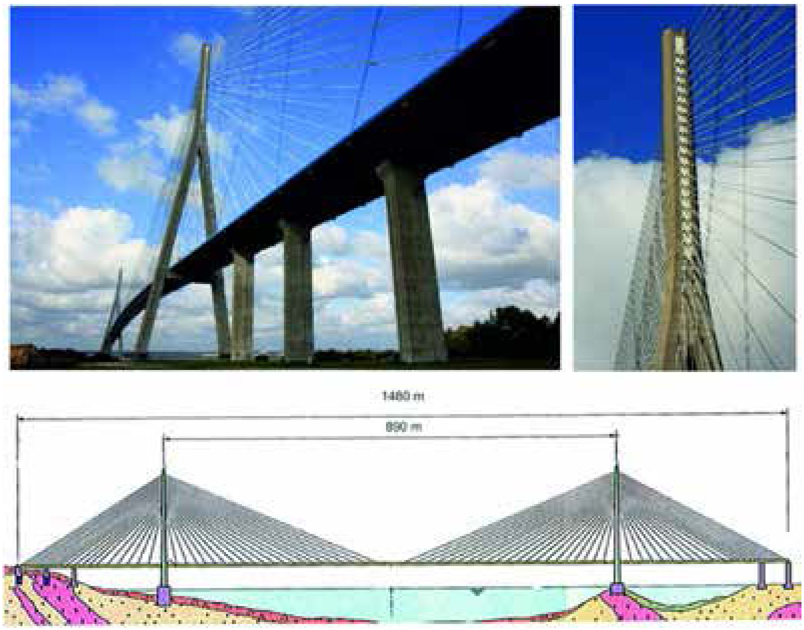

Fig. 19. Normandie Bridge, Michel Virlogeux, France, 1975 [4–6] (photo: K. Zoltowski)

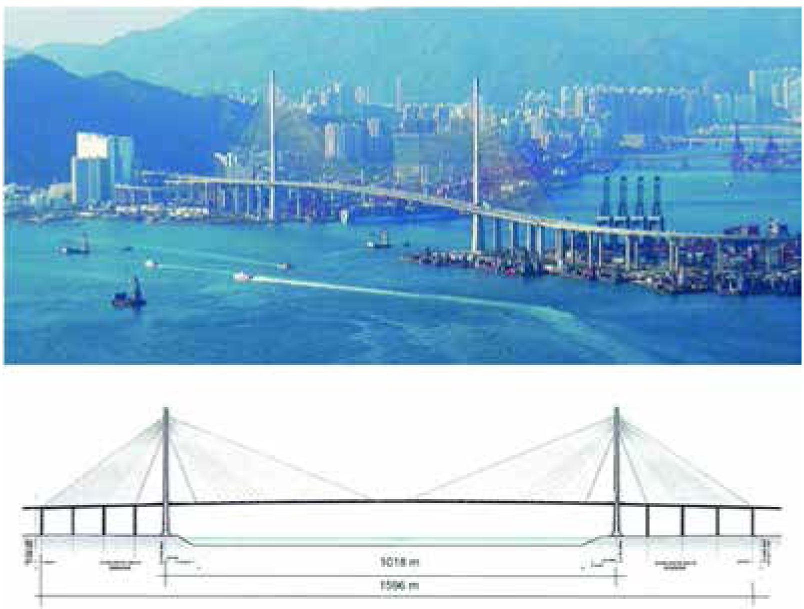

Fig. 20. Stonecutter Bridge, Hong Kong, Jan Firth, 2009, [5] (photo: wikipedia)

2.2. Single-pylon bridges

The above-described static concepts for suspension bridges can be applied to a single pylon structures. The principles of work described above are almost similar in this case.

Typical schemes are presented on Fig. 21. These schemas are often modified by adding a short span on the end of a main span, to reduce deflections and rotation over the abutment (Fig. 22). A negative aspect in this solution is large, local bending of the span and negative support reaction. Representative examples of contemporary bridges of this type are the Bridge across the Danube in Bratislava in Slovakia (Fig. 23), the Heinola Bridge in Finland (Fig. 24) and the John Paul II in Gdańsk, Poland (Fig. 25).

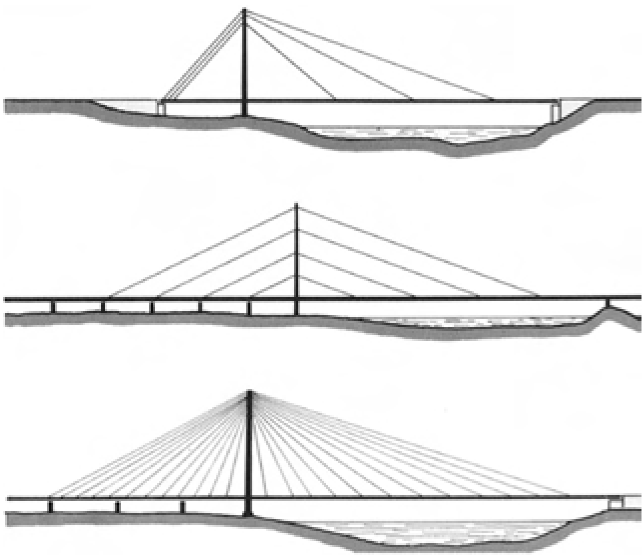

Fig. 21. Typical static diagram of modern single-pylon cable-stayed bridges [4]

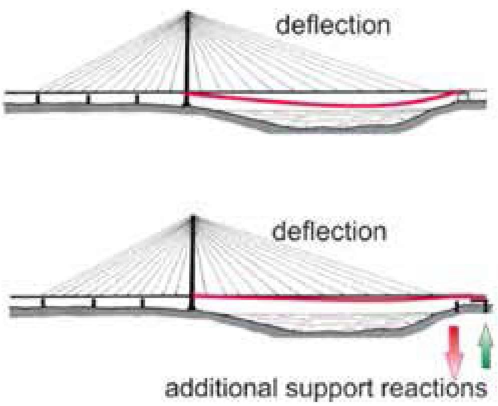

Fig. 22. Effect of restraining of the end of the free span

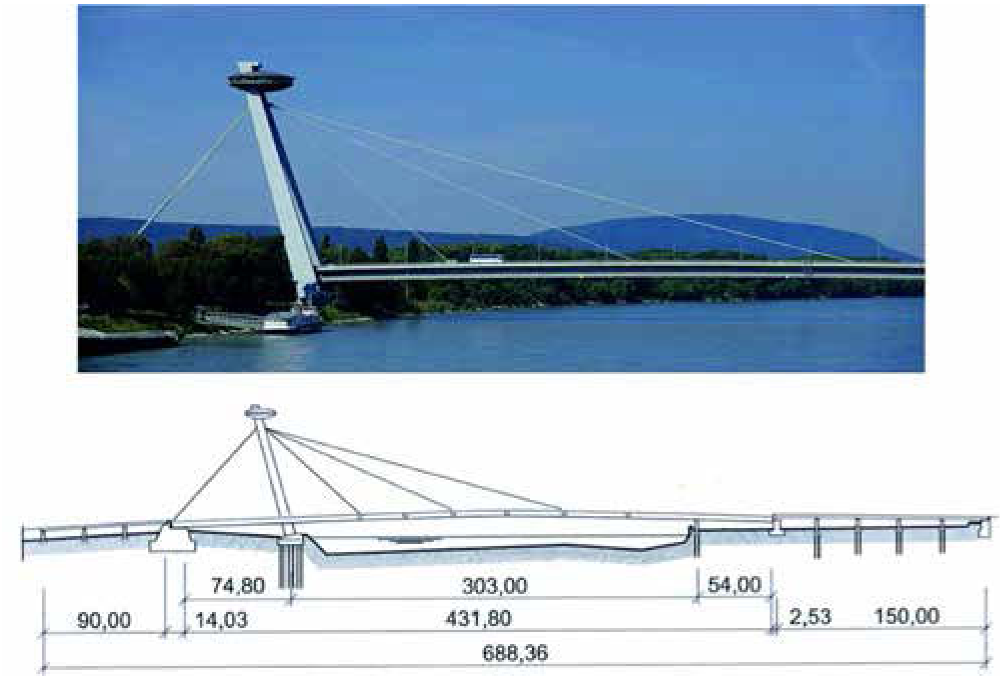

Fig. 23. Bridge over the Danube River in Bratislava. Slovakia, A. Tesár, J. Lacko, I. Slameň, 1972, [1–6] (photo: archinfo.sk)

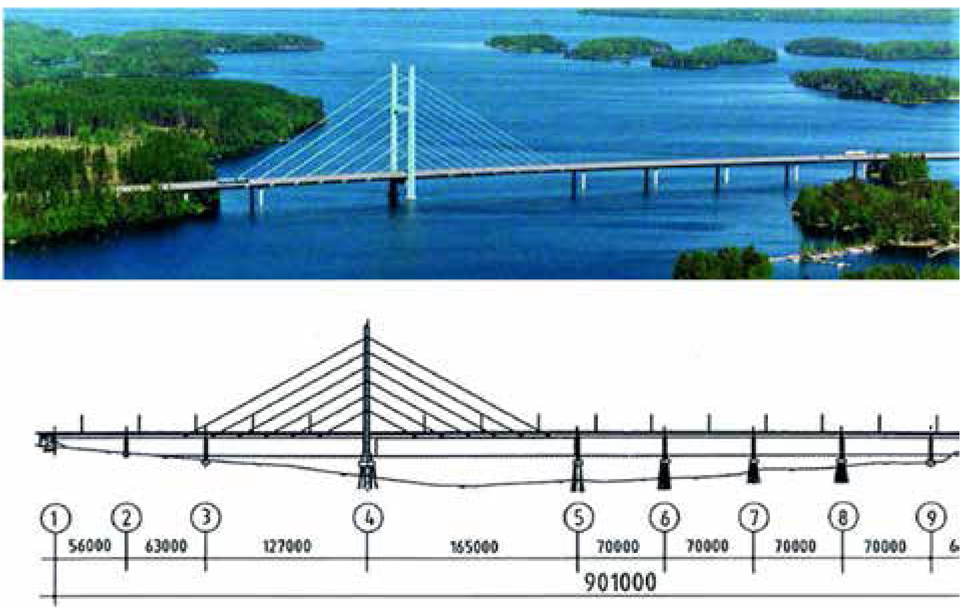

Fig. 24. Heinola Bridge, Finlandia, Mestra Engineering, 1994 [5] (photo: discoweringfinland.com)

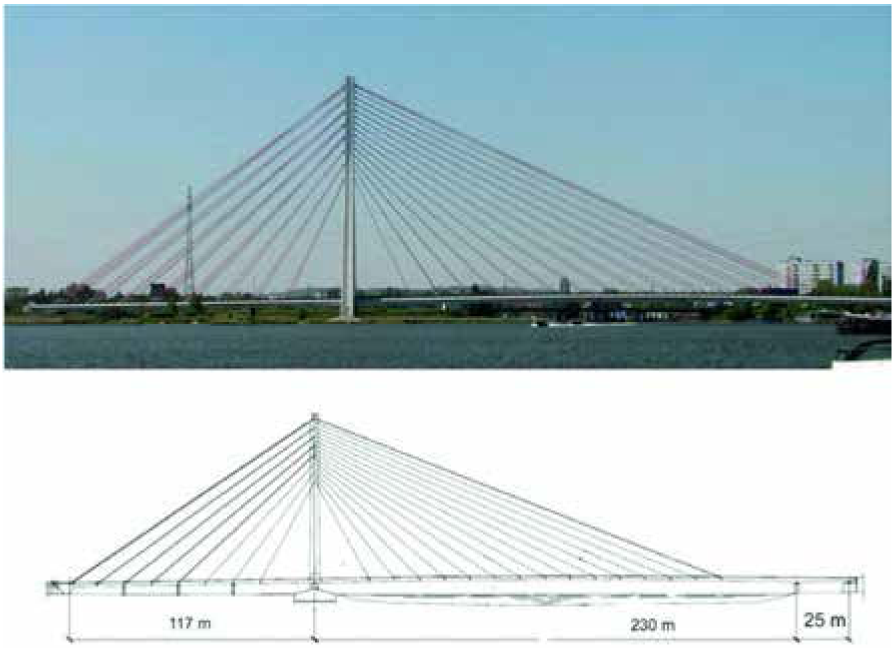

Fig. 25. The John Paul II Millennium Bridge in Gdansk, Poland, K. Wachalski. 2001, (photo: K.Zoltowski)

2.3. Single-pylon symmetrical bridges

As mentioned before, the main factor important for the proper work of the cable-stayed superstructure is the stabilization of the top part of the pylon. This effect can also be achieved by radically increasing its stiffness or developing it into a trestle structure. Then the pylon becomes the main element in transferring not only vertical loads, but also horizontal those resulting from asymmetrical service load of the structure.

Fig. 26 shows a schematic diagram of the trestle system working under service loads. The flexibility of the main girder depends, as before, on the elastic elongation of the cables and on the horizontal displacements of the top of the pylon. If the self-weight of the structure is large enough, the trestle work effect does not cause global tensile forces and negative reactions in

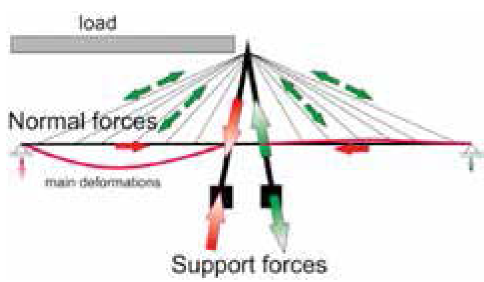

Fig. 26. Schema of the trestle system under service load

the static system. Representative examples of such solutions are bridges designed by Riccardo Morandi (Fig. 27), the bridge across the Rhine in Niuwaid, Germany (Fig. 28) and the Olympic Bridge in Seoul (Fig. 29).

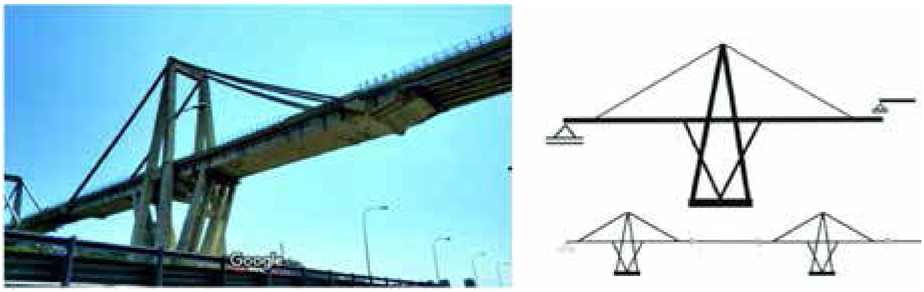

Fig. 27. Viaduct in Genoa, Italy, 1967 (photo: Google Maps, July 1998) and a schema of bridges developed by R. Morandi

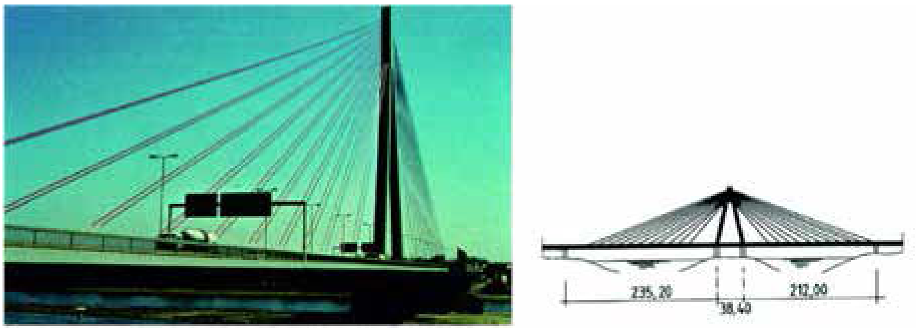

Fig. 28. Bridge across the Rhine in Niuwaid, Helmut Hommberg, Germany, 1978 [5]

Fig. 29. Olympic Bridge w Seoul, Corea, 1990, (photo: wikipedia)

Another symmetrical solution for cable-stayed bridges are systems with a central slender pylon. This intuitively attractive static form requires careful design. However, service loads are usually non-symmetrical and can cause problems with deformations and dynamic behavior. To prevent this, it is necessary to ensure the stability of the top of the pylon as before. Otherwise, a well-designed self-weight bridge may be not stiff enough under the service load. Fig. 30 shows the symmetrical system operation with the tower pylon in three variants.

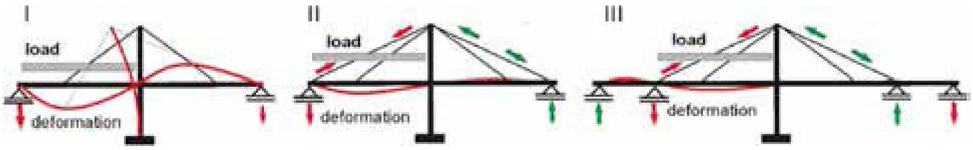

Fig. 30. Deformation of the symmetrical systems with a slender pylon. Basic cases

Case I is sensitive to live loads, therefore it can function efficiently only if a structure is stiff and span is small. A historic example of such a solution is the pioneering aqueduct from 1929 designed by Eduardo Torroja. Fig. 31. A modern example is the Ludwig-Erhard-Brücke viaduct in Ulm, Germany 1989 (Fig. 32).

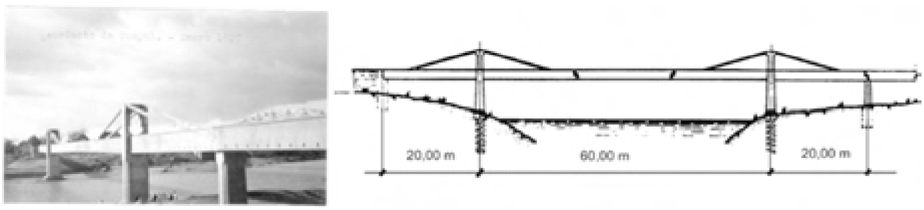

Fig. 31. Aqueduct from 1929 designed by Eduardo Torroja

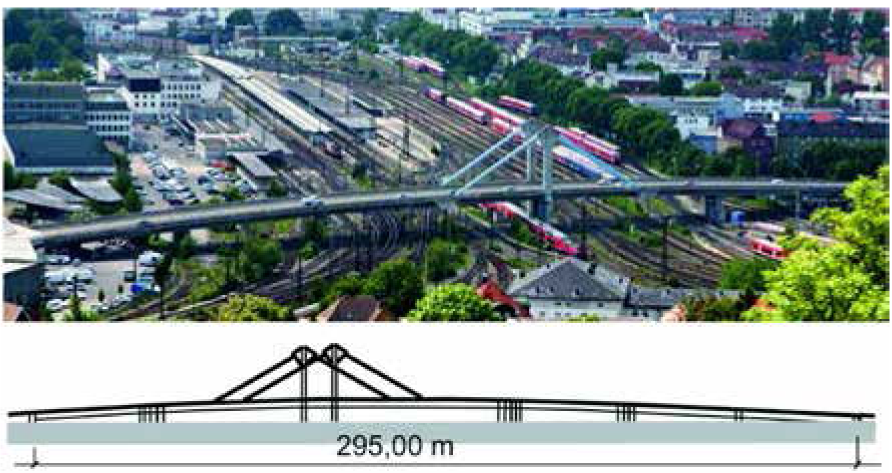

Fig. 32. Ludwig-Erhard-Bridge in Ulm, Germany. Span ~60 m, LAP, 1988 [5] (photo: ulm.de)

Case II (Fig. 30) has cables stabilizing the top of the pylon. Therefore, it meets the general assumption related to the shaping of cable-stayed bridges. A historical example of such a one-pillar bridge is a reinforced concrete footbridge over the Central Canal in Obourg, [3,7] (Fig. 33).

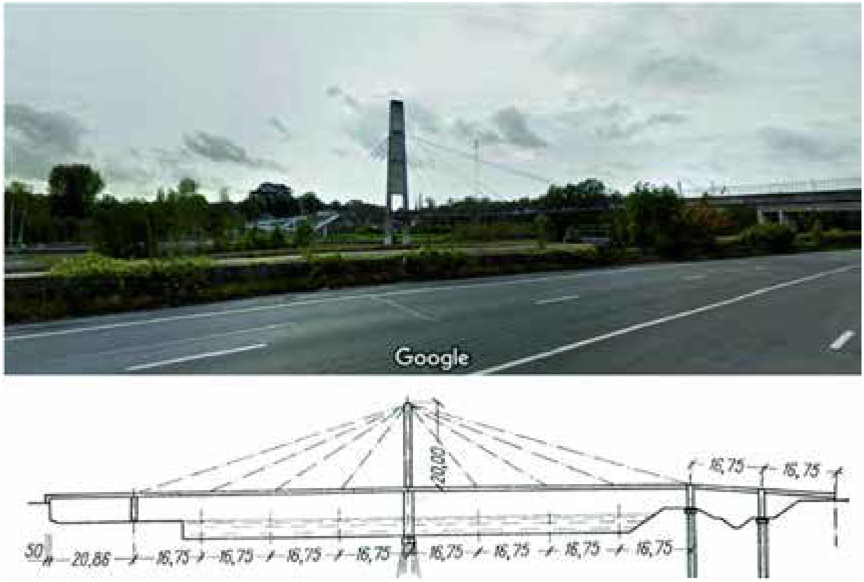

Fig. 33. Footbridge over the Central Canal in Obourg [3, 7], Belgium, 1966 (photo: Google Maps)

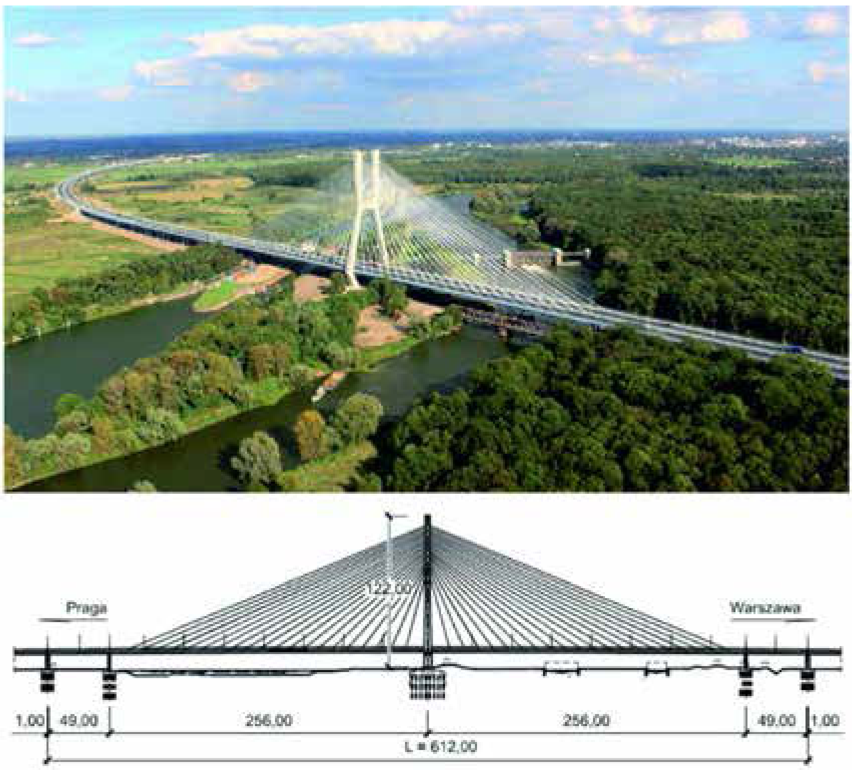

Fig. 34. Rędziński Bridge in Wrocław, Poland, Jan Biliszczuk, 2011, [8]

Case III (Fig. 30) is the most developed version of the symmetrical scheme, supplemented with short side spans. This arrangement gains additional stiffness by quasi restraining the free ends of the suspended spans. The representative example of such an implementation is the Redzinski Bridge over the Odra River in Wroclaw, Poland, [8] (Fig. 34). This design includes many innovations, but the overall structural idea corresponds to diagram no. III in Fig. 30.

It should be remembered that in case II and III (Fig. 30), the pylon stabilizing cables should have a cross-section much larger than the others and must be pre-tensioned enough not to lose tension in any service load.

2.4. Multi span, multi pylon bridges

In any case of a multi-span suspended structure, the following assumptions must be met:

– The tops of the pylons should be stabilized as far as possible or stiff spans must be implemented.
– The problem of movements and longitudinal deformations of the deck, mainly due to rheology and temperature, must be resolved.

The simplest solution used in the past is to divide the structure into independent segments. A historical already mentioned example of such a solution is Morandi construction (Fig. 35). Trestle pylons ensure stability, and the freely supported connecting spans compensate rheological and thermal effects [1–5, 7].

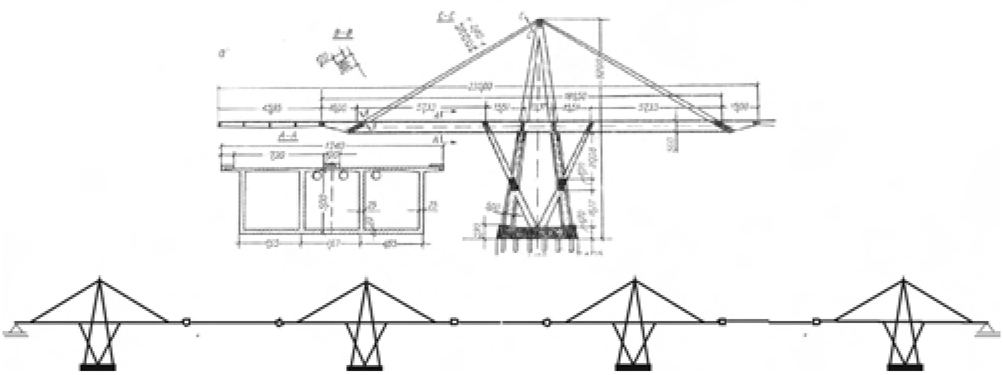

Fig. 35. Multi span system developed by R. Morandi

Another idea used for smaller spans is a continuous beam, supported by its entire length on bearings that allow movement. The pylons are rigidly connected to the deck. An example of such projects is Arenas Viaduct, built in Spain in 1993 (Fig. 36). The span is 105 m. Due to the sufficient stiffness of the spans, the structure functions without additional pylons stiffening. Viaduct is curved in plane.

Next idea is commonly used in the construction of high viaducts in a frame system, using the cantilever technique of erection. It consists in dividing the piers vertically into two discs. This results in a frame system which is flexible to the longitudinal displacement and at the same time stiff transversely. In such a solution, the pylons are monolithically connected with the span

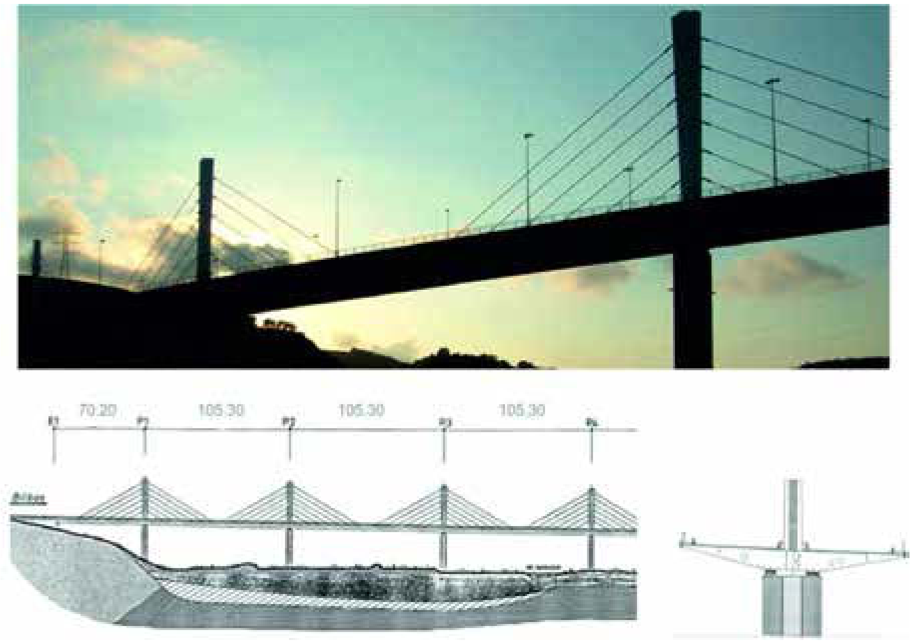

Fig. 36. Motorway viaduct next to Bilbao, Spain, 1993, Arenas&Asociados

and the support. During cantilever erection separate discs are braced temporary. An example of such a solution is the Golden Ears Bridge in Vancouver, built in 2009. It is a five-span system with a main span of 242 m (Fig. 37).

Fig. 37. Golden Ears Bridge, Vancouver, Canada, Miller Group 2009, [5], (fot. The Miller Group)

Ting Kau Bridge in Hong Kong is a spectacular example of the implementation of a multi-span system with the flexible piers in the frame structure and the cables stabilizing the middle pylon (Fig. 38). However cables stiffening the middle pylon have a limited effect because of the sag. In the recently built Queensferry Bridge across the Firth of Forth, a basic idea was probably inspired by the pioneering solution of Albert Gisclard (Fig. 7–9). A frame system of spans, pillars and pylons with overlapping cable stays from neighbor pylons was used. This procedure, combined with the stiffness and high self-weight of the spans, ensured the required flexibility under external loads (Fig. 39).

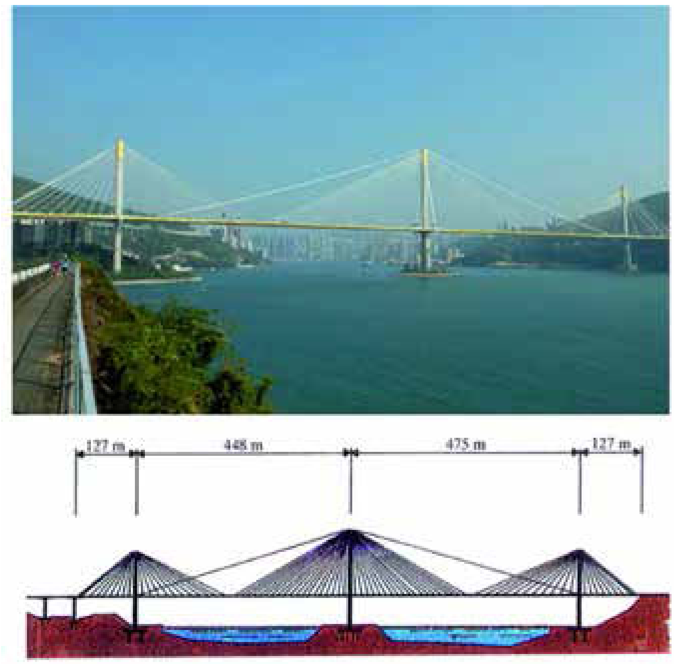

Fig. 38. Ting Kau Bridge, Hong Kong, SBP Stuttgart, 1998 [5], (sbp.de)

Two recently built multi-span structures deserve special attention. Both were completed in 2004 and both feature innovative and unconventional solutions. The Milau Viaduct [5] is a structure composed of repeatable spans with a span of 342 m and a total length of 2,460 m (Fig. 40). The largest pillar measures 244 m from the foundation to the deck. The pylons rise above the road to a height of 90 m. The pillars are made as reinforced concrete towers, separated at the top. The spans integrated with the pylons are made of steel. After assembly, the structure works as a frame system, but because of construction phases the spans are placed on pillars via specially designed spherical bearings stressed to avoid uplifting. The static idea of structure is presented on Fig. 40. The Milau Viaduct is undoubtedly an outstanding work of engineering combining spectacular aesthetic and engineering effects. Particularly noteworthy is the spectacular assembly technology.

The Rion-Antirion Bridge was built as part of the expansion of the road infrastructure prior to the 2004 Olympics. It crosses the Gulf of Corinth (Fig. 41). The total length of the crossing

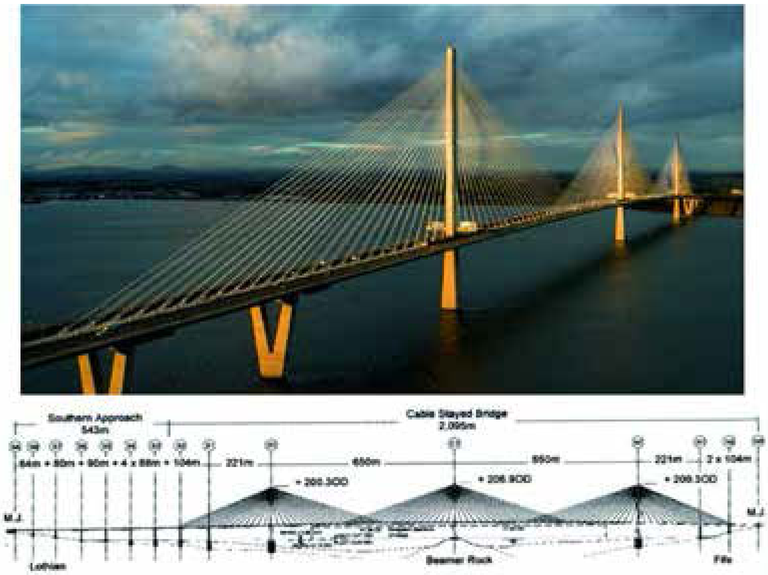

Fig. 39. Queensferry Bridge, Scotland, Arup and Jacobs, 2017, [5] (reaerialfilming.com)

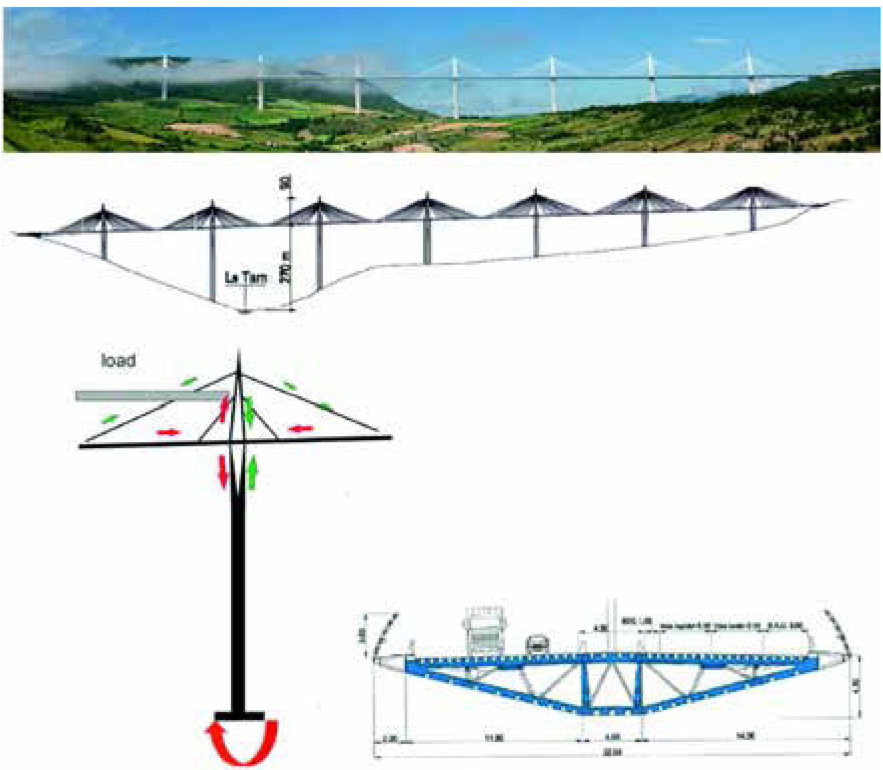

Fig. 40. Milau Viaduct [5], Michel Virlogeux, France, 2004 (photo: wikipedia)

is 2880 m, of which the cable-stayed part has 2252 m. Four trestle pylons create a system of 5 spans with the length of 286 m, 3 × 560 m and 286 m. Massive supports and structurally extensive pylons ensure the required stiffness of the structure. The spans were made of steel, combined with a reinforced concrete road slab. The spans are a continuous structure along the entire length of the bridge, fully suspended from the pylons. They do not have any vertical support on the pillars. Thermal movements are realized by the flexibility of the suspension system. The bridge was designed considering seismic requirements of the region.

Fig. 41. Rion-Antirion Bridge. Greece, Jacques Combault, 2004 [5], (photo: wikipedia.com)

3. Conclusions

The bridges presented in the study have an extensive bibliography and each of them can be the subject of a separate study. Most of the cited static systems and principles certainly deserve wider support with realized objects or studies of a scientific nature. Many important issues concerning the shaping of suspension bridges in cross-section have not been mentioned. The specificity of construction materials and their influence on static systems have not been characterized. Many aspects have been overlooked that should be studied and understood before working on a cable-stayed bridge project. The works [1–8] were used as monographic studies containing an overview of world achievements. The elements that, in the author's opinion, are the most important for the reader starting his adventure with suspended bridges were selected from them, and they were provided with proprietary comments and diagrams.

The static scheme is the most important element of the structural and architectural concept of the bridge. Knowledge of the principles achieved by pioneers is the most important element of a designer success. Omission of the established rules is a way to the unknown. Therefore, innovative concepts must be thoroughly and deeply studied before they are transferred to reality.

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Mosty podwieszone. Podstawowe schematy statyczne

Słowa kluczowe: most podwieszony, schemat statyczny, kształtowanie konstrukcji

Streszczenie:

W artykule przedstawiono przegląd podstawowych informacji dotyczących zasad kształtowania mostów wantowych. Zamieszczono tło historyczne, podstawowe szkice statyczne i przegląd wybranych mostów. Omówiono podstawowe idee i najważniejsze zasady. Przykł ady i szkice opatrzone zostały komentarzem autorskim. Przedstawiono schematy statyczne układów dwupylonowych z trzema wariantami rozmieszczenia lin podwieszenia. Omówiono szczegóły istotne dla konstrukcji oraz wskazano konsekwencje wyboru wariantu. Przedstawiono konstrukcje jednopylonowe w układzie asymetrycznym i symetrycznym. Omówiono rozwiązania i wskazano szczegóły istotne dla konstrukcji. Przedstawiono również przegląd konstrukcji wielopionowych, zwracając uwagę na istotne szczegóły. Wszystkie omówione schematy statyczne zostały wzbogacone o zrealizowane przykłady. Omówiono zasadnicze pomysły i idee pozwalające osiągnąć zamierzony efekt przy opracowaniu niestandardowych konstrukcji mostów podwieszonych.

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