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 in China. At a cost of approximately US $920 million dollars, it is an important project with a goal of reducing the economic gap between Suzhou and Nantong city and promoting balanced development in the area. Completed in the summer of 2007, Sutong Bridge is the longest cable-stayed bridge in the world. The total length of the cable-stayed portion of the project is 2,088 meters with a 1,088-meter main span and a pylon height of about 300 meters. This paper briefly describes the project and discusses some of the structural design and static analyses that were undertaken in the design of Sutong Bridge.

Introduction

The Suzhou-Nantong Yangtze River Bridge Project is located in China's Jiangsu Province – a fast-growing industrial region with a population of 74 million people. In recent times, Southern Jiangsu Province has developed rapidly, but the presence of the Yangtze River has restricted access to the northern portion of the province, limiting its development. Sutong Bridge will provide an important link between the cities of Suzhou and Nantong and assist in driving toward the ultimate goals of eliminating poverty and accelerating mutual prosperity.

The total length of the bridge portion of the project is 8.2 kilometers. The bridge comprises a Primary Fairway Bridge (the Sutong Bridge), a Special Fairway Bridge, and both approach spans. The Primary Fairway Bridge is a cable-stayed bridge, and the Special Fairway Bridge is a pre-stressed concrete continuous rigid-frame bridge with a span arrangement of 140 + 268 + 140 (548) meters. The approach spans are pre-stressed concrete continuous girder bridges 75 meters, 50 meters, and 30 (155) meters in span length. At the bridge site, there are two navigation channels, the Primary Fairway and the Special Fairway for the exclusive use of the port of Nantong.

Chinese officials take pride in the fact that this enormously challenging project has been an all-China effort without international assistance in fabrication or construction. Main contractors for management and construction were the Jiangsu Sutong Bridge Construction Commanding Department (project management) and the China Harbor Engineering Company Group (construction).

China's Highway Planning and Design Institute (HPDI) Consultants, Inc. designed the bridge in cooperation with Jiangsu Provincial Communication Planning & Design Institute and the Architectural Design & Research Institute of Tongji University. Several international companies served as consultants for special tasks in the design and planning processes. These firms included COWI Consultants and CHODAI Co. Ltd., which independently reviewed the design documents.

Permission granted for foreign companies to contribute to special tasks enabled HPDI to deploy **RM Bridge** software. Dorian Janjic, vice president of Bentley Software's bridge engineering group, supported the HPDI design team in its use of RM during the design process.

HPDI chose Bentley's RM software solution for its proven versatility combined with the Bentley bridge engineering group's experienced and solution-oriented development and consulting team. The versatility of Bentley's RM software had been demonstrated in its extensive use on Hong Kong's Stonecutters Bridge, the first cable-stayed bridge to surpass the theretofore accepted limit of 1,000 meters for a main cable-stayed span.

This gave HPDI confidence that all obstacles, even those unanticipated, would be overcome through the joint endeavor. This trust was justified; in spite of significant project challenges and the owner's stringent demands, the team met the July 2004 deadline to complete the detailed design.

Project Challenges

Various environmental factors and operational demands posed extraordinary design, analysis, and construction challenges:

- Navigational requirements – Large container ships and large-scale fleets pass under the bridge regularly. Clearance for the shipping lane required a width greater than 891 meters and a height greater than 62 meters. Moreover, the main bridge had to be designed to resist the impact of a 50,000-ton ship.

- Poor climate – Each year the region averages 30 days of heavy fog, more than 120 days of heavy rain, and high wind speeds caused by typhoons and tornados. As a result, construction teams had to follow aggressive schedules to complete work in seasonal windows.

- Complex hydrology – Because the river is tidal, it has varying flow speeds, directions, and depths. Waves sometimes reach 3 meters in height and currents can be quite strong. Tides can vary by up to 4 meters. The design allowed for an average flow passing through the river cross section of 4.1 meters per second.

- Deep bedrock – The bedrock is at a depth of 270 meters and is covered by sediment, sand, and silt. This meant that a special solution was needed for the foundations – one that didn't involve drilling into bedrock.

These challenges required sophisticated analyses that studied large displacements caused by many different potential conditions. Particularly important were studies of the dynamic behavior resulting from wind impacts, seismic events, and ship collisions with the pylons. Analyses were performed for the full construction sequence, with special emphasis being placed on optimizing the cable tensioning that is essential at every stage of cable-stayed bridge construction. The analyses included:

- ***Optimization of Cable Forces*** – For cable-stayed bridges, cable tension is fine-tuned to achieve ideal internal force distribution in the completed structure. Generally, in such projects, the ideal final state is predetermined by basic conditions such as minimal bending moments in the deck and pylons under permanent loads. These criteria govern the strategy of cable tension adjustment. **AddCon,** a special RM function, automatically calculated the optimal distribution of cable forces and the required cable stressing sequence.

- ***Construction Stage Analysis*** – Forward analysis with the AddCon module was used for all erection stages to achieve the optimal final dead load situation required by the designer. The analysis model included a wide range of conditions for various construction stages. The project team also investigated equivalent static wind actions from different directions at construction phases deemed to be the most problematical.

- ***Large Displacements*** – The project team paid particular attention to geometric nonlinearities throughout the process. Engineers conducted a special study on nonlinear effects – the results of which provided notable characteristics of the influence of geometrical nonlinearities. Each stay cable was divided into specially developed *catenary* elements in order to consider cable sagging more accurately, rather than using Young's modulus for an approximation. Comparisons show that for cable-stayed bridges longer than 1,000 meters, the catenary approach is essential to achieve the required accuracy.

- In the construction phase, large deviations from the design shape have to be adopted as *pre-camber* values to get the required design shape under permanent load at the end of the construction sequence – without allowing prohibited internal constraint forces.

- ***Wind Impact*** – The project team performed several investigations to gauge the impact of heavy winds:

    1. The team developed a suitable girder cross section that satisfies operational demands and bearing capacity requirements as well as the wind-loading requirements. Wind tunnel tests performed at Tongji University led to a streamlined, closed steel box girder with wind fairings.

    2. The team studied cable vibration caused by wind and rain or periodic excitation. Using RM, the team investigated different methods for minimizing stayed-cable vibrations.

    3. The team performed full dynamic wind-buffeting analyses of the bridge structure with and without traffic. These analyses were based on aerodynamic coefficients and other data derived from the wind tunnel tests. Analyses included nonlinear damper elements required for cable stabilization and the girder/pylon connections.

- ***Dynamic Behavior*** – Large displacements, often caused by temperature changes, can occur in these types of structures – during construction as well as in service. During analysis, these movements must not be constrained in order to avoid overstraining. For this project, nonlinear dampers were applied for this purpose and for the dynamic loadings. However, these dampers did not confine displacements caused by natural conditions. Defining appropriate characteristic design parameters of the damper elements – including gap value, elastic stiffness, and dynamic characteristics – was essential. RM was used to perform the required parametrical studies to design the layout of these devices. The dynamic parameters were based on time-history analysis results for some typical seismic inputs.

Description of the Bridge

Span Arrangements

After considering various geotechnical conditions at the bridge site, including technical feasibility and constructability, the project team opted for a double-plane, twin-pylon, cable-stayed bridge design for the Primary Fairway Bridge with a continuous span arrangement of 2,088 meters (100+100+300+1,088+300+ 100+100), as shown in Figure 1. Two auxiliary piers and one transitional pier were erected in each side span. The main span of the bridge is 1,088 meters, which is the world's longest main cable-stayed bridge span at the present time.

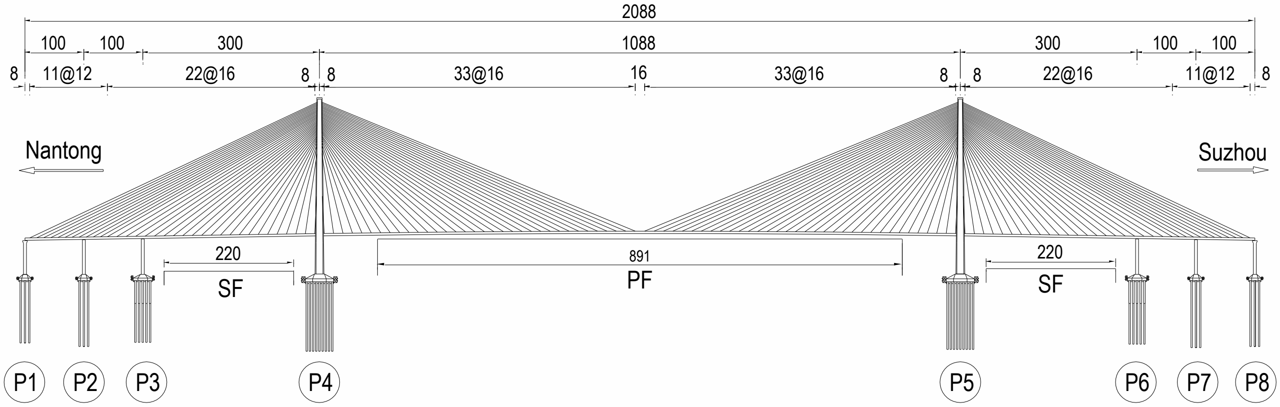

Fig. 1 Span Arrangement (unit: m)

Girder

The bridge girder is a streamlined, closed, flat, steel-box girder. The total width, including wind fairing, is 41.0 meters to accommodate eight dual-traffic lanes. The cross section height is 4.0 meters. The steel-box girder is generally stiffened in the longitudinal direction with closed steel troughs. Transverse plate diaphragms are provided with a typical distance of 4.0 meters and with smaller distances down to 2.27 meters locally around the two pylons. The characteristic yield strengths of the structural steel are 345 MPa and 370 MPa (MPa is a metric unit of measure for steel strength).

Figure 2 illustrates the standard cross section of the girder. The thickness of the skirts and stiffeners vary along the longitudinal direction of the bridge.

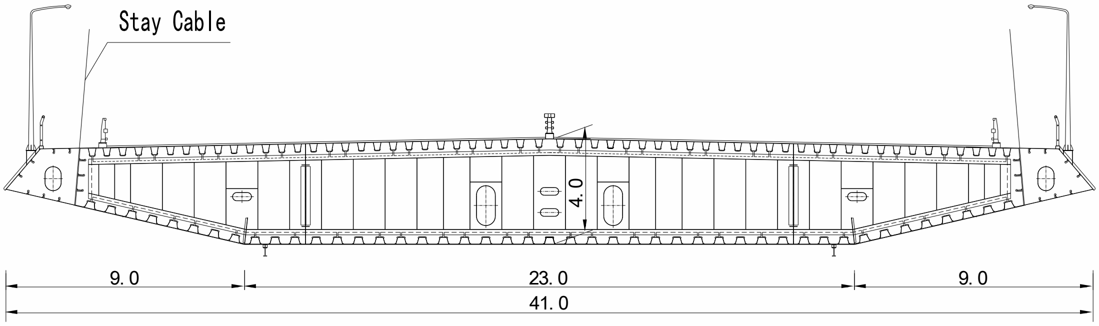

Fig. 2 Cross Section of the Girder (unit: m)

Pylons

The two 300-meter tall, inverted Y-shaped pylons are constructed of concrete grade C50 to comply with Chinese standard JTJ01-89. The pylons hold 36-tonne steel boxes fastened to the concrete by shear studs at the top of the pylon to anchor the stay cables. Tie beams between the pylon legs are fully post-tensioned to gain an outward thrust from the pylon legs under service and seismic loads. According to project specifications and review comments by COWI Consultants, the cracking width of the concrete pylon wall is controlled within 0.2 millimeters.

Stay Cables

The stay cables are arranged in double inclined cable planes with a standard spacing of 16 meters in the central span and 12 meters near the ends of the back spans along the girder. To reduce wind-load effect, the cable-stay systems are made of the parallel wire strand consisting of 7 millimeter wires, each with a cross sectional area of 38.48 millimeters^2. The nominal tensile strength of the cables is 1,770 MPa. Cable sizes range from PES7-139 for the main span stays near the pylons to PES7-313 for the longest back stay. The longest cable is about 577 meters and weighs 59 tonnes.

During the design process, the project team studied the cable vibration issue caused by wind in combination with rain or parametric excitation. The project team investigated different ways of minimizing stay cable vibrations, including two kinds of cable surface treatments to prevent rainwater flows from forming on the cables and internal or additional external damping devices. The final measures would be chosen after detailed testing.

Foundations

Bored friction piles support the piers and pylons from pier 1 to pier 8 with diameters from 2.8 meters near the pile-head to 2.5 meters from the top along the piles. Piers 1, 2, 7, and 8 each have 19 piles, while piers 3 and 6 each have 36 piles, each driven separately. The pylons for pier 4 and pier 5 are supported by 131 piles, varying in length from 108 to 116 meters.

Connection Between Girder and Pylons

The project team used the same type of nonlinear dampers used on the Great Belt East Bridge in Denmark to select the permanent connection between the girder and the pylons. These dampers do not confine the displacement of the steel girder induced by temperature, moderate wind, and vehicle traffic, but instead transfer the loads induced by gusts, earthquakes, and other forces from specific load combinations from the girder to an alternative pylon.

The dynamic characteristics of one damper is described by the formula $\boldsymbol{F=C\cdot V^{\alpha}}$

- V is the relative displacement velocity between pylon and girder
- α is a constant exponent equal to 0.4
- C is a constant equal to 3,750 kN/(m/s)$^{0.4}$

Four dampers were placed at each pylon with a maximum relative displacement between the girder and the pylons of less than 750 millimeters to meet the design requirements. Each of the dampers at one pylon has a linear stiffness of 100 MN/m to guard against a relative movement beyond 750 millimeters.

Figure 3 shows the static force-displacement relationship for each damper unit.

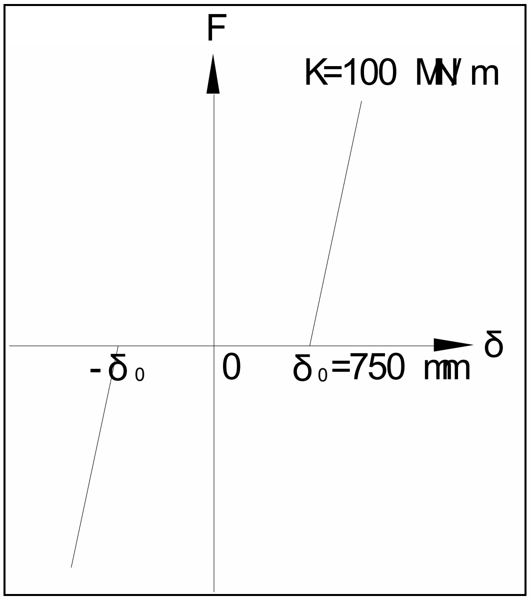

Fig. 3 Static force-displacement relationship for each damper

Global Static Analysis

Global Analytical Model

The HPDI team used RM Bridge[1] for the global analysis of the Sutong cable-stayed bridge during detailed design. The designers also used QJX and BAP programs for design checking. Figure 4 illustrates the finite element model of the bridge. The structural modeling of stays was performed in accordance with the planned construction schemes. Each of the stay-cables was divided into eight sub-elements to consider cable-sag effects rather than approximating this effect by using an effective module of elasticity. Other interacting nonlinear effects such as the P-delta effect, large displacements, and shear displacements were considered in the calculation. Creep and shrinkage effects were calculated according to the CEB/FIP 90 code. The flexibility of the pylon foundations was modeled with spring elements. The connections between the girder and both pylons were treated as nonlinear static spring elements with a gap value of 750 millimeters and a linear stiffness of 100 MN/m.

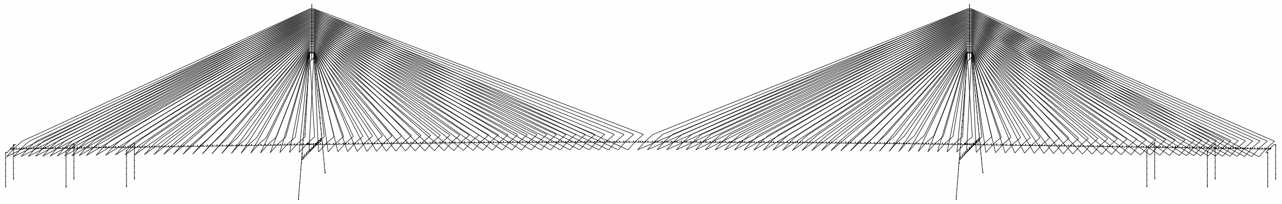

Fig. 4 Finite element model of the bridge

Definition of the Bridge's Final State and Analytical Results

Cable-stayed bridges distribute internally the forces in the completed structure using very specific adjustments in cable tensioning. Cable force distributions are designed to minimize or even eliminate bending moments in the deck and pylons under permanent loads while at the same time avoiding dramatic variations between any two adjacent cables.

The contribution ratio of traffic loading for the Sutong Bridge was heavy for deck stress and counterweight arrangements in the back spans. The definition of the final state took into account situations with and without traffic. Figure 5 shows the bending moment envelopes in the deck under dead load and load combination. At 28.0 MN/m, the maximum moment of the pylons (shown in the graph in Figure 5) was very minor. The results illustrate the suitability of the achieved final state of the bridge.

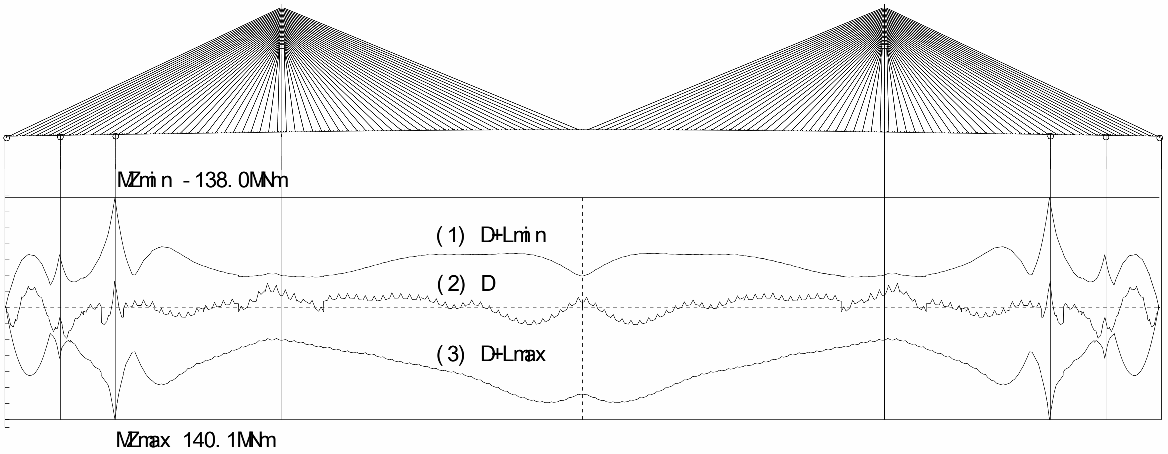

Fig. 5 Bending moment envelope in deck

Stage Analysis

Using RM ADDCON's forward analysis method^2 for the erection stages, the team was able to match the final-state conditions described above – as derived from the original construction schedules of the designer. The analysis model included, at various stages, all temporary supports, tie-downs, and derrick movements for construction, temporary loading, and permanent loading. The team also investigated equivalent static wind actions from different directions at the most critical construction stages – the maximum double cantilever, the maximum single cantilever, and the bridge completion stage.

RM automatically computed the *pre-camber* of all construction. With the exception of the design elevation of the deck, the third-order effect of pre-camber shapes was taken into consideration. Results from construction stage analysis showed a minimal amount of stiffness before closure. For instance, initial tensioning of the longest stay cable in mid-span yielded a vertical deflection of 1.3 meters at the end of the cantilever. Even after closure, the superimposed dead load (including paving, barriers, etc.) still yielded a vertical deflection of 1.8 meters in the center of the mid-span. The results clearly demonstrate the benefits of RM's geometric nonlinearity analyses, especially concerning the deck erection geometry.

Structural System and Parametrical Analyses

As mentioned, the dampers do not confine the displacement of the steel girder induced by temperature, moderate winds, and vehicle traffic, but transfer the loads of the girder induced by gusts, earthquakes, and other forces to the tower. Therefore, defining appropriate characteristic design parameters of the dampers – including gap value, elastic stiffness, and dynamic characteristics – is critical to achieve the desired results. Relevant parametrical analyses were carried out for some dominant load cases, including static loadings and dynamic inputs.

The dynamic parameters are based on the results of time history analyses for some typical seismic inputs.

For static actions, a proper gap value was 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 reasonable spring stiffness according to the interaction curve between the bending moment response at pylon bottom (the longitudinal displacement at the end of the girder) and longitudinal wind inputs.

Figures 6-8 show results of the parametrical studies with the spring stiffness in the range of 1 to 1000MN/m. These graphs illustrate that a spring stiffness of 100MN/m is practicable. An assumption was introduced here that only the dampers at one pylon of pier 4 or pier 5 would be engaged before the other pylon. This assumption reflects construction inaccuracy and bridge deck elongation due to temperature.

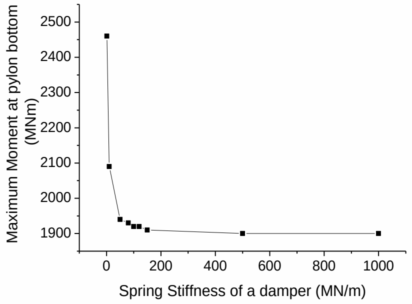

Fig. 6 Maximum moment at pylon bottom

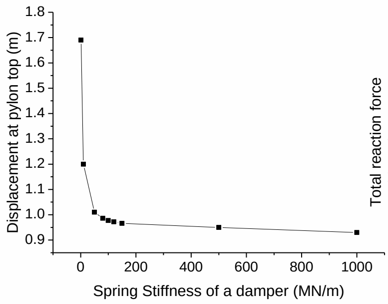

Fig. 7 Displacement at pylon top

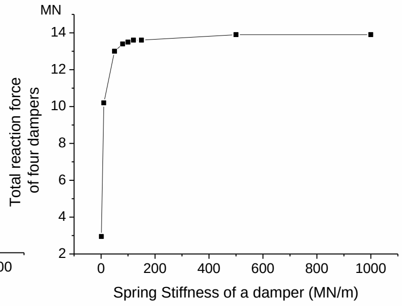

Fig. 8 Total reaction force of four dampers

For the Sutong Bridge, the connection between girder and pylons is essential for 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) was assumed as one of the design prerequisites. Meanwhile, the comparison between the results of HPDI and COWI Consultants confirmed that the material nonlinearity of the pylons plays a significant role for the resultant reaction forces under ULS state.

Geometric Nonlinearity Effects

Designers gave much attention to geometric nonlinearities all the way from the preliminary design phases to the detailed design. The designers carried out a special study on nonlinear effects.[3] Two notable remarks on geometric nonlinearities are abstracted as follows:

- Compared with linear analysis, effects of geometrical nonlinearity may result in a net offset of 10 to 20 percent of the maximum/minimum stress of the girder and the pylons together with a shift in the critical location of these stresses.

- Generally, the finite element model of the stay cables employs a straight truss element with the effective modulus of elasticity, or using RM to divide each stay cable into many sub-elements, or by the new catenary cable element. Different means to deal with cable-sagging effects result in various options for the fabrication or construction processes. The means of the equivalent truss element may induce a maximum offset of 0.538 meters away from the desired location at the end of stage analyses.[4] One of the possible reasons is inaccurate chord-force vectors in long-stay cables. For cable-stayed bridges longer than 1,000 meters, this simplification should be restricted, especially for erection processes. Certainly, the use of catenary cable elements is better than dividing sub-elements, but within the tolerance range.

Concluding Remarks

Certainly, the Sutong Bridge is an amazing feat of design and engineering. The design and construction of the bridge itself has provided a very good opportunity to promote cooperation and interaction among many famous bridge designers from China and abroad – all the more appropriate in this fast-growing area of the world. Most important, the bridge brings a new level of convenience to the people along the Yangtze River and should accelerate economic development and mutual prosperity within the cities it bridges.

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