General scheme design of ShiZiYang Suspension Bridge

J. B. Marcussen
COWI, NYC, USA

ABSTRACT: The ShiZiYang suspension bridge in the GuangDong province in China will when constructed have a world record main span of 2180 m and carry an impressive 2 x 8 lanes of traffic on the two-level truss girder. A bridge of this previously unmatched proportion requires innovative design concepts to develop a feasible and constructable bridge. COWI carried out a General Scheme Design in the initial design process to develop a concept for the overall configuration of suspended deck, tower, and cable system. Various alternatives for these main structural components were defined and pros and cons evaluated. Some component alternatives are mutual dependent such that for example the deck structural concept may define the cable system and type of towers. Several concepts were compared by a quantitative cost comparison to determine the preferred concept which was subsequently detailed further.

1 INTRODUCTION

The ShiZiYang suspension bridge in the GuangDong province in China will when constructed have a world record main span of 2180 m and carry an impressive 2 x 8 lanes of traffic on the two-level truss girder. The ShiZiYang Bridge will become the longest two-level truss-girder suspension bridge in the world and will set records in span, load, deck width, and main cable diameter.

A bridge of this previously unmatched proportion requires innovative design concepts to develop a feasible and constructable bridge. With the technical challenges in mind, it was decided to engage three bridge design companies to work simultaneously in the General Scheme Design stage, which is an early design phase (Jun, X et al. 2022). The three companies are:

- CCCC Highway Consultants Co. Ltd., China (HPDI), package bid winner.
- China Railway Major Bridge Reconnaissance & Design Institute Co., Ltd. (BRDI), package bid winner.
- COWI, design consultant of the main bridge.

The purposes of the General Scheme Design are to decide main technical parameters, collect design basis, perform subject studies, and most importantly make conceptual designs.

To ensure that the most suitable concept for the main bridge is determined, the three companies separately investigated various bridge concepts to derive each their preferred concept. In this paper, the General Scheme Design developed by COWI is presented. It noted that this does not correspond to the bridge final design, which is not done by COWI and is still in progress.

The process for developing the General Scheme Design follows the following steps:

1. Provide alternatives for the main structural components suspended deck, cable system, towers, anchor blocks and evaluate these independently.
2. Determine how the structural components are mutual dependent to determine multiple bridge concepts that include choices for each structural component. Evaluate these concepts qualitatively.

3. Determine the preferred concept based on a quantitative approach where the costs of the concepts are compared.
4. Detail the preferred concept and the structural components.

The structure of the present manuscript follows the order of the items listed above.

2 BASIS

Certain global design parameters determined in a Baseline Design for the bridge were decided at the onset of the General Scheme Design. This includes overall alignment, tower positions, and double level 16 traffic lane configuration. Main structural concepts and other parameters could be changed compared to the Baseline Design.

Figure 1 shows the plan and elevation for General Scheme Design and shows the main bridge overall dimensions, while Figure 2 shows the suspended deck cross section.

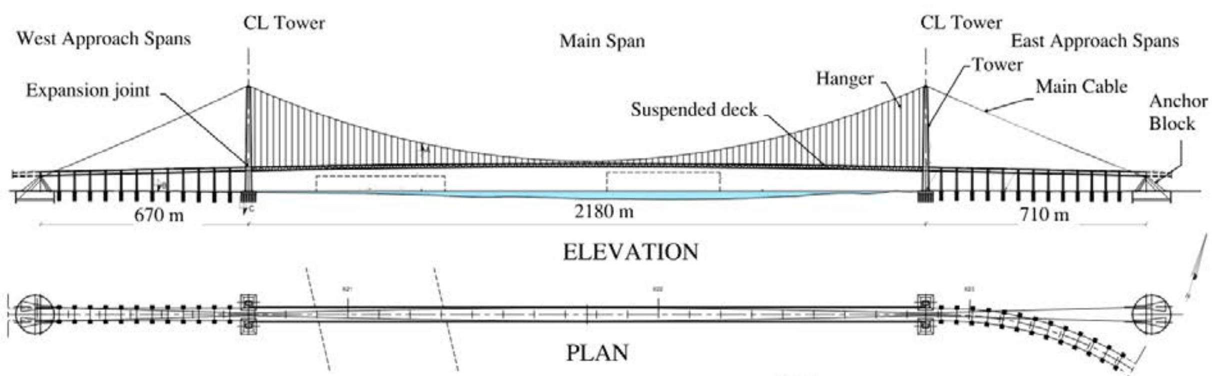


Figure 1. Elevation and Plan of ShiZiYang Main Bridge.

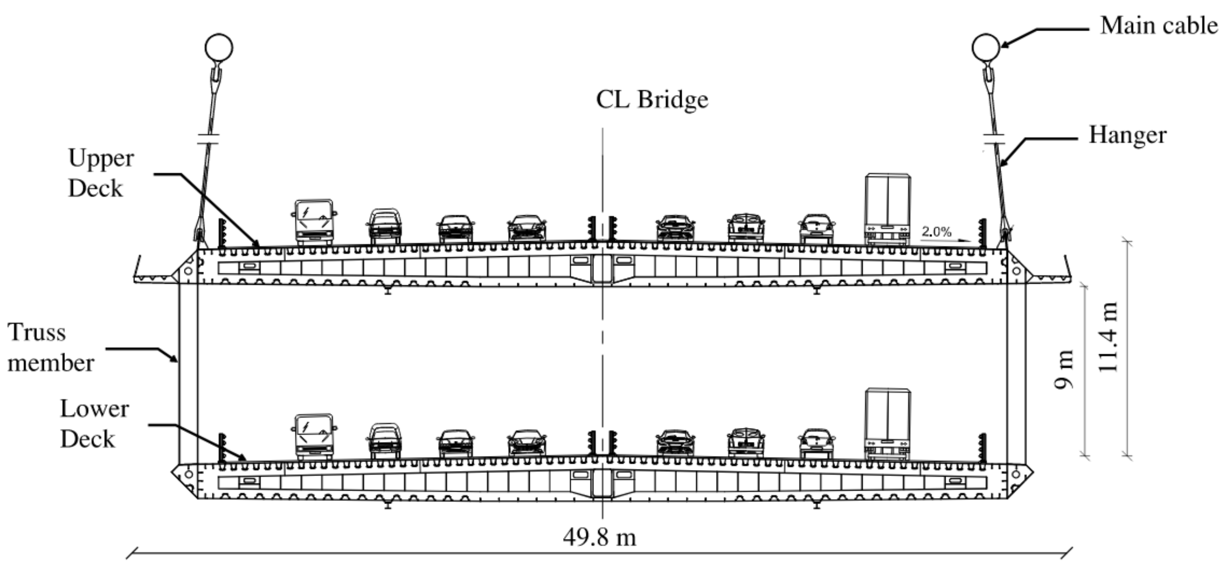


Figure 2. Suspended deck cross section.

The basis and loads for the design are based on Chinese codes, environmental conditions, and traffic requirements etc. In terms of the structural verification methodology and load combinations, the Chinese designers BRDI and HPDI made their design according to Chinese codes, whereas COWI's design was based on Eurocode. It was considered as an additional value of the General Scheme Design that the bridge was analyzed based on these two different code systems particularly since this bridge is beyond what codes are generally prepared to cover.

3 KEY DESIGN DRIVERS

Key design drivers are the most significant design features that will likely be controlling the design or features that shall be considered in the early phase. Design driver are fundamentally main focus areas that have a consequence on the cost, time, and quality. The objective is to identify the main design drivers in the beginning of the concept design phase to achieve a robust and reliable concept design which is cost effective and where future risks can be mitigated early and controlled during the subsequently design phases.

The General Scheme Design has been based on considerations of the various general demands to a modern state-of-the-art bridge design, such as:

- Weight optimized bridge deck design
- Strength and stability as load carrying element for the roadway traffic
- Robust structural design solutions
- Aeroelastic wind stability - Extreme winds
- Durability and long-term performance
- Economic efficiency & life cycle cost
- Sustainability
- Reliability and predictability
- Aesthetics (landmark)
- Functional requirements
- Soil conditions
- Constructability

4 STRUCTURAL CONCEPT DEVELOPMENT

4.1 *General considerations*

Key to the success of any long span suspension bridge is minimum weight, so starting with the deck, several deck arrangements were examined to explore opportunities for weight saving. Factors affecting operation and maintenance as well as the visual appearance were considered concurrently. Minimizing long term maintenance requirements is a critical factor, particularly on such a busy and long structure, and access for easy maintenance is considered a high priority.

The main cable sag profile (distance between towers divided by vertical height of cable curve) is an important parameter as it has a significant influence on the cable tension and thus the size of the cables, anchorages, and towers. A span to sag ratio of 9 is most commonly used for suspension bridges and considered the default value. If choosing a higher ratio of say 9.5 this has the effect of reducing tower height and cable length but also increasing cable tension. The span-to-sag ratio also affects the bridge behavior since the overall stiffness of the system is related to cable sag, and the appearance of the bridge is also similarly affected. Therefore, the concept development has considered this range of options to evaluate the magnitude of the effects and identify the preferred configuration.

Considering the challenges of cable compaction leads to a practical limit on the main cable diameter of about 1.5 m. This is significantly larger than any suspension bridge cable built to date but is considered feasible by those with experience of suspension bridge construction. Currently the largest cable diameter applied is 1.3m on the WuFengShan Yangtze River bridge (road and railway combined located in JiangSu province with a main span of 1092m）with 4 railway tracks on lower deck+8 road lanes on upper deck. With only two main cables (one on each side) it is clear that the cable diameter will be close to the 1.5 m limit, even with high strength wires. Thus, consideration has been given to bridge configurations involving two, three and four cables in the cross section. In the case of four cables, these would be arranged as two pairs of closely spaced cables in two cable planes. In the case of three cables, these would involve an extra truss in the girder running along the bridge centerline supported by the center cable.

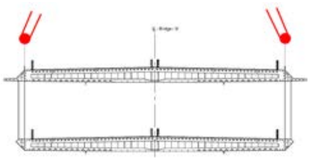
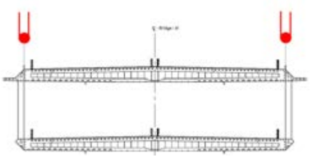
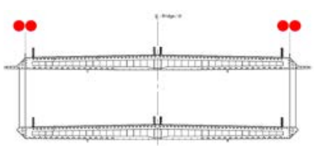
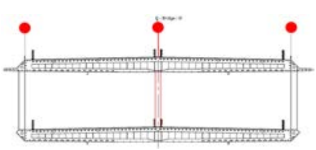
The towers are the major visual feature of the bridge and will be very dominant features in the landscape. It is therefore imperative that they are not only functional and efficient, but also beautiful and elegantly shaped. The desire for a landmark bridge is to conceive something unique and perhaps unusual as the defining feature for this bridge. There is a desire that the ShiZiYang bridge should be instantly recognizable with a characteristically unique tower shape, and this has strongly influenced the design development. Thus, in parallel with considering the pros and cons of two or three cable planes, both H-shaped and A-shaped towers have been considered with either vertical or inclined cable planes. In the case of the 3-cable design, the center cable plane is always vertical, but the two outer cable planes could be either vertical or inclined, and this leads to the possibility of A-shaped tower options.

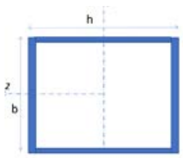
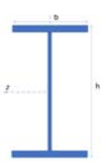
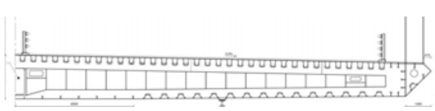
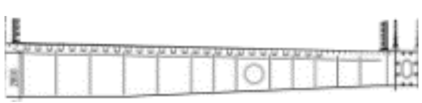
Aerodynamic behavior is of paramount importance for long span suspension bridge design, and the behavior in wind is influenced by the cable arrangement, the shape and nature of the bridge girder and the distribution of bridge mass. All of these have been considered in the concept design development to ensure that the behavior in wind is acceptable.

4.2 *Component alternatives*

Table 1 gives an overview of advantages and disadvantages for various alternatives for the different main structural components.

Table 1. Alternatives for structural components.

Alternative	**Advantages**	**Disadvantages**
Main cables and suspended deck support		
2 inclined cable planes, 2 trusses 	Aesthetically preferred compared to vertical cable planes. Provides lateral stiffness.	Large diameter of main cables. Complexity in erection due to pushing the main cables away from their vertical plane.
2 vertical cable planes, 2 trusses 	Easier execution than inclined cable planes.	Large diameter of main cables.
2 cable planes with pairs of cables 	Feasible option if cable diameter becomes too big when single cables are used.	Complicated detailing of anchorages and saddles. Increases space requirements and requires deck widening. Construction complexity. Cable aerodynamic instability (wake galloping).
3 cable planes, 3 trusses 	Reduced weight of the suspended deck as the cable system provides an additional support. Smaller diameter of main cables and associated components such as hanger anchorages.	Increased median width and therefore requires wider deck. Complexity in erection.
Towers		
A-shaped towers 	Aesthetically preferred. Possibly structural advantages due to increased stiffness. Weight saving compared to H-shaped tower.	Some complications in erection of deck segments. Increased tower foundation footprint.

Alternative	Advantages	Disadvantages
Diamond shaped towers 	Small foundation foot-print.	Likely too small dimensions at the tower base in relations to foundations. Large deviation forces in the tower due at the kink of the tower legs. Aesthetically inferior to A-tower.
H-shaped towers 	Leads to suitable dimensions at tower base in relation to foundation requirements.	Traditional appearance. Increased weight compared to A-tower.
Suspended deck options		
V-type trusses (Warren truss) 	Aesthetically preferred with approx. 45° diagonals.	May lead to longer superstructure segments than preferred.
N- or M-type trusses 	Increased flexibility in choosing segment lengths.	Likely heavier than V-type truss. Reduced view for lower deck traffic. Aesthetically inferior to V-type truss.
Box elements in truss (closed section) 	Aesthetically preferred. Easy maintenance: inside dehumidified and outside surfaces easy to paint.	Possibly heavier than open section in case of 3 trusses where demands are smaller.
H-shaped truss elements (open section) 	Reduced weight in case of 3 trusses. Easy transfer of hanger force, as truss diagonal web can be placed directly below hanger.	Reduced robustness. Maintenance not as easy as for box elements.
Decks with bottom plate (closed box) 	Dehumidification possible (inside painting omitted). Easy repainting on outside. Superior Aerodynamic performance	Heavier than open deck in case of 3 trusses.
Decks without bottom plate (open deck) 	Weight saving in case of 3 cable planes.	Aerodynamic performance inferior to closed box. Difficult maintenance and repainting, especially above lower deck.

Alternative	Advantages	Disadvantages
Large vertical spacing between upper and lower decks (12 m)  	More headroom at lower deck improves driver comfort and fire safety. Higher stiffness.	Increased weight of diagonals.
Small vertical spacing between upper and lower decks (8 m)  	Reduced weight of diagonals.	Likely reduced wind stability. Low headroom at lower deck provides less fire safety.

4.3 Qualitative concept evaluation

It is evident from the alternatives presented in Table 1 that some choices are mutually dependent between the various components. As previously mentioned, the key for a suspension bridge is minimum weight so the starting point should be the suspended deck. Considering the deck:

- If two longitudinal trusses are chosen, there needs to be two cable planes and H-tower shape would be the most conventional although A-tower shape would also work
- If three longitudinal trusses are chosen, three cable planes would be the obvious choice although two cable planes could also work. With two cable planes, there is little benefit of the third truss, as the cross beams at hanger locations shall still span the distance between the outer trusses. In between hangers the cross beams could instead be supported by a central longitudinal beam at upper and lower deck. With three cable planes both A-tower and H-tower would both be valid options.

There are other parameters in Table 1 that are independent on the fundamental choice of number of trusses and cable planes (for example vertical space between decks). However, the fundamental choice for the concept is number of cable planes and tower shape. The fundamental concept options are presented in Figure 3.

The four concept options shown in Figure 3 are qualitatively compared in Table 2.

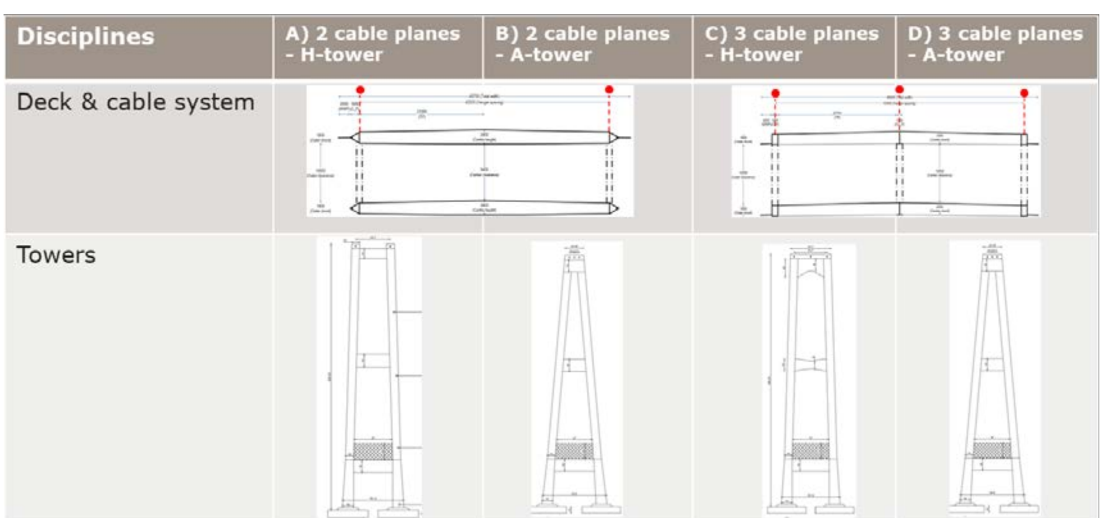


Figure 3: Fundamental concept options.

Table 2. Qualitative comparison of concepts.

		A) Two cable planes, H-tower	**B) Two cable planes, A-tower**	**C) Three cable planes, H-tower**	**D) Three cable planes, A-tower**
Suspended deck	**Advantages**	Closed upper and lower deck can be used without weight penalty. Increased stiffness. Can be dehumidified. Access inside the deck. Better appearance. Wind load reduction due to more aerodynamic shape.		Reduced weight / material saving (in case no bottom plate of the upper and lower deck). Reduced lifting capacity requirements.	
	Disadvantages	Panel handling/fabrication due to larger/heavier members and closed decks.		Additional detailing. Deck width must be increased due to median required by center main cables. Dehumidification of deck not possible (unless adding bottom panels). Limited access under the deck plate. Steel added for center truss is not utilized efficiently for wind load cases.	
Cable system	**Advantages**	Most straight forward. Possibly one tower saddle type.	Possibly one tower saddle type. Architectural preference. Slight improved behavior for wind.	Reduced cable diameter. Lighter tower saddles.	Reduced cable diameter. Lighter tower saddles. Slight improved behavior for wind.
	Disadvantages	Large cable diameter. Heavy tower saddles.	Complexity of inclined cable planes. Large cable diameter. Heavy tower saddles.	At least 2 different saddle types. Architectural disadvantage.	Complexity of inclined cable planes. At least 2 different saddle types. Architectural disadvantage.
Towers	**Advantages**	Easier construction.	Aesthetics. Lighter cross beams. Reduced tower quantities.	Easier construction.	Aesthetics. Lighter cross beams. Reduced tower quantities.
	Disadvantages	Visually not a unique concept.	More difficult to construct. Tie beam required at the base.	Lower cross beam to support deck center truss required. Heavy transfer structure at tower top due to center cable.	Lower cross beam is required to support deck center truss.

The anchor blocks are almost neutral regarding the 4 options and thus not decisive for the choice of the preferred option. Three cables require more workmanship for the anchor blocks and the approach span shall have an allowance/opening for the middle cable. The anchor block quantities will be approximately the same for all options.

4.4 Quantitative concept evaluation and decision

A qualitative comparison is not sufficient to identify the preferred concept. The four concept options shown in Figure 3 and Table 2 are therefore in the following compared quantitatively based on estimated relative fictive costs of the four concepts. The prices are relative only, since only the main structural components are evaluated. The prices are fictive only as for example the unit prices of structural steel, concrete etc. are not known. The relative price difference between the unit prices have been estimated based on experience from projects in Europe. The overall philosophy in the comparison is to assign all concept attributes to a financial value so that the options can be compared by looking at the total cost only.

Such a comparison can only be very approximative at this concept design stage. An exact comparison would require detailed insight about contractor construction preferences, quantity prices, salaries, equipment availability etc., and information about what value the owner and contractor would assign to items as maintenance and operation, aesthetics, and sustainability. It does not require the same detail to make a quantity comparison of the 4 concepts, which is shown in Table 3.

Table 3. Quantitative comparison of concepts (fictive prices).

		A) Two cable planes H-tower	**B) Two cable planes A-tower**	**C) Three cable planes H-tower**	**D) Three cable planes A-tower**
Material cost:					
Suspended deck	Material cost	4,340	4,340	4,089	4,089
Cables	Material cost	7,151	7,152	6,881	6,882
Towers	Material cost	4,800	4,710	4,800	4,710
Anchor blocks	Material cost	7,640	7,640	7,640	7,640
Material cost total		*23,931*	*23,842*	*23,410*	*23,321*
Other cost:					
Suspended deck	Additional maintenance cost as no dehumidification	0	0	204	204
Suspended deck	Handling / fabrication of heavier components and closed box	130	130	0	0
Cables	Inclined cables added complexity	0	286	0	344
Cables	Construction added complexity due to 3 cable planes	0	0	550	551
Towers	Propping of inclined legs in construction	0	63	0	63
Towers	Cross beam at tower top due to center cable	0	0	165	78
Anchor blocks	Anchor blocks complexity	0	0	100	100
General	Visual appearance	300	0	600	400
Towers	Cross beam supporting the center truss	0	0	165	78
Suspended deck	wind	0	0	500	500
Cables	Risks associated with high diameter main cables	200	200	0	0
Cost other than material cost, total		*630*	*679*	*2,224*	*2,256*
Total		**24,561**	**24,521**	**25,633**	**25,577**

Based on the material cost alone, option C and D have the smallest cost and would thus be preferred from a pure material perspective. However, due to added other cost from additional construction complexity due to 3 cable planes, additional maintenance due to open suspended deck system, and visual appearance, options C and D become approximately 5% more expensive than option A and B.

Comparing options A and B shows that they are almost equally favorable from a cost perspective. There is a small tower quantity saving for the A-tower, but the A-tower construction is more complicated due to the higher inclination of the legs that requires more propping, and the inclined cables also add construction complexity. The visual appearance is deemed to be favorable for the A-tower and it is basically the visual appearance that is decisive for achieving a lower total cost for option B. Since option B has the lowest fictive cost, option B is the chosen concept. This choice is also based on the desire to produce something unique compared to the H-tower concept. The two options are so close cost wise that only a more detailed study can determine, which would be most favorable.

The order of magnitudes for the "other cost" (values in Table 3) are compared to the material cost. Considering the chosen concept B, the percentage cost for each of the main structural components suspended deck, cables, towers, anchor block, and "other cost" are presented in the pie chart in Figure 4.

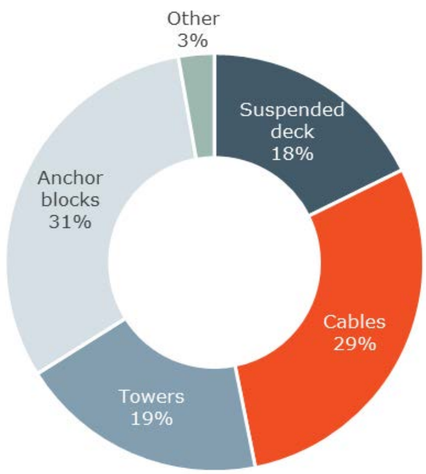


Figure 4. Cost percentage for main components of chosen concept B.

It is seen that the material cost makes up 97% of the total cost and only 3% cost is due to other evaluated costs. The anchor blocks and the cables are by far the costliest structural items for the bridge. The ratio between material cost and other cost could change slightly but the overall conclusion is that the material cost for this large-scale bridge is very dominant.

Since concept Option B is chosen, the main features for deck, towers, cables are:

- Suspended deck with two trusses
- Cable system with two cable planes and inclined cables
- A-shaped towers

The suspended deck, cable system, and towers are presented further in the subsequent chapters. In addition, features that do not have a direct impact on the concept decisions above (e.g. part of the suspended deck detailing) are also discussed.

5 ARCHITECTURAL APPRECIATION

The General Scheme Design is developed in cooperation with UK based Knight Architects. The vision is to create a unique bridge for a unique part of the world where the bridge is situated. Within the complex engineering constraints, the bridge shall become a fitting addition to the natural and built landscape, to provide an exceptional user spectator experience, and become an important part of the future identity of the area. The scheme should capture the public imagination, galvanize ambition, and contribute to unlock the wider value of the whole area. The key design elements that offer the opportunity to achieve this are:

- Tower geometry and shaping
- Deck truss type and proportions
- Geometry of anchor blocks for the main cables

Figure 5 shows a bird's eye view rendering of chosen concept, while Figure 6 shows rendering of deck and bridge view of chosen concept.

Figure 5. Rendering of chosen concept, bird's view.

Figure 6. Rendering of chosen concept, deck and bridge view.

While seeking high architectural quality, structural honesty is also essential as bridge design should be driven by engineering and science. The triangular shape became the shape in which the various structural elements relate to each other. The triangular shape occurs in the side view of the bridge made by the deck, cables and towers and can also be found in the Warren Truss, A-tower, as well as anchor blocks. The main features of the main structural components are described in the following chapters.

6 SUSPENDED DECK

The suspended deck is made up of upper and lower closed girders connected by two planes of diagonals in a Warren truss arrangement. The triangular shaped edges of the box girders break their visual depth into two by creating two different shadows, providing aerodynamic benefits, and increasing the perceived slenderness of the deck. Figure 7 shows the main features of the suspended deck.

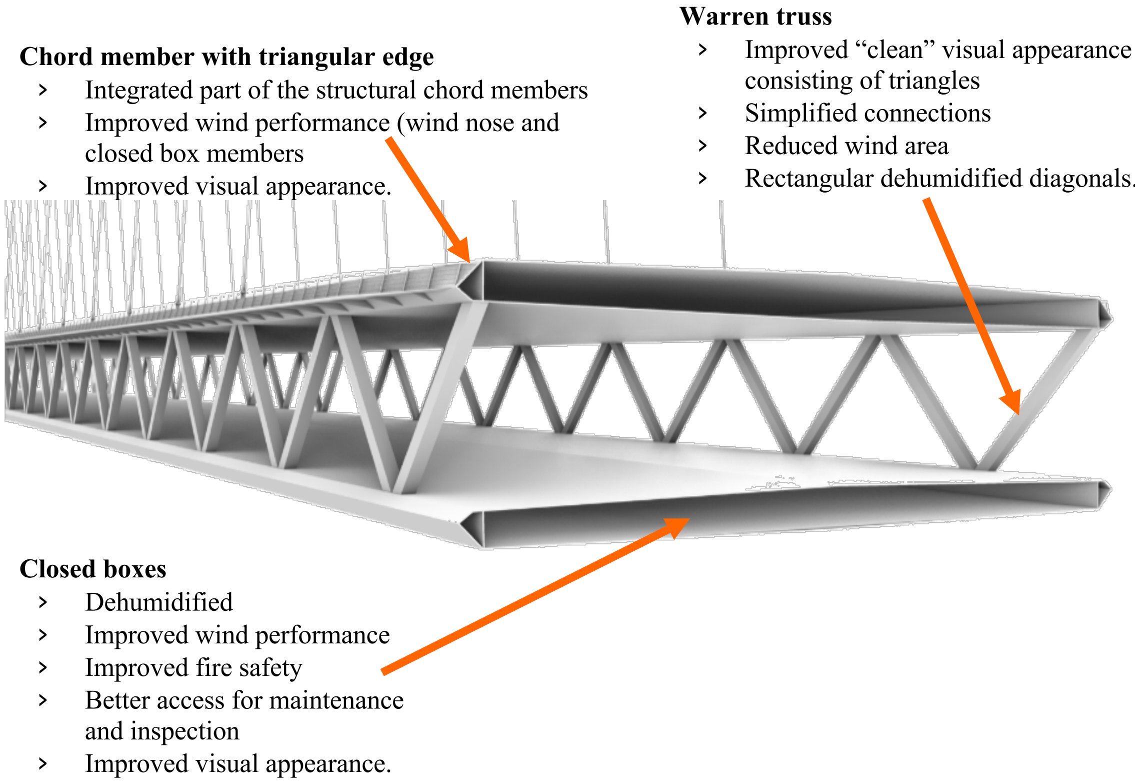


Figure 7. Suspended deck main features.

7 CABLE STRUCTURES

The main cables have a span to sag ratio of 9 and are parallel wire strand cables with strength of 2060 MPa. The highest possible steel strength is preferred to minimize the main cable diameter, which will also allow for easier cable compaction and reduce size of related structures (anchor blocks, saddles, cable clamps).

The main cable diameter is approx.1.4 m and the cross section consists of 372 strands formed by 127 no. of 5.8 mm diameter wires. Hangers are parallel wire strands (PWS) with strength 1860 MPa.

The hanger system consists of single hangers with 20 m spacing. Single hangers have been selected due to simpler arrangement of the cable clamps and hanger anchorages (compared to dual hangers) without using unconventionally large hanger cross sections.

The hangers are connected to cable clamps by means of pinned connections at the top, and also with pinned connections at the bridge deck eye plates.

Due to the A-shaped towers, the main cable planes are inclined, which provides additional lateral stiffness compared to vertical cable planes, which is particularly beneficial for transverse wind loads on the bridge (Jamal, A & Sundet, E, 2021).

8 TOWERS

The towers are because of their scale and verticality the elements of a suspension bridge with the highest impact in how the crossing is perceived and remembered. The 360 m high A-shaped towers will be elegant and make the bridge unique.

In the past, a range of different tower forms have been proposed for cable supported bridges (Gimsing, N & Georgakis, C, 3rd 2012), but long span suspension bridges are by far most commonly designed with H-shaped towers.

The A-shaped tower is chosen partly for aesthetic reasons, but it also has structural advantages in comparison with the conventional H-shaped tower in terms of higher stiffness and material savings due to smaller bending moment demands (Proverbio, M et al., 2022).

Figure 8 shows rendering of tower concept from bridge deck while Figure 9 shows rendering of tower at night.

With the aim of making the tower composition clear and clean, a faceted dome made of translucent fiber reinforced polymer (FRP) is placed above the main cable saddles to extend the shape and narrow the tower top. It will glow at night and act as a roof for a potential vantage point at the tower tops and contribute to the interest of the bridge as a destination.

Figure 8. Rendering of chosen concept. View from bridge deck.

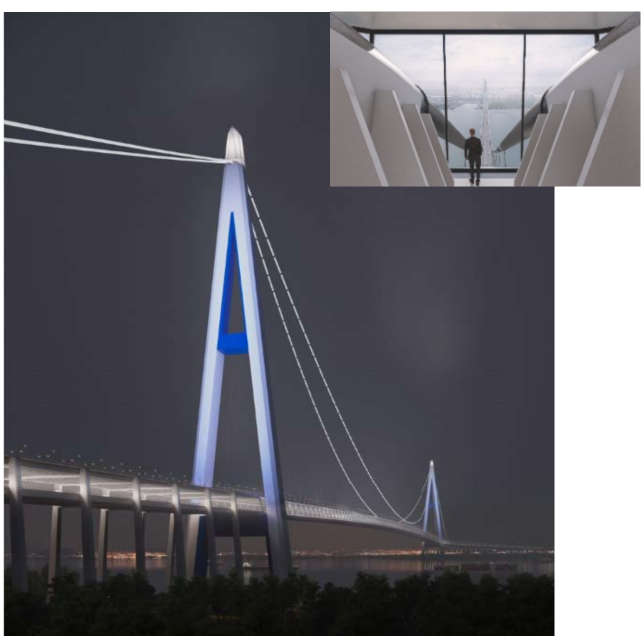


Figure 9. Rendering of chosen concept. Tower night view and the panoramic view of Pearl River Delta from tower top (inset).

9 ANCHOR BLOCKS

The triangular shape of the anchor blocks in elevation is a result of the pure structural requirements and is an excellent starting point from a visual point of view, Figure 10. A faceted geometry has been used for the anchor blocks at both ends, to sculpt the base structural shape into different surfaces that will vary in how they reflect the light. This helps to increase the visual quality and their apparent slenderness.

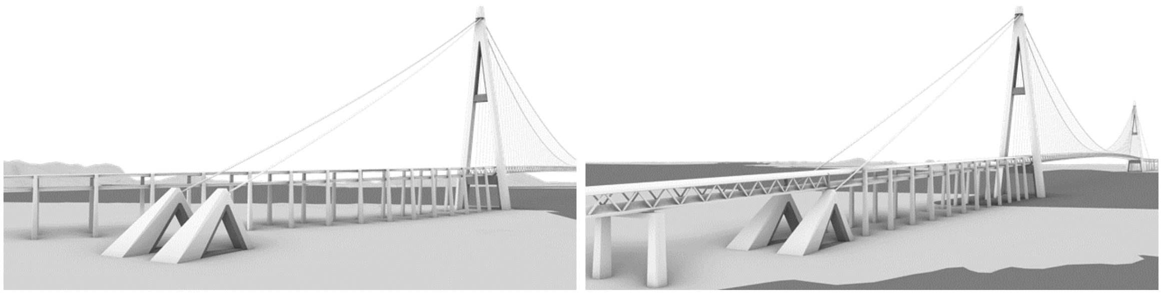


Figure 10. Anchor blocks on East and West ends of the bridge respectively

The anchor block foundation consists of a circular slab constructed within a diaphragm wall with a diameter of 125 m and a height of 30 m, Figure 11.

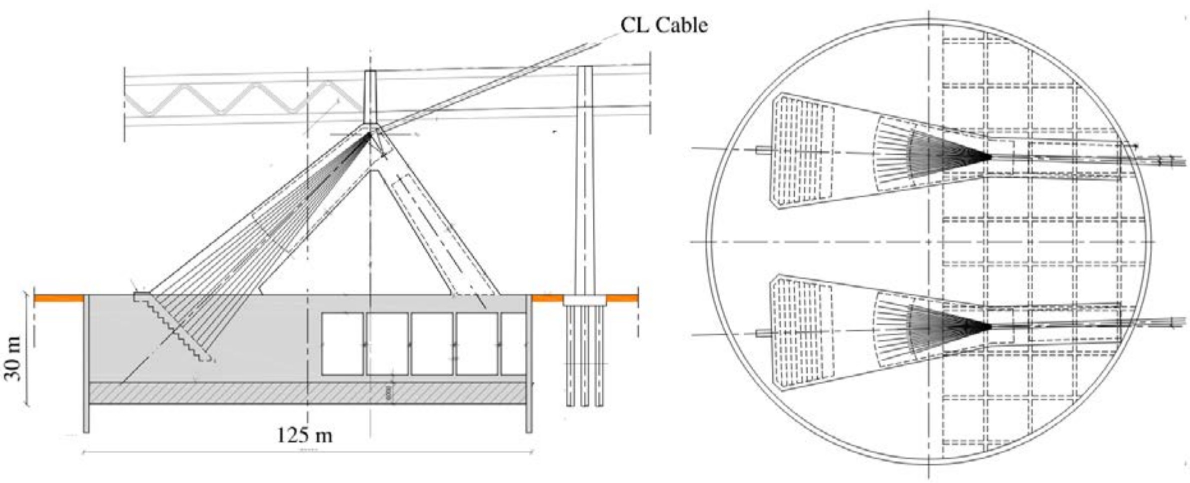


Figure 11. Anchor blocks elevation and plan

10 CONCLUSIONS

The ShiZiYang bridge with previously unmatched proportions requires innovative design concepts to develop a feasible and constructable bridge. Based on qualitative and quantitative studies COWI developed their preferred concept for the bridge. The preferred concept consists of as suspended deck with two truss girders, two inclined cable planes and A shaped towers. Although a saving in material could be achieved by adopting three trusses and three cable planes this would not make up for the added complexity and maintenance cost. H-shaped towers would be equally suitable and the decision between A-shaped and H-shaped towers would come down to a detailed cost estimation also accounting for the value of aesthetics.

The material cost is found to make up 97% of the total cost and only 3% cost is due to other evaluated costs relating to construction, risks, operation, aesthetics etc. The anchor blocks and the cables are by far the costliest structural items for the bridge. The ratio between material cost and other cost could change slightly during design developments, but the overall conclusion is that the material cost for this large-scale bridge is very dominant.

REFERENCES

Gimsing, N & Georgakis, C, 3rd 2012. *Cable supported bridges*. Wiley.

Jamal, A & Sundet, E, 2021. Hålogaland Bridge - a landmark in arctic Norway. *Structural Engineering International.*

Jun, X & YuGang, W & TaiKe, Z & Marcussen, J, 2022. ShiZiYang Bridge – General Scheme Design Options for Mega Suspension Bridge. *IABSE Congress Nanjing,* China.

Proverbio, M & Jamal, A & Marcussen, J, 2022. Conceptual design of long-span suspension bridges: tower structural forms. *IABSE Congress Nanjing*, China