# Structural Analysis of the Sutong Bridge

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## Summary

The SuTong cable-stayed bridge is the Primary Fairway Bridge of the Suzhou-Nantong Yangtze River Bridge Project. It will be the most important project with a significant target to reduce the economy gap and promote balanced development between Suzhou and Nantong city in China. The total length of the cable-stayed portion of this project is 2088 m with a 1088 m main span. The height of the pylons is about 300 m. When completed it will be the longest cable-stayed bridge in the world. This paper gives a brief description of the bridge and some considerations on structural design and static analysis.

**Keywords**: cable-stayed bridge; steel box girder; long span; nonlinearity; damper; structural system; global analysis.

## 1. Introduction

The Suzhou-Nantong Yangtze River Bridge Project is located in the southeast of the Jiangsu Province in China. In recent years, the economy of the South part of Jiangsu Province developed very rapidly, but the north part kept almost as before because of the obstruction of the Yangtze River. Take the cities of Suzhou and Nantong as an example, the ratio of the GDP value per person of two cities was about 2.65:1 in the year of 1998. Therefore, the construction of this project will be an important link between the cities of Suzhou and Nantong with a significant target to reduce the economy gap and promote balanced development between the north and the south part of Jiangsu Province. In this sense, this project is not only subjected to the national communication demands but also one of pivotal political levers to eliminate local poverty and accelerate conjunct richness.

The total length of the bridge portion in this link is about 8.2 km. At the bridge site there are two navigation channels, the Primary Fairway and the Special Fairway for the exclusive use by port Nantong. The proposed bridge project consists accordingly of the Primary Fairway Bridge, the Special Fairway Bridge and the approach spans. The Primary Fairway Bridge (hereinafter named the bridge in brief) is a cable-stayed bridge. The Special Fairway Bridge is a pre-stressed concrete continuous rigid frame bridge with a span arrangement of (140+268+140) m. And the approach spans are some pre-stressed concrete continuous girder bridges with 75 m, 50 m and 30 m in span lengths.

From the very beginning Chinese officials took pride in realizing this challenging project as an all-China project, i.e. no international participation has been invited in the construction of the Sutong Bridge. The design tasks of the project are carried out by “China Highway Planning and Design Institute (HPDI) Consultants, Inc.” in cooperation with “Jiangsu Provincial Communication Planning & Design Institute”, and the “Architectural Design & Research Institute” of Tongji University. Main contractors for management and construction are the “Jiangsu Sutong Bridge Construction Commanding Department”, and the “China Harbour Engineering Company Group”.

However, foreign companies have been involved as sub-contractors for special tasks, in the design process as well as currently in the construction phase. E.g., COWI Consultants and CHODAI Co. Ltd have independently performed the review of the design documents. TDV at Graz, Austria was selected to install its bridge design software *RM* in the charged design institute HPDI and to assist and support the Chinese design team in close cooperation throughout the whole design process.

The reason for choosing TDV was the proven versatility of the software product together with its experienced and solution oriented development and consulting staff, giving confidence that all problems, even any not yet known arising ones, can be solved successfully with joint endeavor. The trust was justified: in spite of the great challenges to be solved and the stringent demands of the owner, the detailed design could be successfully and in time completed in July 2004.

The extraordinary challenges for the design and analysis resulted from various environmental factors and operational demands, which had to be taken into consideration:

- Navigational requirements: 50000t container ships and large scale fleets will be allowed to pass under the bridge – the navigation clearance required a width greater than 891 m and a height greater than 62 m and the main bridge had to be designed to resist the impact of a 50000t ship.
- Poor climate: each year the area has on average 30 days heavy fog, more than 120 days of heavy rain (typhoon), and frequent tornados with associated high wind speed.
- Complex hydrology: the river has varying flow speeds and directions, and depths vary as the river is tidal – the maximum design average flow passing through the river cross-section is 4.01 m/s.
- Deep bedrock: the bedrock is at a depth of 270 m, which is covered by sediment and silt.

These problems required sophisticated analyses taking into account large displacements, dynamic behavior with respect to wind impact as well as with respect to seismic events and ship impacts on the pylons, and the full construction history with optimization of the cable tensioning procedure.

***Optimization of cable forces:*** An obvious characteristic of cable-stayed bridges is the ideal internal force distribution in the completed structure, which can be achieved by cable tension adjustment. Generally, the ideal final state should be close to some basic conditions (minimal bending moments in the deck and pylons under permanent loads), and this demand governs the strategy of cable tension adjustment. A special function (*AddCon*) in RM allows for automatically determining the optimum distribution of cable forces and the related required cable stressing sequence.

***Construction stage analysis:*** The forward analysis with the *AddCon* method implemented in *RM* was employed for all erection stages to achieve the optimum final dead load situation as required by the designer. All temporary supports, tie-downs, and movements of derricks for construction, temporary loading, and permanent loading were included in the model at various stages. The equivalent static wind actions from different directions were also investigated at the most detrimental construction stages such as the maximum double cantilever, the maximum single cantilever and the completed bridge.

*RM* computed the ***pre-camber*** of all construction stages automatically. The third-order effect of pre-camber shapes apart from the design elevation of the deck was also considered. The results of the construction stage analysis showed that the global stiffness of the bridge is very small before closure. For instance, initial tensioning of the longest stay cable in mid-span yields a vertical deflection of 1.3 m at the end of the cantilever. Even after closure, the superimposed dead load (including paving, baluster, etc.) will still yield a vertical deflection of 1.8 m in the centre of mid-span, i.e. geometric nonlinearity has obviously remarkable effects, especially for the erection geometry of the deck.

***Large displacements:*** The designer has given much attention to geometric nonlinearities all the way from the preliminary design phases to the detailed design. A special study on nonlinear effects was carried out, giving some notable remarks on the influence of geometrical nonlinearities:

- Compared with the linear analysis, effects of geometrical non-linearity may induce an offset of 10 to 20 % of the maximum/minimum stress of the girder and the pylons, and the critical location can also be shifted.
- Each of the stay-cables was divided into specially developed "catenary" elements in order to consider cable sagging more properly than by approximating this effect with a fictitious effective Young's modulus. Comparisons showed, that for cable-stayed bridges beyond 1000 m this is essential to achieve the required accuracy.
- In the construction phase, big deviations from the design shape have to be adopted as pre-camber values, in order to get the required design shape under permanent load at the end of the construction sequence without accepting forbidden internal constraint forces.

***Wind impact*:** Several different investigations had to be performed with respect to the heavy wind impact. First of all, an appropriate girder cross-section had to be developed, which satisfies operational demands and bearing capacity requirements as well as the requirements with respect to wind loading. The wind tunnel tests were performed at the Tongji university and led to a streamlined closed steel box girder with wind fairings. The total width is 41.0 m accommodating dual 8 traffic lanes. The cross-section height is 4.0 m.

Secondly, the problem of cable vibration due to wind and possibly in combination with rain or periodic excitation had to be studied. Different measures to minimize stay cable vibrations have been investigated with the analysis program *RM*, including two kinds of cable surface treatments to prevent the formation of rainwater flows on the cables and internal or additional external damping devices. The final measures will be chosen after detailed testing.

Last but not least, full dynamic wind buffeting analyses of the whole structure had to be performed for both, the bridge under traffic and the empty bridge. These analyses were based on the aerodynamic coefficients and derivatives derived from wind tunnel tests, and included the required non-linear damper elements provided for cable stabilization as well as for connecting the girder with the pylon.

***Dynamic behavior*:** Large displacements can occur in the structure, as well in the construction stages as also in the final stage, e.g. due to temperature change. These movements must not be constraint in order to avoid overstraining. However, additional constraints are required for dynamic loading. Non-linear dampers are applied for this purpose. These dampers do not confine the displacement induced by temperature, moderate wind, and vehicle traffic, but transfer the loads induced by gust, earthquake, etc from the girder to pylons and foundations.

The definition of appropriate characteristic design parameters of the damper elements including gap value, elastic stiffness, and dynamic characteristics is essential. *RM* was also used to perform the required parametrical studies for designing the layout of these devices. The dynamic parameters are based on the results of time history analyses for some typical seismic inputs.
The maximum relative displacement between the girder and the pylons is less than 750 mm. A gap of 750 mm between pylon and girder was therefore selected to fit the design requirements. The static connection spring in the model was therefore bi-linear, with a spring constant of 0 up to a displacement of 750 mm, and a spring constant of 100 MN/m above.

With respect to the dynamic characteristics, the selected permanent connection between the girder and the pylons is accomplished by nonlinear dampers of the same type as used for the Great Belt East Bridge in Denmark The dynamic characteristic of one damper is described by the formula $F = C \cdot V^{\alpha}$ with C being a constant, V being the relative displacement velocity between pylon and girder and α being a constant exponent equal to 0.4.

# 2. Description of the Bridge

## 2.1 Span Arrangements

Taking full consideration of various geotechnical conditions at the bridge site, technical feasibility, and especially construction ability, the selected design for the Primary Fairway Bridge is a double-plane twin-pylon cable-stayed bridge with a continuous span arrangement of (100+100+300+1088+300+100+100) m, as shown in Figure 1. Two auxiliary piers and one transitional pier are erected in each side span. The main span of the bridge is 1088 m, which is the longest main cable-stayed bridge span at present.

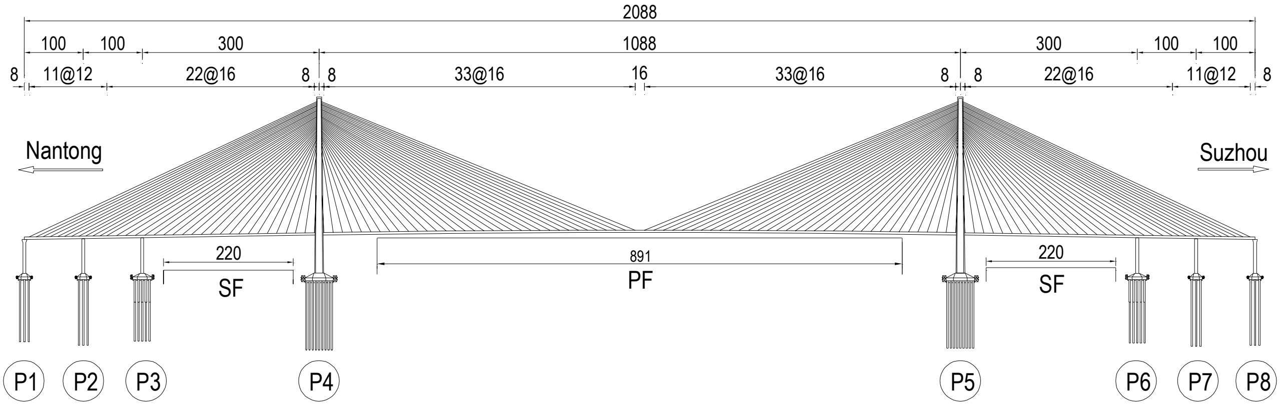


*Fig. 1 Span Arrangement (unit: m)*

## 2.2 Girder

The bridge girder is a streamlined closed flat steel box girder. The total width including wind fairing is 41.0 m accommodating dual 8 traffic lanes. The cross-section height is 4.0 m. The steel box is generally stiffened in the longitudinal direction with closed steel troughs. Transverse plate diaphragms are provided with a typical distance of 4.0 m and with smaller distances down to 2.27m locally around the two pylons. The characteristic yield strengths of the structural steel are 345 MPa and 370 MPa. The standard cross-section of the girder is illustrated in Figure 2. The thickness of the skirts and stiffeners vary along the longitudinal direction of the bridge.

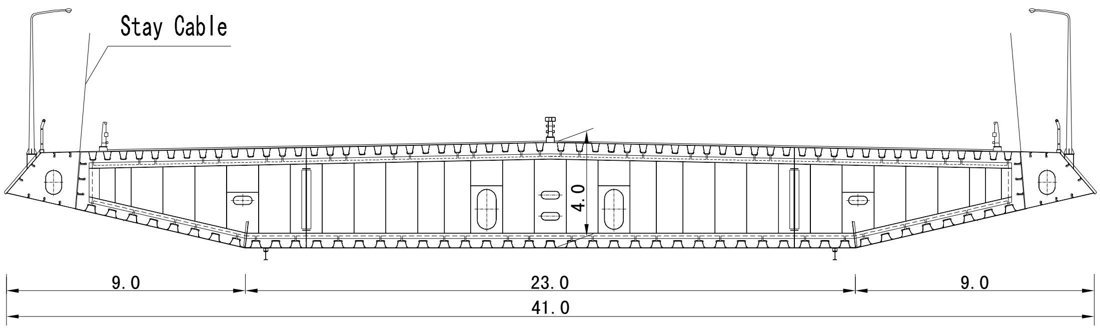


*Fig. 2 Cross Section of the Girder (unit: m)*

## 2.3 Pylons

The inverted Y-shaped pylons are about 300 m in height and are made of concrete grade C50 according to the Chinese standard JTJ01—89. The stay-cables are anchored inside steel boxes fixed to the concrete by shear studs at the pylon top. The maximum segment of a cable anchorage steel box weighs about 36 tons. The tie-beam between the pylon legs is fully post-tensioned for outward thrust from the pylon legs under service loads and seismic load. According to the project specifications and the review comments from COWI the cracking width of the concrete pylon wall is controlled within 0.2 mm.

## 2.4 Stay Cables

The stay cables are arranged in double inclined cable planes with standard spacing of 16 m in the central span and 12 m near the ends of the back spans along the girder. To reduce the effect of wind loads, the cable stay systems are made of the parallel wire strand consisting of 7 mm wires, each with a cross sectional area of 38.48 $mm^2$. The nominal tensile strength of the cables is 1770 MPa. Cable sizes range from a minimum of PES7-139 for the main span stays near the pylons to a maximum of PES7-313 for the longest backstay. The longest cable is about 577 m with a weight of 59 tons.

The problem of cable vibration due to wind and possibly in combination with rain or parametric excitation has been studied during the design process. Different measures to minimize stay cable vibrations have been investigated including two kinds of cable surface treatments to prevent formation of rainwater flows on the cables and internal or additional external damping devices. The final measures will be chosen after detailed testing.

## 2.5 Foundations

Bored friction piles support the piers and pylons from P1 to P8 with diameters from 2.8 m near the pile-head to 2.5 m away from the top along the piles. Each of P1~P2 and P7~P8 has 19 piles. 36 piles are driven for P3 and P6 separately. Each pylon of P4 and P5 is supported by 131 piles. The pile lengths vary between 108 to 116 m.

## 2.6 Connection between Girder and Pylons

The selected permanent connection between the girder and the pylons is accomplished by nonlinear dampers as used for the Great Belt East Bridge in Denmark. These dampers do not confine the displacement of the steel girder induced by temperature, moderate wind, and vehicle traffic, but transfer the loads from the girder induced by gust, earthquake and other forces from specific load combinations to an alternative pylon.

The dynamic characteristics of one damper is given as

$$F = C \cdot V^{\alpha} \quad (1)$$

V is the relative velocity between pylon and girder
$\alpha$ is a constant equal to 0.4
C is a constant equal to 3750 kN/(m/s)$^{0.4}$
A total of 4 dampers are placed at each pylon. A relative movement of 750 mm between girder and pylon is allowed before the displacement restriction equipments are activated. Each of the four dampers at one pylon has a linear stiffness of 100 MN/m in the event that a relative movement beyond 750 mm occurs. The static force-displacement relationship for each damper unit is shown in Figure 3.

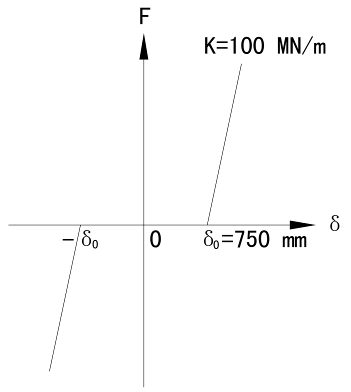


*Fig. 3 Static force-displacement relationship for each damper*

# 3. Global Static analysis

## 3.1 Global Analytical Model

The RM2000 program [1] developed by TDV, Austria, has been used for the global analysis of the SuTong cable-stayed bridge in the detailed design. Two other programs named QJX and BAP have also been used for checking by the designer. The finite element model of the bridge is illustrated in Figure 4.The structural modelling keeps accordance with the planned construction schemes. Each of the stay-cables was divided into 8 sub-elements to consider cable-sag effects rather than approxima-ting this effect by using effective module of elasticity. Other interacting non-linear effects such as P-delta effect, large displacements and shear displacements were also considered in the calculation. Creep and shrinkage effects were calculated according to the CEB/FIP 90 code. The flexibility of the pylon foundations was modelled with spring elements. The connection between the girder and both pylons were treated as nonlinear static spring elements with a gap value of 750 mm and a linear stiffness of 100 MN/m.

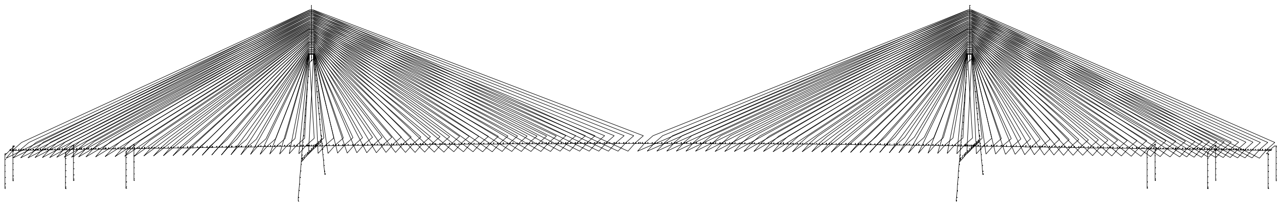

*Fig. 4 Finite element model of the bridge*

## 3.2 Definition of the Bridge Final State and Analytical Results

An obvious characteristic of cable-stayed bridges is the ideal internal force distribution in the completed structure which can be achieved by cable tension adjustment. Generally, the ideal final state should be close to some basic conditions. That is to say, the strategy of cable tension adjustment should aim to eliminate/minimise bending moments in the deck and pylons under permanent loads. The cable force distributions should avoid dramatic variations between adjacent cables.

For the SuTong Bridge the contribution ratio of traffic loading is heavy for deck stress and counterweight arrangements in the back spans. The definition of the final state gives attention to both situations with and without traffic. The bending moment envelops in the deck under dead load and load combination 1 is shown in Figure 5. The maximum moment of the pylons (in the bottom) at 28.0 MN-m is very small. The results illustrate the suitability of the achieved final state of the bridge.

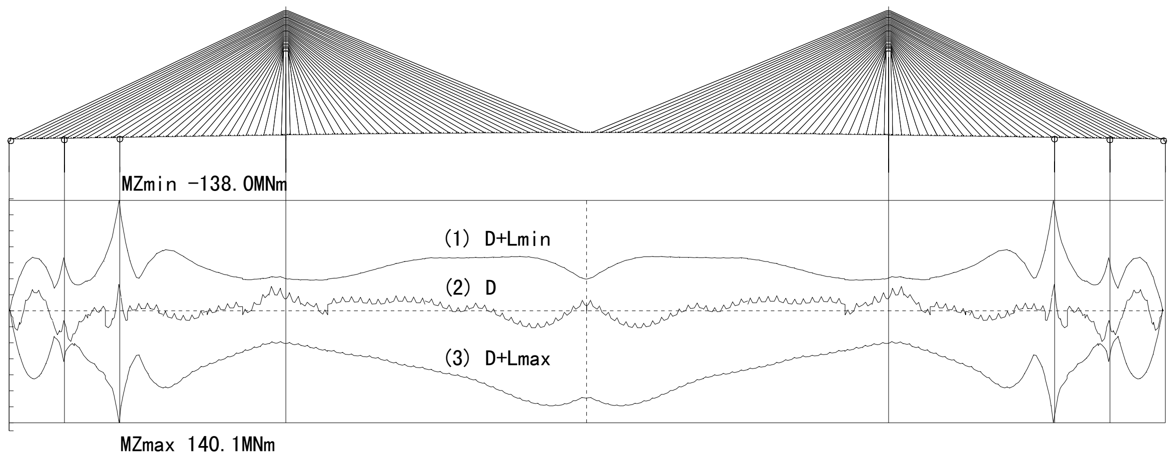


*Fig. 5 Bending moment envelop in deck*

### 3.3 Stage analysis

The forward analysis with the *ADDCON* method implemented in RM2000 [4] was employed for all erection stages to achieve the final situation as described above according to the construction schedules of the designer. All temporary supports, tie-downs, and movements of derricks for construction, temporary loading, and permanent loading were included in the model at various stages. The equivalent static wind actions from different directions were also investigated at the most detrimental construction stages such as the maximum double cantilever, the maximum single cantilever and the completed bridge. The pre-camber calculation of all construction stages was computed by RM2000 automatically. The third-order effect of pre-camber shapes apart from the design elevation of the deck was also considered approximately.

The results of the construction stage analysis also showed that the global stiffness of the bridge is very small before closure. For instance, the first tension of the longest stay cable in mid-span leads to a vertical deflection of 1.3 m at the end of the cantilever. Even after closure, the superimposed dead load (including paving, baluster, etc.) can still result in a vertical deflection of 1.8 m in the centre of mid-span. In addition, geometric nonlinearity in general has remarkable effects, especially for erection geometry of the deck.

### 3.4 Structural System and Parametrical Analyses

As mentioned before the dampers do not confine the displacement of the steel girder induced by temperature, moderate wind, and vehicle traffic, but transfer the loads of the girder induced by gust, earthquake, and other forces to the tower. Therefore, definition of appropriate characteristic design parameters of the dampers including gap value, elastic stiffness, and dynamic characteristics is critical to achieve those intentions. Relevant parametrical analyses were carried out for some dominate load cases including static loadings and dynamic inputs. The dynamic parameters (see 2.6) are based on the results of time history analyses for some typical seismic inputs. The maximum relative displacement between the girder and the pylons is smaller than 750 mm.

For static actions, a proper gap value is the governing parameter. Taking into account all of the responses of the above loads and considering the current product specifications of large expansion joints, a gap of 750 mm was selected to fit the design requirements. Consequently, some parametrical analyses were carried out to define a reasonable spring stiffness according to the relationship curve between the bending moment response at pylon bottom (the longitudinal displacement at the end of the girder) and longitudinal wind inputs. Some results of parametrical studies are shown in Figure 6~8 with the spring stiffness in the range of 1~1000MN/m. These graphs illustrate the fact that a spring stiffness of 100MN/m is proper and practicable. Here an assumption is introduced that only the dampers at one pylon of P4 or P5 may be engaged before the other pylon. This assumption reflects construction inaccuracy and bridge deck elongation due to temperature.

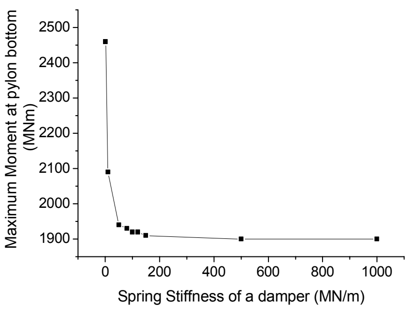


*Fig. 6 Maximum moment at pylon bottom*

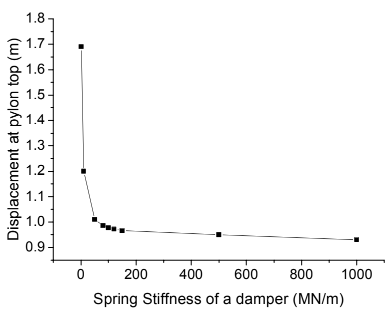


*Fig. 7 Displacement at pylon top*

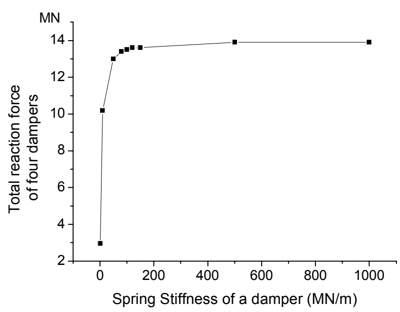


*Fig. 8 Total reaction force of four dampers*

For the SuTong Bridge, the connection between girder and pylons is essential to the safety of the pylons under extreme wind and seismic loads. Therefore, based on the performed detailed parametrical studies and some further considerations for installation tolerances and safety margins a maximum force for one damper of approximately 10 MN (under ULS state) is assumed as one of design requirements. Meanwhile, the comparison between the results of designer and COWI Consultants confirmed that the material non-linearity of the pylons plays a significant role for the resultant reaction forces under ULS state.

### 3.5 Geometric nonlinearity effects

The designer has given much attention to geometric nonlinearities all the way from the preliminary design phases to the detailed design. A special study on nonlinear effects was carried out. Two notable remarks on geometric nonlinearities are abstracted as follows.

- For the SuTong Bridge, compared with linear analysis, geometrically non-linear effects on the completed bridge may induce an offset of 10~20 percent of the maximum / minimum stress of the girder and the pylons under traffic loads, and the critical location can be also shifted.
- Generally, the FE model of the stay-cables employs a straight truss element with the effective modulus of elasticity, or dividing each stay cable into many sub-elements like RM2000, or by the newly catenary cable element. Different means to deal with cable sag effect make a certain effect on the fabrication of construction process. The means of the equivalent truss element may induce a maximum offset of 0.538 m apart from the desired location at the end of stage analyses finally, as the mentioned in reference [2]. One of the reasons is possibly inaccurate chord force vectors in long stay cables. To cable-stayed bridges beyond 1000 m, this simplification should be restricted, especially for erection process. Certainly, the means of catenary cable elements is better than dividing sub-elements but within the tolerance range.

## 4. Concluding Remarks

The SuTong Cable-Stayed Bridge is the most critical part of the Suzhou-Nantong Yangtze River Bridge Project. It costs about 380 million dollars. It will supply much convenience to the people beside the Yangtze River and accelerate economy development to make the adjacent cities rich together. By the way, the design and construction of this bridge itself also provide a very good chance to promote cooperation and intercommunion among some famous designers at home and abroad.

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