Investigating Pylon Configurations in the Design of Cable Stayed Bridges

[1] James J. Afonso, [2] Purnanand P. Savoikar
[1] PG student, [2] Professor Civil Engineering,
[1,2] Goa College of Engineering, Ponda, Goa, India

Abstract—**Cable Stayed Bridges are among the most aesthetic and structurally reliable of all bridge systems. The lean structural design added to its long span possibilities are two of many advantages that a cable stayed bridge has over other bridge systems. The range of cable stayed bridges is second only to cable suspension bridges. There are Four Cable stayed bridges which span more than 1000m. Cable stayed bridges are regularly used for spans above 500m. One of the advantages that the cable stayed bridge has over suspension bridges is the avoidance of high-tension forces to be transferred directly to the soil at the anchor ends of the cables. This is a prominent advantage of cable stayed bridges over cable suspension bridges. This makes it unsuitable to anchor cables in strata which is not rock. Due to such advantages, it is possible that cables stayed bridges will surpass the record spans of cable suspension bridges. One of the disadvantages of the cable stayed bridge is that with the increase in span the height of the pylon will increase. Naturally, for super long bridges the height of the pylon would be prohibitively high. At this point there will be effects on other components of the bridge. For long span bridges the number of cable planes plays a major role. The longest of spans have either two cables planes or three cable planes. Thes cables have to be anchored onto the pylon face. Further the higher the pylon the more the dead weight and corresponding dead load on the foundation. This would require the material of the pylon to be studied closely. The shape of the pylon will come into picture to resist dynamic load such as wind, seismic and lateral loads transferred from the deck. This paper studies the various configurations of pylon from bridges across the world and studies why those configurations are used. The materials used in these pylons are studied and why they were used. Suggestions for pylon shape and configuration for super long span bridges and improvements for the same are given.**

Keywords—Cable Stayed Bridge, Pylons, Pylon Configurations

I. INTRODUCTION

Many bridges are characterised as being long by counting viaducts and other elevated approach methods when determining their total length from point to point. Although there are numerous reasons why this is a good way to gauge the length of a bridge, in structural engineering the main span of a bridge serves as a gauge for not only length but also complexity in terms of structural stability, cost, and execution.

In cable stayed bridges the longer the bridge the higher the supporting pylon. While the main span design and construction is challenging, the desing of the pylon is critical. As the bridge gets longe the forces on the pylon get larger. The pylon has to resist all the loads and transfer them safely to the ground. These could be gravity loads or wind and seismic loads. Besides this the pylons have to resist force of water flow and waves at the base of the pylon. The ratio offered by most of the pioneers of bridge design is 0.2L where L is the main span and the ratio is for the part of the pylon above the deck. This ratio has an impact on almost every other component of the bridge.

The height determines the slope of the cable and in turn the vertical or horizontal component of force acting on the deck and the pylon. The cable design gets influenced as the sag of the cable has to be taken into account and hence the cables cannot be too flat. So the height of the pylon is a governing factor in the design on cable stayed bridge. As the pylon gets higher its self-weight also increases along with the loads which it has to transfer from the deck and the cables.

There could be many disadvantageous situations when the weight increases. First if the soil strata are not good enough then the foundations could become very large or they could be too expensive. They could also be such that the foundation is entirely not possible if loads are not reduced. Second the cost of the project could become prohibitive if the concrete sections are too large.

From the literature review it has been found out that concrete seems to be the preferred option for most pylons. However, the possibility of steel needs to be investigated especially when it comes to super long span bridges which could be solutions of the future. With advancement in material technology, it is possible to think of steel as a solution.

One of the inherent disadvantages of steel are the buckling possibilities and magnified effects of P-Delta and secondary effects. These issues can be taken care of by using proper design methods and construction techniques. Pre-fabricated sections can help to accelerate the process and as such speed could be an advantage with steel pylons. Further, the control of pre tension in the cables can be monitored from the hollow sections where the anchorages can be placed. This will of course be a critical area of design and necessary design factors will have to be taken into account.

In this paper the pylon structure of the longest bridges in the world are studied and their configurations, heights and materials are studied along with other parameters of the selected bridges. Comparisons are drawn. Suggestions are given and conclusions are drawn.

II. LITERATURE SURVEY

The literature review of Cable Stayed Bridges across the world suggests that most of the bridge engineers over time agree to the basic proportioning of cable stayed bridges. This is the corner stone of cable stayed bridge design. The classical three span cable stayed bridge is the type which can be used to span large channels without the requirement of intermediate pylons. The literature survey is thus, limited to the classical three span cable stayed bridge and its derivatives.

Troitsky (1988) opines that a ratio of 0.19 for the pylon to the main span is crucial since the influence of the cables' inclination on cable design is vital and has to be taken into account at the very conceptual stage of the design. The height of the pylon will affect maintaining this ideal slope since the sag of the cable becomes more obvious as the cable becomes flatter with longer lengths of deck. This behaviour of the cable is critical when it comes to the pretensioning of the cables. Larger pretension forces are needed as the cable becomes flatter and this is avoided to an extent with the optimal slope which is possible due to this ratio [1].

Virlogeux (2001) described the behaviour of the traditional three-span cable-stayed bridge in comparison with the Series of Cable-stayed bridges. Fig. 1. shows the conventional three-span cable-stayed bridge's deflected shape when it is subjected to live loads. Tensile forces in the main span cables are transferred from the pylons to the backstay cables when the main span is subject to an active load. Due to the deflection of the side span, when the side spans are loaded, the intermediate cables undergo tensile force while reducing the tension in the back stay cable. This repetitive or cyclic loading and unloading of the back stay cable results in fatigue stresses in the back stay cable and this is a governing stress in the design of cable stayed bridges. [2]

Svensson (2012) reported that the ratio of side span to main span was 0.4. This is based on a factor that is based on the ratio of dead load to live load carried over the bridge. The alternate live load on the side span and then on the main span results in changing pressures on the backstay cables. The back stay cables' fatigue range is established by this variance, which is crucial. This fatigue range dictates how the conventional three-span cable stayed bridge should be built, therefore the cables must be safely designed for it. He further reported that the Fan, Harp and Intermediate Fan-Harp are the three cable systems used in Cable Stayed bridge design. The case in favour of the Fan System is its aesthetic appeal while the case against it is the complicated stress patterns on the pylon. Similarly, the Fan system had advantages such as the structural system being the best for analysis but practically not a very suitable system as all cables converge to one point at the top of the pylon. An intermediate approach is the way forward and is followed for all long span cable stayed bridges in existence. It is called the intermediate Fan-Harp system. It was reported that the number of cable planes play a major role in the determination of many components of the bridge. Most long span bridges have two or three cable planes as opposed to having only one, which can be the case with small spans. Two or three planes distribute the forces in more cables thereby reducing the size requirement of cables. They also provide stiffness to the bridge under lateral loads. The number of cable planes impacts pylon configuration and design [3].

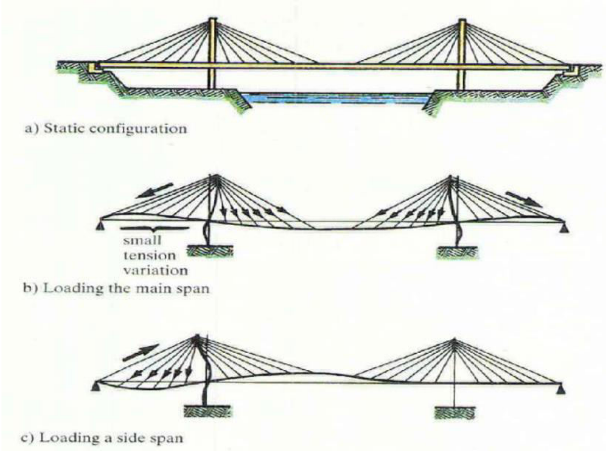

Fig.1. Behavior of Classical Three Span Cable Stayed Bridge [2]

III. METHODOLOGY

A tabulated study and comparison of the five longest cable stayed bridges in the world is shown in the table. The study shows the height of all the pylons from the foundation level as well as the material from which they have been constructed. [Table I]. The bridges are then shown with their tower configurations from various available sources. Fig.2., to Fig.11 with the exception of the Stonecutters bridge shown in Fig.9, which is a single shaft, all other bridges have an ‘A’ shaped pylon with certain modifications to take in local requirements. The shape of the pylon with the inward leaning outer members to form an ‘A’ noticed throughout the study and the height of the pylon reduces with reducing length of bridge. The tabulated data also shows that the pylons are all made of concrete. The critical accommodation in the pylons is the anchorage of the cables. The cable stay arrangement i.e. whether the bridge would be Fan, Harp or Intermediate Fan-Harp is a critical decision to be taken. From the literature review it has been understood that it is the Intermediate Fan-Harp that is to be used for optimal results. This is of absolute importance as the anchoring of the cables on the pylon is directly related to this. The pretension forces in the cables are also adjusted during the various stages of construction in the hollowed-out volume of the pylon i.e on the inside of the pylon. Further the length of the bridge is also tabulated and it can be seen that as the spans increase the pylon heights also increase.

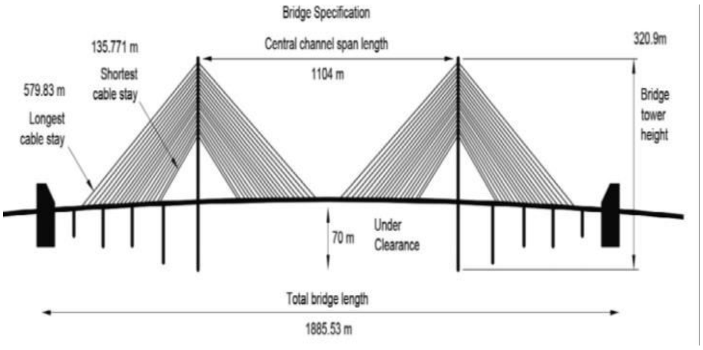

Fig.2. Russky Bridge (Painato, 2016) [4]

TABLE I. COMPARISON BETWEEN THE FIVE LONGEST CABLE STAYED BRIDGES

Sr. N	Bridge Name	Pylon Height	Pylon Material	Cable Planes	Main Span
1.	Russky Bridge	320.9m	Concrete	2	1104m
2.	Hutong-Yangtze	325m	Concrete	3	1092m
3.	Sutong-Yangtze	304.4m	Concrete	2	1088m
4.	Stonecutters Bridge	293m	Concrete with stainless steel skin	2	1018m
5.	Qinshan-Yangtze	279.5m	Concrete	2	938m

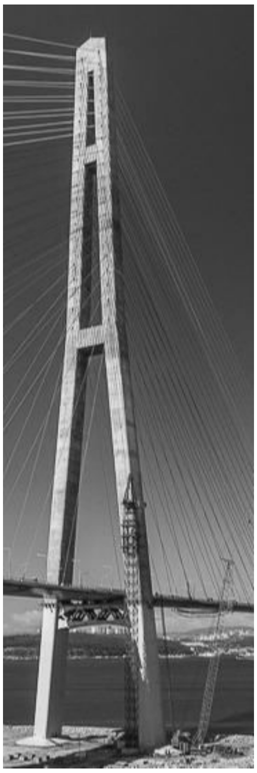

Fig.3. Russki Bridge Pylon. (https://structurae.net/en/structures/russky-bridge) [5]

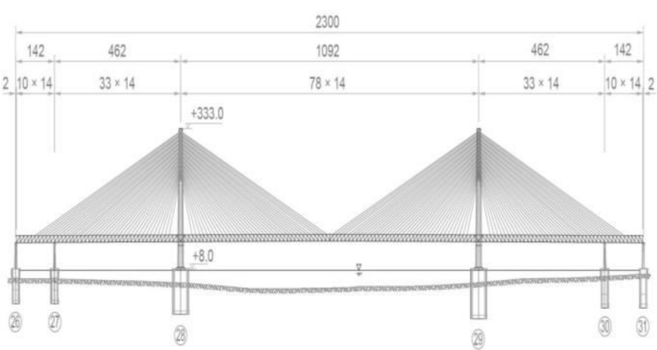

Fig.4. Hutong Yangtze River Bridge (Qin & Gao, 2017) [6]

Fig.5. Hutong-Yangtze. (https://structurae.net/en/structures/hutong-yangtze-river-bridge?r=/ouvrages/pont-hutong) [7]

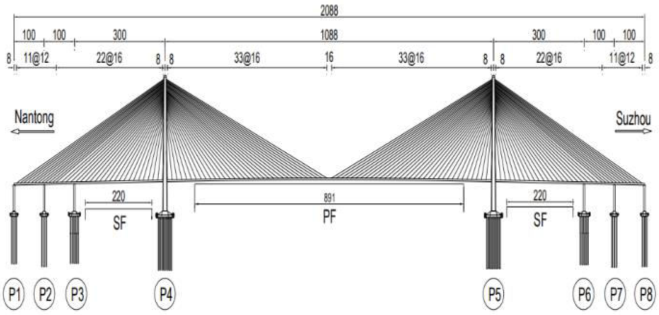

Fig.6. Sutong Yangtze Bridge (Janjic, 2005) [8]

Fig.7. Sutong Yangtze. (https://structurae.net/en/media/143216-sutong-bridge) [9]

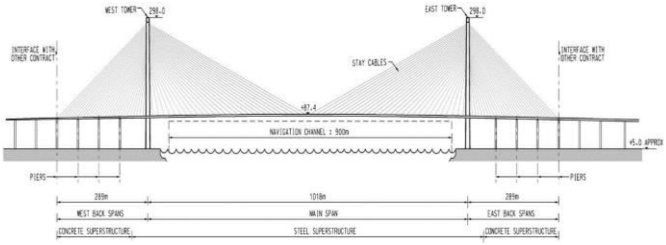

Fig.8. Stonecutters Bridge (Sham & West, 2010) [10]

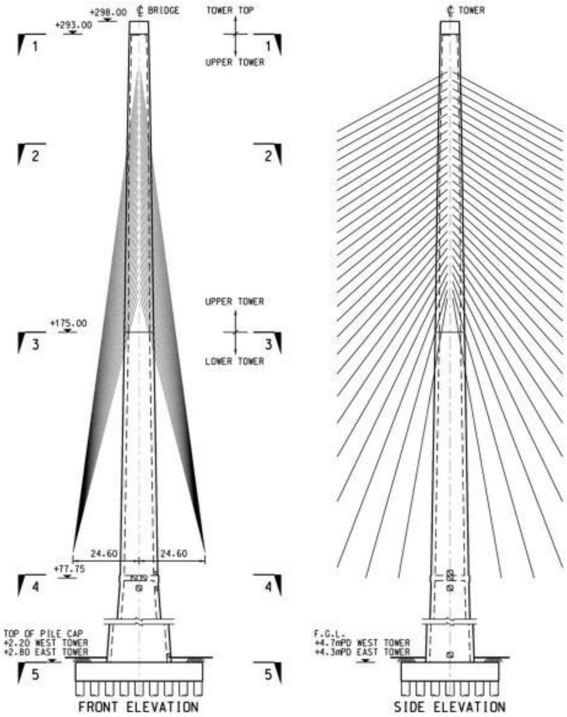

Fig.9. Stone Cutters Bridge Pylon. (Sham & West, 2010) [10]

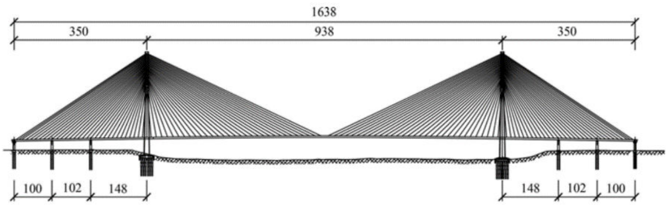

Fig.10. Qingshan Yangtze River Bridge (Li et al., 2018) [11]

Fig.11. Qingshan Yangtze river bridge pylon. (https://structurae.net/en/structures/russky-bridge) [12]

IV. DISCUSSIONS

A. Pylon Material

We can see that most of the long span bridges use reinforced concrete as the preferred material for pylon. All of the five bridges used for the comparison have concrete as the pylon material. One of the reasons for this could be the practicality of concrete construction. The Pylon rises as a single vertical member and formwork is relatively simple for such a system. Self-climbing formwork has made this process even more easy with the time component also being taken care of by this type of technology. Further high strength concrete with various properties induced into high performance concrete give a boost to the use of concrete. Concrete can be designed to be used in all slots of climates. However, the weight of concrete could be a matter of concern in areas where soil conditions are not favourable. In such places steel could be a favourable alternative for pylon design. Steel offers a light solution for design. High Strength steel can be used for the purpose. The disadvantages of steel are in the buckling effects and P-Delta effects which could take prominence due to the predominantly compressive loads which are experienced by the pylon.

B. Pylon Configuration

The figures Fig.12, Fig.13, Fig.14 show the general likeness of different pylon configurations and are related to the bridges in Table I. Fig. 12. Shows the configuration which is usually used for a single cable plane in a front view. However, in the case of the stone cutters bridge, Sr.No.4 in Table I. the towers are designed as single shafts with a tapered cross section as shown in Fig. 8. This gives us an indication that even if the plane is a single shaft, it can be used for two cable planes.

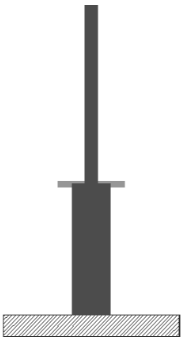

Fig.12. Single Plane Pylon front view.

Fig. 13. Shows the general configuration for two cable planes in a front view. This is the type of configuration which is used generally for two cables. This type of configuration also provides lateral stability.

The Russki Bridge, Sr. No.1, in the table uses an `A' shaped geometry as is shown in Fig.13. (b), however it also has two additional members joining the two inclined members as shown in Fig.3.

The Hutong-Yangtze, Sr. No.2, in the table uses a geometry as in Fig.13(c). Fig.5. shows the pylon of the Hutong-Yangtze bridge. It can be seen that it the pylon has been modified at the top of the pylon to accommodate three cable planes, as can be referred to in Table I and in Fig.5. This top end modification can be seen in Fig.14.

The Sutong-Yangtze bridge, Sr. No.3, in the table uses an `A' shaped geometry as is shown in Fig.12. (b), with no further modifications.

The stone cutters bridge, Sr.No.4 in Table I. the towers are designed as single shafts with a tapered cross section as shown in Fig. 8. This gives us an indication that even if the plane is a single shaft, it can be used for two cable planes.

The Qingshan Yangtze river bridge, Sr. No.5, in the table uses an `A' shaped geometry as is shown in Fig.13. (b), it has one additional members joining the two inclined members as shown in Fig.11.

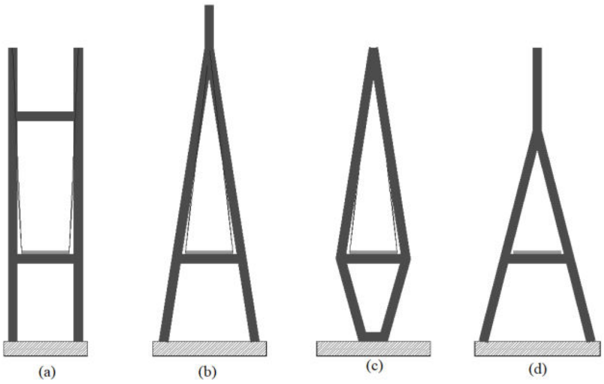

Fig.13. Two Plane Pylon front view.

Fig. 9. Shows the configuration for two cable planes in a front view.

Fig.14. Three Plane Pylon front view.

From the study it had become clear that for long span the 'A' shaped pylon seems to be the preferred shape for the pylon and all other local modifications have to be added such as cross members above the deck or having the pylon section below the deck inclined in the opposite direction to form a diamond shape. Further the use of 'A' shape for two or more cable planes indicates that the stiffness of the structure has got to do this shape of pylon as the shape being a triangle is the most stable of shapes.

C. Anchorage on the Pylon

All the bridges which have been referred to use the Intermediate Fan-Harp system and so the anchoring of the cables on the pylon becomes convenient. This is a very important consideration as there are many associated activities such as anchoring the cables, inducing the pre tension in the cables and possible cable exchange in the future. In all the studied bridges this is possible.

D. Some Different Configurations Suggestions for super large spans bridges and ultra high towers

Where the weight of the towers becomes too much and the soil conditions are not favorable, structurally as well as economically the design may not be possible and it might become necessary to think of steel as an alternative to concrete for the pylon. Also, if massive pylons are required for super long span bridges steel may be the only option to bring down the loads. In such a situation the Pylons can be designed as steel structures. These being vertical cantilevers with high lateral loads acting on them the pylons can be designed as trusses. The bracing system will take care of the lateral forces while the overall system can be designed to take predominantly compressive forces. It has been established that the height of the pylon will increase with increase in length and this is of critical importance. For long span bridges exceeding the current maximum spans the base of the pylon will have to be proportionally large. The carriageway can be taken within the truss members of the towers. The truss system also allows for two or more carriageway systems. However, very importantly, in such a system the provision for the anchor slots for the cables on the pylon face have to be designed and proper access to such areas are needed to control pre tension forces and also to protect the anchors from the elements. The main members could be of solid steel with hollow sections. Fig.15 shows the cable stayed bridge with steel trussed pylon. Fig.16 shows a close view of one side of symmetry of the bridge while Fig.17 shows the front vied of the trussed pylon.

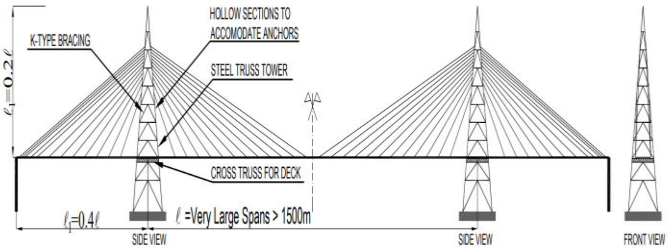

Fig.15. Cable Stayed Bridge with Steel Trussed Pylon

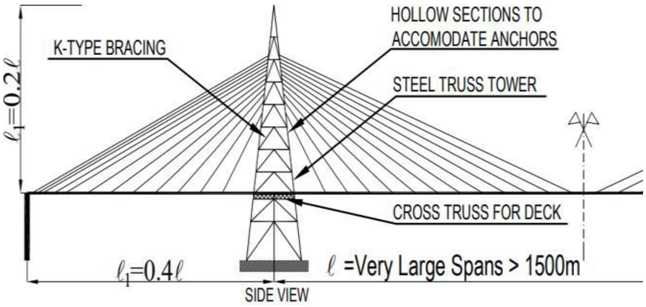

Fig.16. Close view of Cable Stayed Bridge with Steel Trussed Pylon

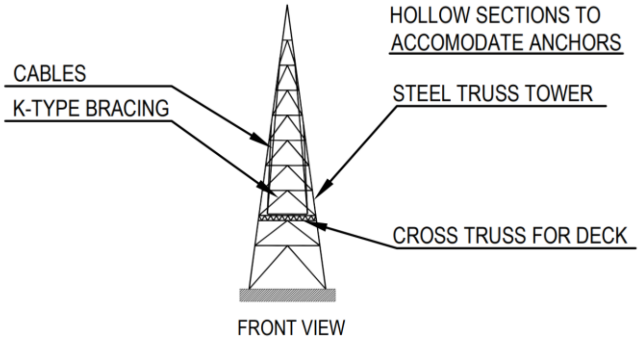

Fig.17. Front view of Cable Stayed Bridge with Steel Trussed Pylon.

V. CONCLUSIONS

Cable stayed design is a form of design which has been in practice for a few centuries but has not been explored to its limit. The advancement of material technology has allowed for this form of bridge design to be explored. Somo the conclusions form this study are as follows,

- The long span cable stayed bridges typically use a ‘A’ shaped pylon with local modifications to accommodate for carriage way, foundation side and other factors.
- Almost all bridges use concrete as the material for pylon construction.
- There are some inherent advantages of concrete being used as the material for pylon construction
- The height of the pylon is very important and the height is determined by the ratio of H=2L where H is the height of the pylon above the deck and L is the length of the main span.
- The anchorage of the cables on the pylon face is a very important consideration in pylon design.
- Steel is a material which can be used for the construction of pylons. Inherent disadvantages such as buckling of the compression members may be a deterrent but this can be taking care of with proper design and factors of safety.
- Vertical trusses with K-Bracing could be the solution for steel pylons with hollow sections to accommodate
- Pylon design and construction is integral to the structural stability and integrity of cable stayed bridges.

REFERENCES

[1] Troitsky, M. S.: Cable-stayed bridges. 2nd edition. BSP Professional Books, Oxford, (1988)

[2] Virlogeux, M.: Bridges with Multiple Cable-Stayed Spans, Structural Engineering International, 1, pp. 63 – 64 (2001).

[3] Svensson, H.: Cable-stayed bridges 40 Years of Experience Worldwide, Wilhelm Ernst & Sohn, (2012).

[4] Painato A.: Case study: the Russky bridge. Innovative Bridge Design Handbook, (2016)

[5] https://structurae.net/en/structures/russky-bridge

[6] Qin, Shun-quan & Gao, Zong-yu.: Developments and Prospects of Long-Span High-Speed Railway Bridge Technologies in China. Engineering. 3. 10.1016/j.eng.2017.11.001. (2017).

[7] https://structurae.net/en/structures/hutong-yangtze-river-bridge?r=/ouvrages/pont-hutong

[8] Dorian Janjic: Global Analysis of the Sutong cable stayed Bridge, IABSE Symposium Report 1(1):343-348, (2005).

[9] https://structurae.net/en/media/143216-sutong-bridge

[10] Morgenthal, Guido & Sham, Robin & West, Brian: Engineering the Tower and Main Span Construction of Stonecutters Bridge. Journal of Bridge Engineering - J BRIDGE ENG. 15. 10.1061/(ASCE)BE.1943-5592.0000042, (2010).

[11] Li, Ming Sun, Yanguo Jing, Hongmiao Li, Mingshui.: Vortex-Induced Vibration Optimization of a Wide Streamline Box Girder by Wind Tunnel Test. KSCE Journal of Civil Engineering. 22. 10.1007/s12205-018-0548-y. (2018).

[12] https://structurae.net/en/structures/russky-bridge