STRUCTURAL ANALYSIS OF A CURVED SINGLE-TOWER SUSPENSION BRIDGE

DING JIAN-MING, HE CHU-SHENG, ZHANG HENG-PING and HUANG XING-BO

Southeast University, 2 Sipailou, Nanjing, Jiangsu, 210096, P.R. China.

ABSTRACT

Constrained by the alignment, the main span of Tong Sha Bridge in Tong Sha Ecological Park in Dongguan, Guangdong Province, China, is a steel box girder, 106 m long, with one pylon and a simple cable stay. The bridge has an ingenious design, harmonises with the park's environment, and also has a modern style.

The authors used various three-dimensional programs to analyse the bridge. The results showed that the main cable alignment satisfied the relevant bridge specifications of China, and that the problem of main cable alignment generated by the three-dimensional displacement and torsion from the pull of the suspenders had been successfully solved. In addition, the problems of the main girder's three-dimensional torsion caused by the unsymmetrical pull of the suspenders and by the compression strength and three-dimensional stability of the tower had been effectively resolved. The solutions involved in Tong Sha Bridge are valuable for the similar kinds of bridge in the future.

Keywords: Suspension bridge, Alignment, Mechanical analysis

1. LOCATION

Tong Sha Bridge is located in Tong Sha Ecological Park in Dongguan, Guangdong Province, China. The design required the bridge to be harmonised with the master plan for Tong Sha ecological tourist region and to contribute to the scenery of the park. The bridge approach is a concrete box girder constructed by the post-tensioning method. The western bridge approach has three 25-m spans and the eastern approach has five 25-m spans. Constrained by the alignment, the main span is a steel box girder 106-m-long with one pylon and a simple cable stay. The radius of the curve is 180 m. The bridge is 13.4 m wide, with double roadways and walkways. The vector-to-span ratio is 1:13. The distance between suspenders is 4.5 m and they connect with chord clips to the box girder. The main tower, made of steel pipes with concrete, is 39 m high above the deck. The girder itself is 2.1 m high and is separated from the tower. The bridge has an ingenious design, harmonises with the park's environment, and also has a modern style (see Figures 1 & 2).

Many scholars studied the alignment of the main cable. Zhu Jin Guo (2002) discussed the difference between two conditions in which catenary equations were employed to analyse the main suspension cable. He also drew some conclusions from these examples. Li Zheng Ren and Liu Zu Guo (2003) surveyed various curved cable-stayed bridges and explored their potential applications. Xiao Ru Cheng and Xiang Hai Fan (1996) presented a back-calculation algorithm based on the status of the constructed bridge. In order to obtain the main cable alignment, they first analysed the axial force of the suspenders, then worked out the balanced status of the main cable, and finally located the tangent point. Xiao Ru Cheng *et al.* (1999) also presented a method of using a fictitious beam to confirm the alignment.

The authors of the present paper used various three-dimensional programs to analyse the bridge. The results showed that the main cable alignment satisfied the relevant bridge specifications of China, and that the problem of main cable alignment generated by the three-dimensional displacement and torsion from the pull of suspenders had been successfully solved. In addition, the problems of main girder's three-dimensional torsion caused by the unsymmetrical pull of the suspenders and the compression strength and three-dimensional stability of the tower had been effectively resolved. The aim of this paper is to confirm the configuration of the suspension bridge.

Figure 1. Artistic rendering of Tong Sha Bridge.

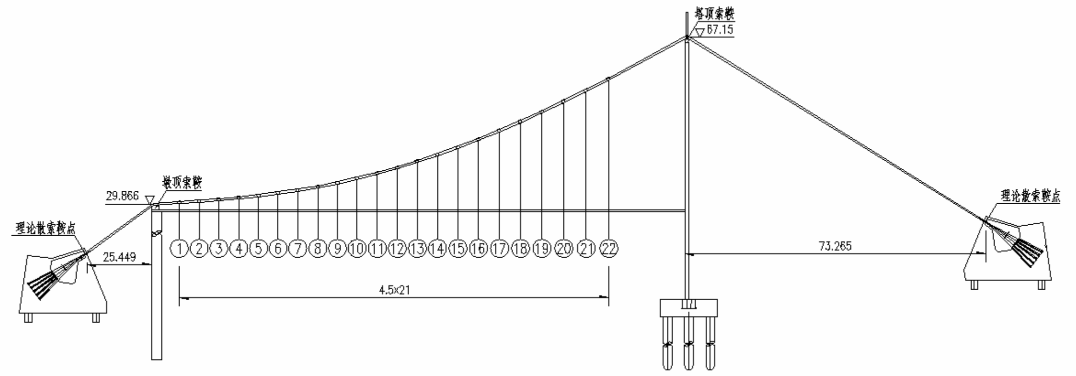

Figure 2. Structural layout of Tong Sha Bridge.

2. FINITE ELEMENT DISPLACEMENT THEORY AND NON-LINEAR THEORY

Finite element displacement theory is applicable to the matrix analysis of the structure due to its fast and strict convergence and its suitability for computer application. It is able to take into account the geometrical non-linear factors caused by the large displacements, such as the displacements caused by load, by the influence of the cable's fall due to its own gravity, and by the influence of the cable's rigidity caused by the initial stress of the constant load.

Because the main span lies along the circular curve of one pylon with a simple cable stay, the suspenders lie on both sides of the main girder's central line. The main cable could take on an "S" shape because of the unsymmetrical strength of the suspenders. The alignment is very difficult to determine because of the strong non-linear geometry. It is therefore necessary to use three-dimensional programs to determine the main cable alignment.

The main girder is an elastic shell element, and the main cable and suspenders are three-dimensional link elements. The element rigidity matrix is shown below (Figure 3):

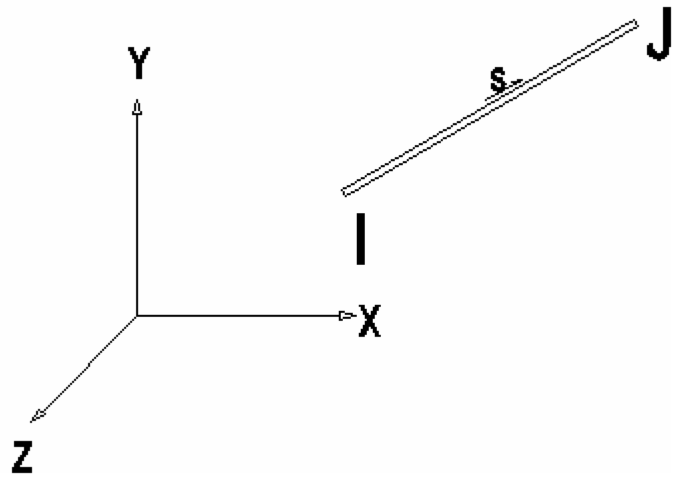

Figure 3. Element co-ordinate system.

$$[K_l] = \frac{AE}{L}\begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (1)$$

In the formula: A = area of suspender

E = elastic modulus of suspender

L = element length

The total element rigidity matrix is:

$$[F] = [K][U] \qquad (2)$$

$[F] = [f_{ix} \quad f_{iy} \quad f_{iz} \quad f_{jx} \quad f_{jy} \quad f_{jz}]^T$ = vector of node force

$[U] = [u_i \quad v_i \quad w_i \quad u_j \quad v_j \quad w_j]^T$ = vector of node displacement

Large non-linear displacement is adopted to consider the influence of non-linear geometry. Prestress is applied to the main cable and suspenders to account for the influence of initial stress.

3. FINITE ELEMENT CALCULATION

The basic assumptions are:

- The suspenders are flexible and cannot handle compression or moments.
- The suspenders work in the elastic range and satisfy Hooke's law.
- The mass of the main cable is uniformly distributed.
- Large displacements and small strains are assumed.
- The initial alignment is a parabola in terms of the influence of the main cable's gravity.

3.1 Calculation of the Parameters (Table 1)

Table 1. Structural data.

Component	**Elastic modulus (Pa)**	**Area (m^2)**	**Mass per unit length (kN/m)**
Main cable	1.90E+11	0.049087	3.776263
Suspenders	1.90E+11	0.001963	0.151014

The thickness of the pavement is 0.10 m and the density is 2 400 kg/m^3. The live loads are in accordance with the *Technical Standard of Highway Engineering* of China (JTG B01-2003).

3.2 Initial Alignment and Iteration

The initial alignment is supposed to be a parabola. The original point of co-ordination is at the top of the saddle on the pile. The equation of the main cable is $y = 0.00261429158x^2 + 0.5$ The constraint on the tower is replaced by vertical constraints.

The initial alignment is shown in Figure 4.

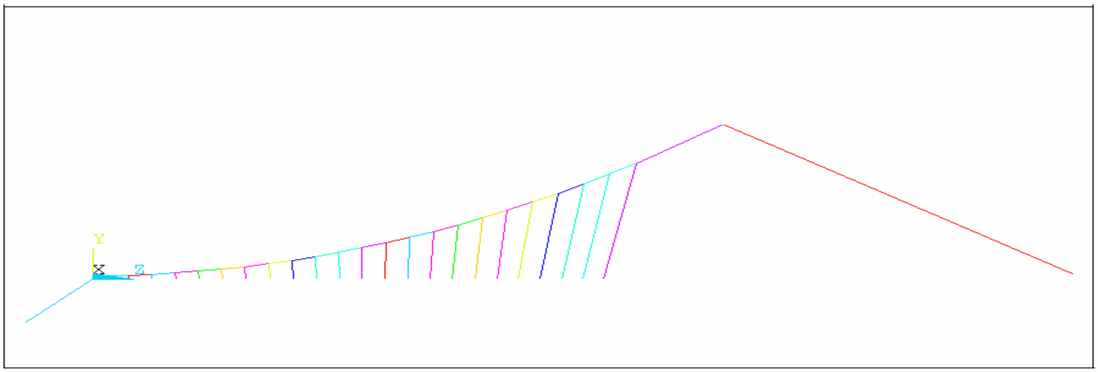

Figure 4. Side view of main cable and suspenders.

Calculations were carried out with the alignment and live loads conforming to the specifications of China. The main cable rotates in the space according to the pull of the suspenders. The main cable's maximum width-wise displacement on the bridge is 0.657 m. The displacement of the bridge width-wise on the saddle is 0.142 m and the counterforce is 325 kN. With those initial conditions set, iteration with the alignment starts.

The iteration steps are:

- Work out the nodal displacement of the main cable and the suspenders.
- Calculate the deformed alignment of the main cable and the axis force of the suspenders.
- Repeat the above two steps to get the final alignment.

The final alignment is neither parabolic nor catenary. It is a spatial curve with an “S” shape. Eventually, the displacement of the bridge width-wise on the saddle is 0.012 m and the counterforce is 3.5 kN.

3.3 Results

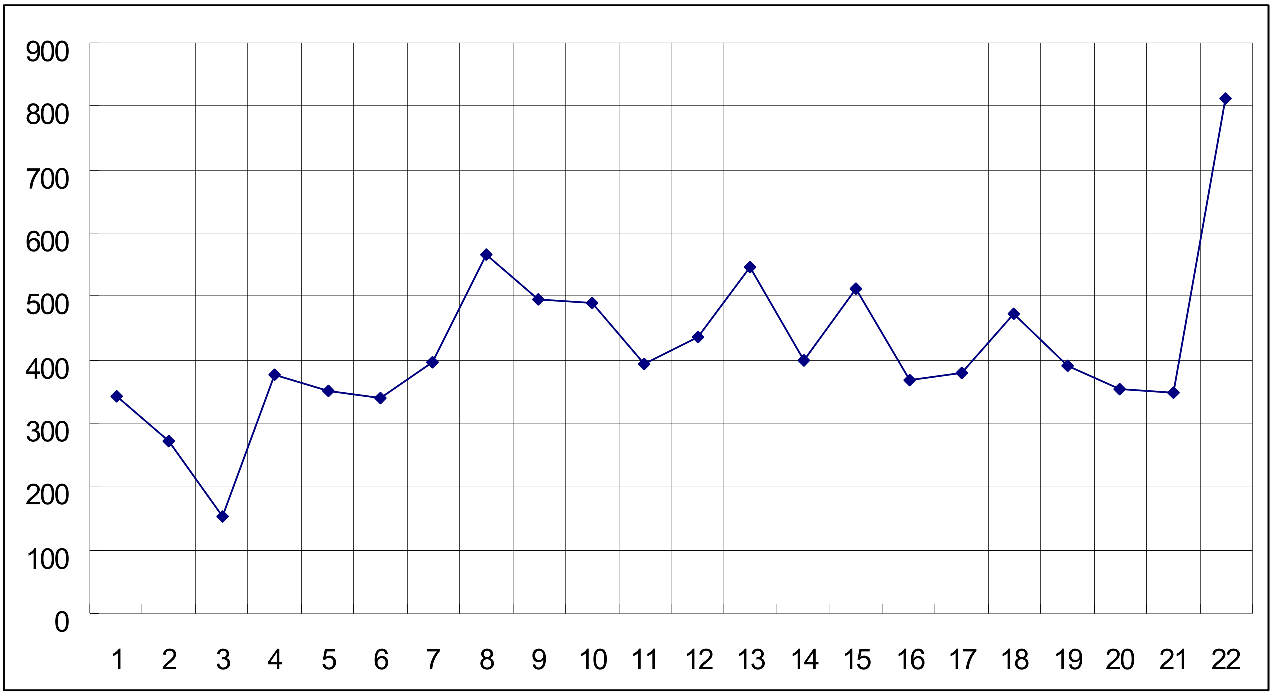

Figure 5. Axial force of suspenders (unit: kN).

As can be seen in Figure 5, the axial forces of the suspenders and the main cable are evenly distributed. The maximum axial force of the main cable is 24 774 kN, and the maximum axial force of the suspenders is 813 kN.

4. CONCLUSIONS

Several conclusions can be drawn from this study:

- The main cable’s maximum width-wise displacement on the bridge is 0.657 m. This is within a reasonable range.
- The axial forces of the suspenders on the main cable are evenly distributed. The counterforce of the saddle is below the allowable stress level.
- The displacement of the girder meets the requirements stated in the literature for suspension bridges constructed in China (Zhou Men Bo, 2003; Lei Jun Qing, 2002; Hu Ren Li, 1999; Niu He En, 1998).

To summarise, based on the finite element displacement theory, the authors were able to obtain the final alignment of Tong Sha Bridge. It satisfies the requirements for deck clearance according to Chinese specifications. Several finite element programs give results comparable to our final results, so this paper can be used as a reference for similar bridges.

5. QUESTIONS REQUIRING FURTHER INVESTIGATION

Although suspension bridges are widely used, suspension with a curved beam is rarely used due to its novelty. A curved beam was used here because of the constrained alignment. It can provide valuable experience for the construction of similar bridges. At the same time, some questions remain and require further study.

These are:

- The issue of construction supervision, i.e. how to construct such a bridge according to the design requirements
- The issue of simulation, i.e. how to decide what is the best procedure for pulling the suspenders
- Analysis of the key parts of the steel box girder
- Necessary experiments in the laboratory and outdoors.

Further investigation is also needed in order to determine the mechanical principles of curved beams of this type. The authors would welcome comments and critical analysis.

6. REFERENCES

[1] China Standard, 2003. Technical Standard of Highway Engineering (JTG B01-2003).

[2] Hu, Ren Li, 1999. Mechanical bridges. China Railway Press.

[3] Lei, Jun Qing, 2002. Suspension bridge design. China Communications Press.

[4] Li, Zheng Ren and Liu, Zu Guo, 2003. Application and foresight of curved cable-stayed bridge. Steel Construction, 18(6), pp 43–45.

[5] Niu, He En, 1998. Suspension bridge of Hu Men Bridge – engineering (second edition).

[6] Xiao, Ru Cheng and Xiang, Hai Fan, 1996. Theoretical method and research of program system to determine the proper design status of suspension bridge. Chang Sha: Hu Nan Science Press, 10.

[7] Xiao, Ru Cheng, Jia, Li Jun and Wang, Xiao Tong, 1999. Fictitious beam method for determination of main cable shape of long-span suspension bridges. Chinese Journal of Computational Mechanics, 16(1), 108–114.

[8] Zhou, Meng Bo, 2003. Suspension bridge handbook. China Communications Press.

[9] Zhu, Jin Guo, 2002. Accurate analysis of suspension main cable shape. An Hui Architecture, 7, pp 91–92.