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The Analysis of South Channel Bridge in Hangzhou Bay Bridge

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Abstract

As the technology of civil engineering develops, many long-span cross-sea bridges are built frequently. These bridges contain many advanced civil engineering knowledge and technology, which is valuable for engineers to investigate. Hangzhou Bay Bridge is one of the most extraordinary long span cross-sea bridges in China. South Channel Bridge and North Channel are the most particular parts in this bridge, which are cable-stay bridges with A-shape tower and diamond-shape double towers respectively. This article aims to introduce and analyze the structure of the South Channel Bridge in Hangzhou Bay Bridge. Before the analysis, the background and basic information would be provided in the section of introduction. In the analysis section, first of all, the materials and construction process would be described. Secondly, the types of design loads and the calculation process would be presented. Thirdly, the analysis of loading situation is provided to indicate route of loads transferring and components reactions. In addition, there are vertical and horizontal structural analysis models would be showed in this article to reflect the loading situations more accurately. Finally, the conclusion would summarize the whole content of article and describe the advantages and weaknesses of South Channel Bridge. According to the comprehensive analysis, the South Channel Bridge is a steel box girder cable-stay bridge with a single A-shape Tower, which obtains the extraordinary stability and durability. However, it is difficult and expensive to construct and maintain the bridge. According to the investigation of South Channel Bridge in Hangzhou Bay Bridge, the engineers could learn the advanced civil engineering ideas and apply these advantages to their future design.

Keywords

Applied Materials; Process of Construction; Calculation of Designed Loads; Route of Loads Transferring; Components Reaction.

1. Introduction

With the development of China's economy, more and more long-span bridges, especially sea crossing bridges, were built to strengthen transportation to meet the demand of production and life. Hangzhou Bay Bridge is one of the extraordinary cross-sea bridges in China, which is used to connect the Jiaxing city with Ningbo city in Zhejiang. Moreover, Hangzhou Bay Bridge obtains different structures for different bridge sections, which is one of the characteristics of the bridge. Hangzhou Bay Bridge is comprised by approach bridge and platform in the sea, North Channel Bridge, and South Channel Bridge. The approach bridge is continuous box girder structure and its piers have rectangular chamfered section. The platform in the middle of the sea adopts double-layer structure, and its foundation is bored pile and steel pipe pile. Nevertheless, the most distinctive designs are the structures of North Bridge and South Bridge. North Channel Bridge is a steel box girder cable-stayed bridge with diamond-shaped twin towers and double cable surfaces, with a main span of 448m, and South Channel Bridge is a steel box girder cable-stayed bridge with A-shaped single tower and double cable surfaces, with a main span of 318m (Wang et al., 2005) [1].

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Figure 1. The image of South Channel Bridge in Hangzhou Bay Bridge (Glabb, 2012)[2]

This article would only describe and analyze South Channel Bridge. The content of the article is organized as: First of all, the construction materials would be introduced and described. Secondly, there is a description for the process of the construction. Thirdly, the magnitude of designed load would be calculated, the wind load, the vehicle load and the self-weight of bridge would be into consideration of design load. In addition, the loading transferring route and each component reaction would be analyzed. In that section, the vertical and horizontal structural analysis model would be built and the designed load would be applied on the model, and the load transferring route and components reactions could be showed visually.

Figure 2. The route of Hangzhou Bay Bridge (Michiel1972, 2007)[3]

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2. The description and analysis of materials, construction process, designed loads calculation, loads transferring and components reactions

2.1 Materials and Process of Construction

The first step of the construction is building the pile foundation. Due to the South Channel Bridge is located in the deep sea area; the all foundations under the bridge are bored piles because the high pressure in the sea not allows existing technology to drain the water in the fixed area. The bored pile is created by using drill machine to construct the holes and adding concrete and reinforcement into the holes. According to Figure 3, the 4 foundations could be identified as D11, D12, D13 and D14 from left to right. The large cross-section could reduce the stress along the pile and the long depth could increase the friction from soil. Thus, these designs could improve the load resistance of piles. Due to the D13 is located at the bottom of the tower and it is the main supported column of this bridge, D13 should bear the maximum load between these piles. Therefore, D13 obtains the largest cross-section and longest depth. Moreover, the soil condition and cost consideration are other elements would determine the size and depth of piles.

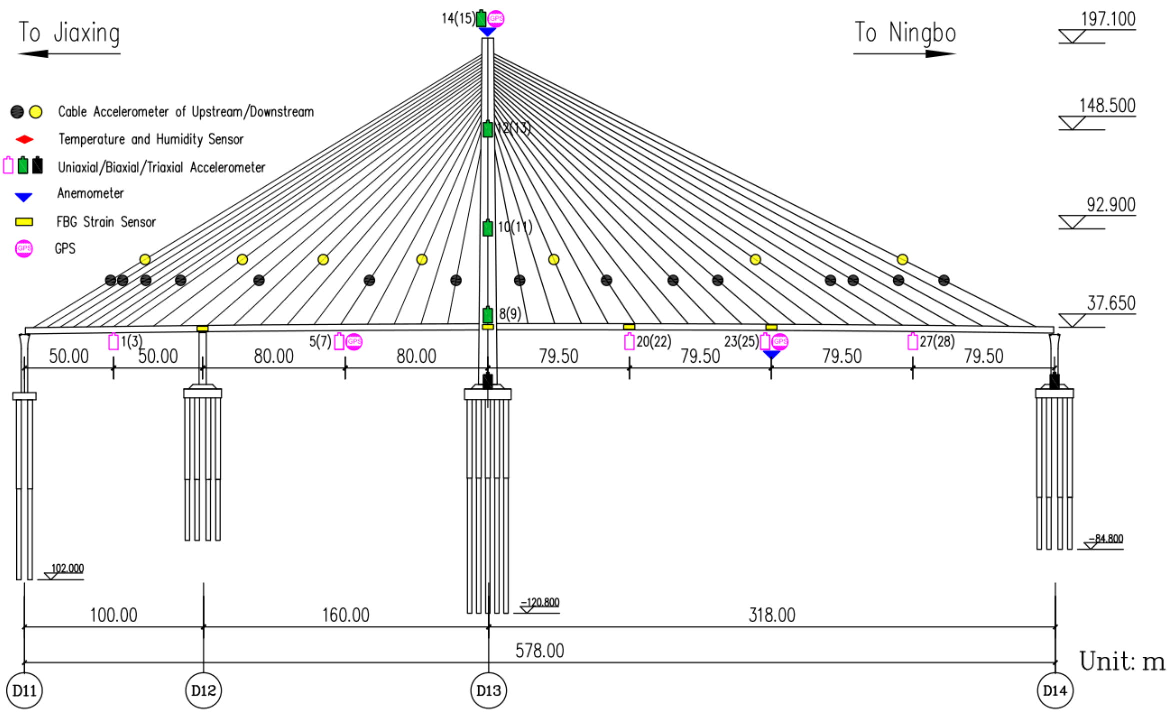

Figure 3. The layout of South Channel Bridge (Li et al., n. d)[4]

In the next section, the A-shape tower and piers would be constructed on the pile foundations. The single A-shaped tower and the piers adopt the reinforced concrete structure because the tower and piers would bear compression when the loading is applied on the bridge and the concrete is a material with excellent compression resistance. Furthermore, the reason why the designers not applied the steel to build the tower and pier is these sections are immersing into the seawater or closed to the sea surface are easy to be corroded and the steel exposes to the marine environment would be corroded severely than concrete. Although the concrete is used to build these structures, the corrosion still could not be avoided. Due to the bridge is constructed on the sea, the Chlorine ion, carbon dioxide from ocean weather and the seawater would cause carbonization of concrete through the penetration of micro-cracks in the surface layer of concrete, resulting in the reduction of pH value of concrete and the corrosion of blunt reinforcement inside the concrete, and the corrosion of reinforcement leads to the cracking and peeling of concrete structure eventually (Lai, 2007)[5]. Therefore, the ocean environment could decline the stability and durability of structure. In order to improve the safety and

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operation life, the researchers invented and manufacture the marine durable concrete which is a high performance structural concrete with high durability, high stability and good workability in marine environment, which is made of conventional raw materials, conventional processes, mineral admixtures and chemical admixtures and optimized by the mixture ratio. Chen (2009) stated that marine durable concrete takes chloride diffusion coefficient as the core control index and USES large proportion of mineral admixtures and low water-binder ratio to reduce chloride diffusion coefficient[6]. Moreover, painting concrete surface coating was also adopted on the reinforced concrete structure to reduce corrosion.

Thirdly, the deck would be built on the piles. In recent years, with the rapid increase in traffic volume, the bridge deck width and bridge span have shown an upward trend. Traditional concrete cable-stayed bridges have been unable to meet practical requirements, and large-span steel box girder cable-stayed bridges have emerged as a result (Zhou et al., 2009)[7]. In this construction, the deck is steel box girder structure which is one of the types of steel structure. For this structure, the deck is comprised by Q35D steel components with different size and this deck has advantages of small self-weight and fast construction process. Wu et al. (2006) stated that the steel box girders were manufactured in sections in the factory, transported to the bridge site by barge, lifted and welded on site[8]. The steel box girders were lifted by the bridge deck crane with four points balance. After reaching the installation position, temporary fittings are used to temporarily connect with the existing beam section. After accurate positioning, the U-rib high-strength bolt of the top plate is screwed, and the full section welding except the U-rib of the top plate is completed. The stay cable of the beam section is tensioned for the first time, and the crane is moved forward to lift the next beam section, and then the stay cable is tensioned for the second time. Moreover, in order to reduce the corrosion of deck, the anticorrosive paint would cover the structure.

As the previous section describes, the cable installment would be implemented when the girder is connected with the existing beam section. According to the research, Li et al. (n. d) introduced that 40 couples of steel cables that contain 109 to 199 steel wires with 7mm diameter are linking the deck and tower[4]. Moreover, he reflected that designed forces for the cable are between 1,425 to 3,892kN. Due to the steel is the ductile material with the advantages of large elastic modulus and strong ductility, it would not fracture immediately but deform gradually when the large loading is applied. Therefore, the steel cable could accept the tension effectively.

2.2 Designed Load

Generally, the design load would take permanent action, variable action and accidental action into consideration. In the designed load analysis, many loads are complicated to measure, thus, this section would estimate a part of loads that could be found the information from other resources. For South Channel Bridge, the variable action would be the vehicle load; the permanent action would be the self weight of bridge and the accidental action would be wind load. Moreover, this section would consider the designed loads of the vertical part and horizontal part.

The vehicle load is one of the important factors which determine the service life of bridge. As Sun et al. (2015) said, the bridges play a significant role in the process of economical development[9]. However, as economy improves, sharp increasing of the traffic volume will be more serious, especially in some big cities, and this situation would affect the safety of bridges and decline the normal service life of their structures. Due to the speed of vehicle is difficult to count, there is another way which is assuming the traffic jam occur on the bridge. The vehicle load of traffic jam is larger than the normal situation. Thus, the traffic jam could reflect the loading resistance ability more accurately. According to the statistics, the proportion of two-axle vehicles was 84.24%, and the proportion of three-axle, four-axle, five-axle, and six- and seven-axle vehicles was 3.44%, 2.84%, 1.6%, 7.78% and 0.01%, respectively (Ma et al., 2019)[10]. On the one hand, assume the weight of two-, three-, four, five-, six- and seven-axle vehicles is 10 ton, 15 ton, 23 ton, 30 ton, 40 ton and 50 ton respectively. On the other hand, assume the number of vehicle is 10,000. Therefore, the vehicle load could be calculated:

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Total Vehicle Weight

$$= (10 * 84.24\% + 15 * 3.44\% + 23 * 2.84\% + 30 * 1.6\% + 40 * 7.78\% + 50 * 0.01\%) * 10000 * 9.8 = 1{,}292{,}620\ (\mathrm{kN})$$

The variable action is given by:

$$\text{Variable Action} = 1{,}292{,}620\ \mathrm{kN}$$

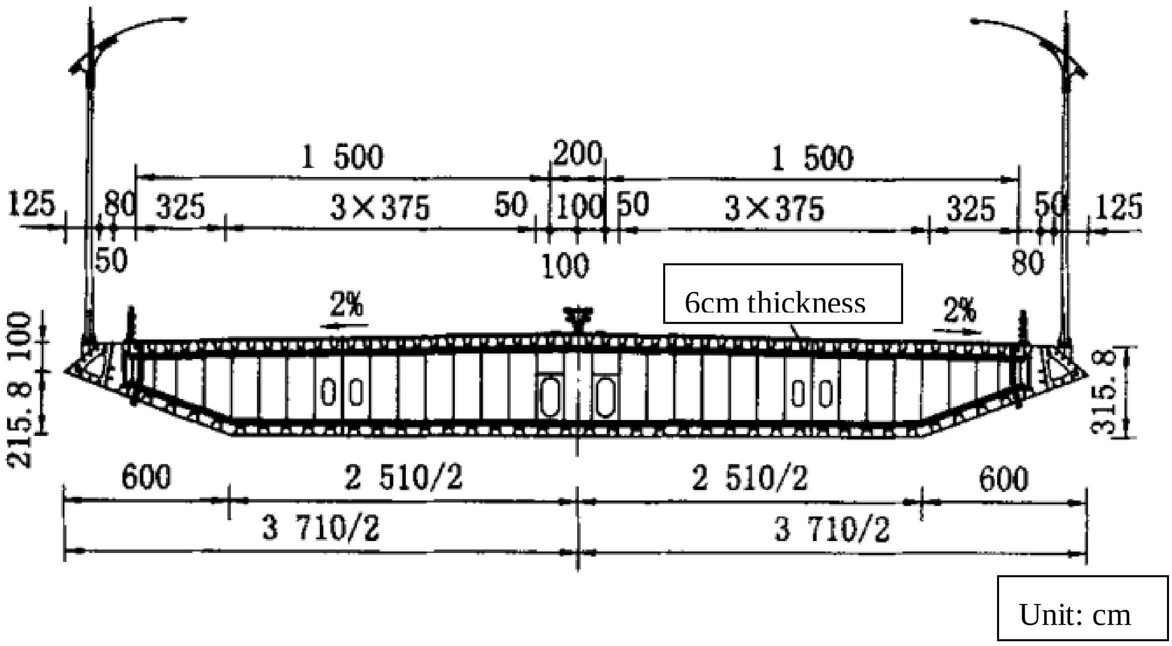

Figure 4. The cross section of deck (Wu et al., 2006)[8]

Moreover, the self-weight would also be considered as a part of designed load. In this section, only the weight of Q345D steel deck should be considered. According to research, the density of Q345D is 7.85*10^3 kg/m^3. The cross section is given by Figure 4. According Figure 4, the width of the above surface is 3710cm, the width of bottom surface is 2510cm, the depth of deck is 315.8cm and the thickness of cover is 6cm. Moreover, according to Figure 3, the total length of South Channel Bridge is 578m and the main span is 318m. Therefore, the area of cross-section could be calculated roughly.

Area of Cross-section

$$= \left(2510 + 1500 * 2 + 200 + \sqrt{215.8^2 + 600^2} * 2\right) * 6 + (100 * 125) * 2$$

$$= 66911.537\ \mathrm{cm}^2 \approx 6.69\ \mathrm{m}^2$$

The Value of Self-weight

$$= 9.8\ \mathrm{m/s^2} * 6.69\ \mathrm{m}^2 * 578\ \mathrm{m} * 7.85 * 10^3 \mathrm{kg/m^3}$$

$$= 297{,}474.46\ \mathrm{kN}$$

Thus, the permanent action is:

$$\text{Permanent Action} = 297{,}474.46\ \mathrm{kN}$$

The wind load is another factor which could not be ignored. Li et al. (2007) said, sea surface friction is less than ground friction, so the wind at sea is usually greater than the wind inland[11]. In addition, he introduced that Hangzhou Bay is located in the subtropical monsoon area, with strong sea-land breeze circulation. Thus, it is essential to calculate the wind load. The wind load combined with the vehicle load is calculated according to the bridge deck wind speed of 30 m/s, and the wind load not combined with the vehicle load is calculated according to the design wind speed of 39 m/s (Wu et al., 2006) [8]. In order to know the vertical wind load and combined loading condition on the bridge, the

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value of wind speed should be chosen as 30m/s. Moreover, the horizontal wind load could be calculated by the wind speed of 39m/s.

The equation of wind load is given by:

$$\mathrm{wp} = 0.5 * \rho * \mathrm{v}^2$$

wp: wind pressure (MPa)

ρ: density of air (ρ=1.293 kg/m^3)

v: wind speed (m/s)

Therefore, the vertical wind load is:

$$\mathrm{wp} = 0.5 * 1.293 * 30^2 = 581.85\ \mathrm{MPa}$$

$$\text{Vertical Wind Force} = \mathrm{wp} * \text{Deck Surface}$$

$$= 581.85\ \mathrm{MPa} * (578\ \mathrm{m} * 37.1\ \mathrm{m}) = 12{,}477{,}075.03\ \mathrm{kN}$$

Thus, the accidental action is:

$$\text{Accidental Action} = 12{,}477{,}075.03\ \mathrm{kN}$$

Therefore, the combined action (vertical load) is:

$$1.35 * \text{Permanent} + 1.5 * \text{Variable} + 1.5 * 0.6 * \text{Accidental Action}$$

$$= 401{,}590.116\ \mathrm{kN} + 1{,}938{,}930\ \mathrm{kN} + 11{,}229{,}367.53\ \mathrm{kN}$$

$$= 13{,}569{,}887.65\ \mathrm{kN}$$

Moreover, the horizontal wind load is:

$$\mathrm{wp} = 0.5 * 1.293 * 39^2 = 983.327\ \mathrm{MPa}$$

$$\text{Horizontal Wind Force} = \mathrm{wp} * \text{Side Area}$$

$$= 983.327\mathrm{MPa} * (3.158\mathrm{m} * 578\mathrm{m}) = 1{,}794{,}890.373\ \mathrm{kN}$$

In the comparison of 3 different actions, the maximum is permanent action which is vertical wind load and its value is 12,477,075.03kN. Moreover, in the vertical combined load aspect, the vertical wind load is main loading which contributes 11,229,367.53kN to the designed load. The second largest load is vehicle load which is 1,292,620kN and provides 1,938,930kN to designed load. The smallest load is self-weight whose value is 297,474.46kN and it only provides 401,590.116kN to total load.

Additionally, in the horizontal load, this calculation only considers horizontal wind load as horizontal load. According to the result, the value of horizontal is 1,794,890.373kN.

2.3 Route of load transferring and components reactions

In the analysis section, in order to know the specific components reaction and loading transferring route, the analysis would be divided to vertical and horizontal parts. The details of loading transferring and reaction of each component for vertical situation and horizontal situation are showed in Figure 5 and Figure 6 respectively. In Figure 5 and Figure 6, the dark blue arrows represent the route of loading transferring and arrows with other colors represent the components reactions. For the vertical part, first of all, when the vertical load is applied on the deck, the load would be transferred to the supports and cables simultaneously, which is shown in Figure 5. In the aspect of supports, the piles and piers would not only transfer the load to the ground, but also bear the compression and provide upward reactions to resist the vertical load. In the aspect of cables, the steel cables would obtain the tension with the obliquely contrary forces to pull the tower and deck, and resist the applied vertical load. Additionally, the cables would transfer the load to the tower. However, the tension from the cables would cause the downward compression and force along the A-shape single tower. The downward force is not only used to balance the upward component forces from cables, but also transfer the load to the supports. Furthermore, the directions of horizontal component forces of the cables on both sides of the bridge are opposite, which causes the extrusion of deck, and this situation leads to the compression along the deck. Moreover, the horizontal component force from cables' tension, vertical

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applied force and compressive force from piers are the shear forces on the deck, which cause the bending on the deck. According to the analysis, these loads would restrain and resist each other to ensure the equilibrium on the structure.

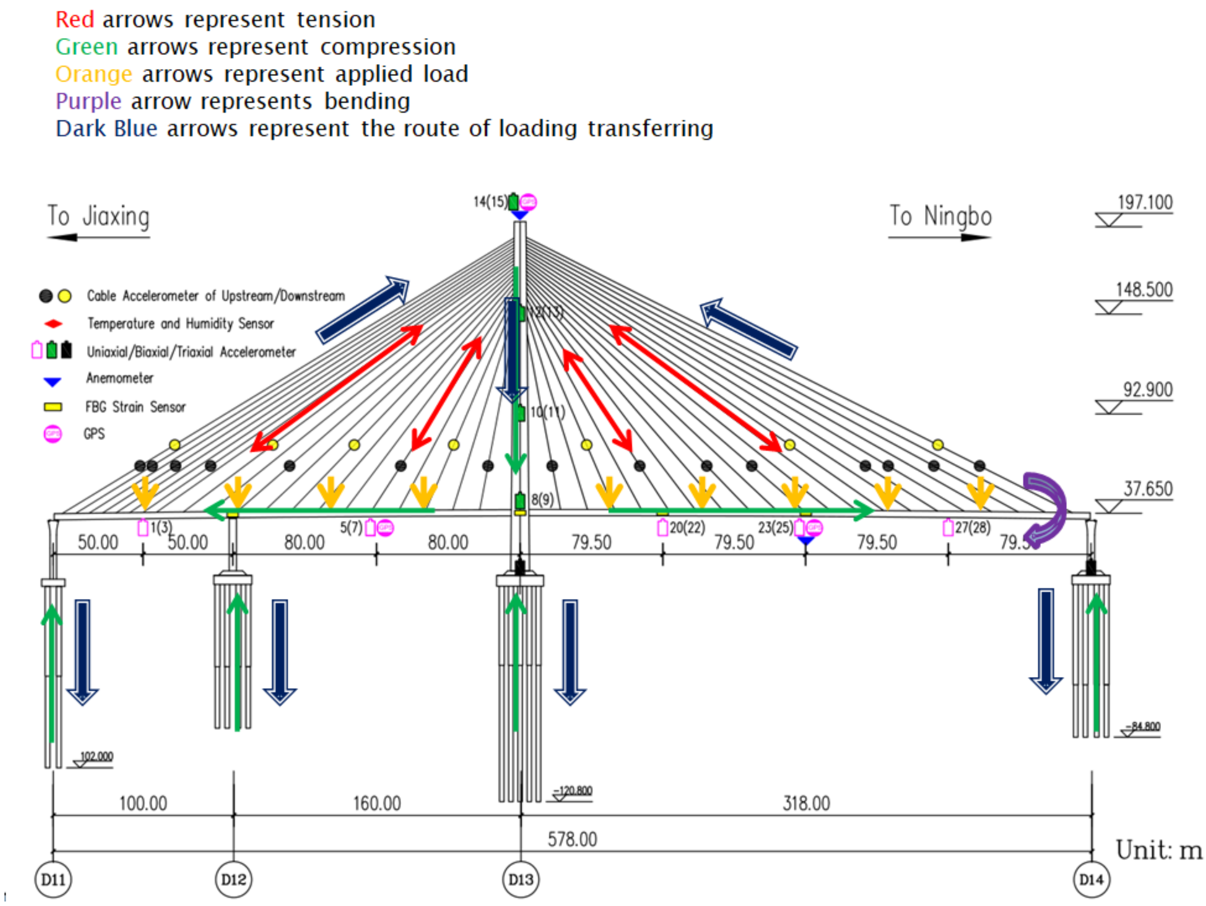

Figure 5. Vertical load analysis (Li et al., n. d)[4]

In the aspect of horizontal part, Figure 6 describes the details of load transferring and components reactions. When the horizontal load acts on the side surface of bridge, the bridge has a movement trend along the direction of horizontal load. The load would transfer to the supports and cables in the meantime, which is same as vertical analysis. The piers and piles would not only obtain the opposite horizontal reactions to resist the horizontal load, but also provide the vertical forces to keep the bending moment equilibrium of the structure. However, the two supports have different loading situation, which is shown in Figure 6. The support in the left side would bear tension and the right side would bear compression. Additionally, the cables obtain the oblique and transverse tension at the meantime to provide lateral resistance to against horizontal applied load. When the load transfers to the tower by cable, the tower would continue transfer the load to the supports. However, the load would transfer along the two arms of the tower, and the loading situations are different in these 2 arms. As Figure 6 shows, the arm in the left is tensile and the right is compressive. The loading situations of the tower's arms are desired to restrain the deformation and return the tower to its original shape. Furthermore, the deck would bear the compression because the tension from the cables causes a trend of contraction along the deck. In addition, the loads which are perpendicular on the surface of deck would lead to the bending on the deck. The bending difference between vertical and horizontal analysis is the arm of force in vertical analysis is only length of deck but the arms are deck's width and thickness in the horizontal analysis. In generally, the route of loading transferring and components reactions could be analyzed by deformation trend and the loads would also restrain each other to keep structural equilibrium, which is same as vertical analysis.

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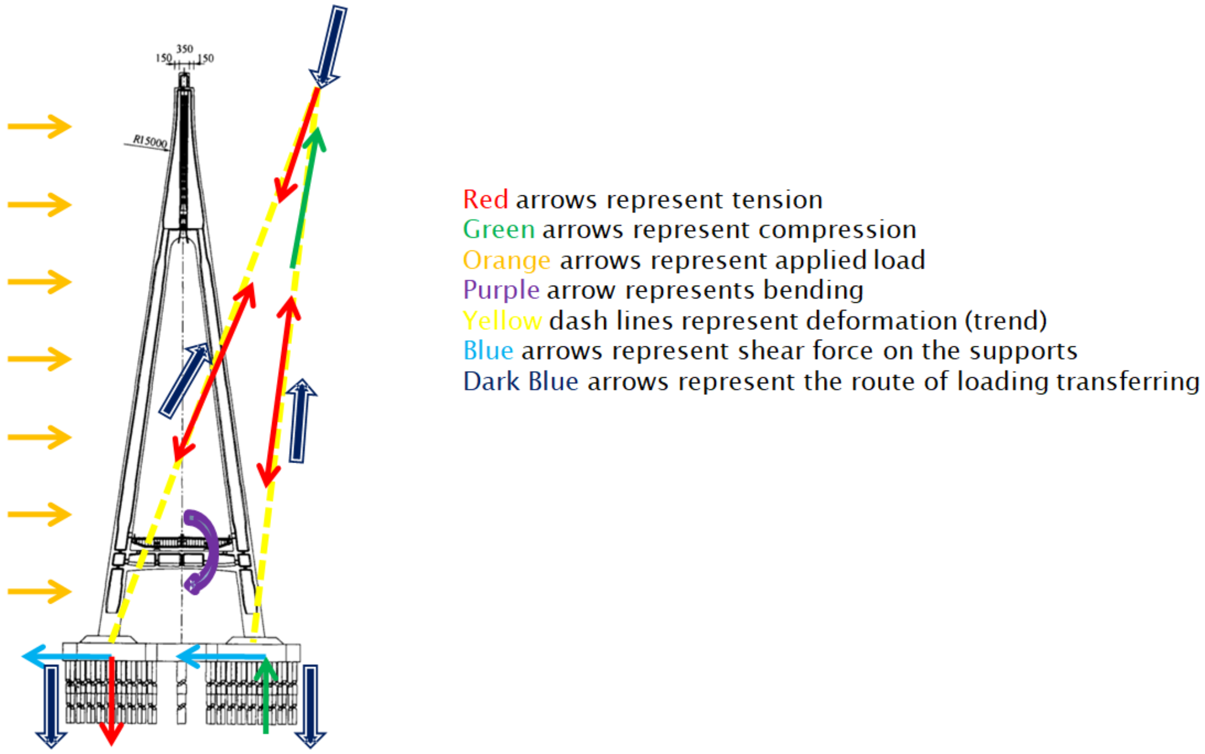

Figure 6. Horizontal Load Analysis (Wang et al., 2005)[1]

3. Conclusion

In Summary, South Channel Bridge is the most extraordinary part with special structure in Hangzhou Bay Bridge. In the materials and construction process part, the bored piles are constructed as foundation of South Channel Bridge because of the high water pressure. The piers and single A-shape tower are built as reinforced concrete structure with marine durable concrete, to improve the service life in ocean. Moreover, due the large width and span requirement of the bridge, the traditional reinforced concrete is not enough to satisfy the demand and the steel box structure should be applied to construct the bridge. Furthermore, there are 40 pairs of cables were installed to connect the tower with deck. These components cooperate with each other to construct the South Channel Bridge as a cable-stay bridge. Additionally, the magnitudes of designed loads, route of load transferring and components reactions are provided in this article. In the designed loads comparison, the loading from the self-weight of bridge is greater than other loads, such as wind load and vehicle load. In the section of load transferring route and components reactions, the loading situation is separate to vertical and horizontal parts so that simplify the analysis. The vertical and horizontal analysis both show the loading transferring route and components reactions in detail. Generally, South Channel Bridge has the advantages of outstanding stability and durability because of the advanced materials and structure. However, this extraordinary bridge still obtains some weakness, which includes high cost and danger of construction and maintenance.

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