Construction Control of the Yamen Cable-Stayed Bridge

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Abstract: Construction control is one of the key steps during erection of cable-stayed bridges. This paper presents a simple and practical procedure for construction control of PC cable-stayed bridges, including erection simulation analysis, field measurements, parameter identification and adjustments of deck elevations and cable forces. The procedure was successfully applied for the erection of the Yamen Bridge located in Guangdong Province of China, a PC cable-stayed bridge of 668 m in length.

1 Introduction

The 668 m long Yamen Bridge, as shown in Fig.1, is a PC cable-stayed bridge with a main span of 338 m and two side spans of 165m each [1]. It serves as a part of the Western Coastal Highway of Guangdong Province in South China and provides the vital linkage between Zhuhai City and Xinhui City originally separated by the Yamen Channel. The bridge deck consists of a PC box girder with a height of 3.48 m and a deck width of 26.8 m for four traffic lanes. The deck is mainly supported by 200 cables approximately 107 mm to 136 mm in diameter, which lay in a single plane emanating from the upper parts of the two main towers. Each tower is of a single reinforced concrete pylon that reduces its section area in steps and rises to a level of 128 m. The Yamen Bridge during erection is shown in Fig.2.

The box girder of the Yamen Bridge consists of 100 segments. The length of each typical segment is 6 m, with 106.3 m^3 concrete in volume which weighs approximately 2670 kN. The girder was built by the balanced cantilever segmental construction method with cable-supported carriages. The framework system for casting segmental concrete *in-situ* is mainly comprised of two parts, namely the cable-supported traveling carriage and the formworks. There are four such systems in work during erection of the bridge girder, each of which has a total weight of about 1800 kN.

2 Objectives of Construction Control

The deck elevations and cable forces are changing throughout the construction process of a cable-stayed bridge. Accordingly, two kinds of errors are frequently encountered, i.e., the geometric error of deck elevation and the tension force error in cables. During construction the structure must be monitored and adjusted carefully; otherwise errors may accumulate leading to substantial influence on the structural performance and even structural safety concerns. The objective of construction control is, therefore, to build a bridge that meets the prescribed aims with acceptable errors. In particular, two basic requirements should be achieved for the completed structure. In the first place, the geometric profile of the girder matches the designed shape well, and, in the second place, the internal forces of the structure are within the designed envelope values, with the bending moments of the girder and pylons being small and evenly distributed.

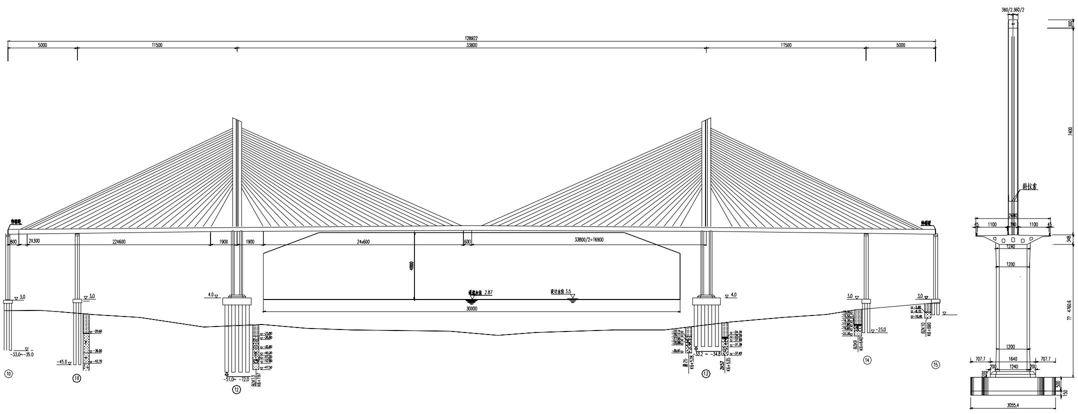

Fig.1　Elevation of the Yamen Bridge

Fig.2　The Yamen Bridge during erection

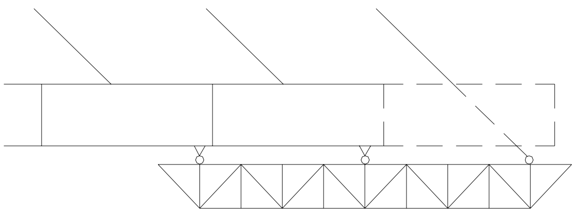

Fig.3　Cable-supported traveling carriage

3　Contents of Construction Control

According to the structural features and the construction method of cable-stayed bridges, the practice of construction control consists of four tasks: (1) simulation analysis of construction process; (2) field measurements during erection; (3) identification of structural parameters; and (4) adjustments of deck elevations and cable forces during construction. The objective of the first task is to obtain theoretical predictions with regard to girder deflections, cable forces and the other internal forces of the structure. The objective of the second task is to grasp the actual conditions of the structure at each construction stage. The above two tasks lay the groundwork for the third task, that is, identification of the structural and material parameters of the bridge. Finally, the fourth task can be readily conducted based on the results of the previous work. The four tasks mentioned above should be repeated for each construction stage until completion of the bridge.

4 Simulation Analysis during Erection

Simulation analysis of construction process for construction control of cable-stayed bridges deals mainly with three jobs: (1) the simulation analysis of segmental construction process; (2) the analysis of creep and shrinkage effects of concrete during erection; and (3) the analysis of temperature effects on the structure during construction. Simulation analysis is performed through finite-element programs with beam and bar elements being adopted.

4.1 Simulation analysis of segmental construction process

With the development of close-cable systems, the girder becomes thinner and more flexible. The girder itself may not be able to carry the cantilever weights of the carriage and the newly cast segment. To solve this problem, an innovative erection method based on cable-supported carriages was proposed. In this method, the carriage is supported not only by the previous segments but also by the stay cables corresponding to the current segment, as shown in Fig.3. After the new segment has been cast and prestressed, the cables are loosened off the carriage and turn into permanent stays. Obviously, the carriage works as a part of the whole structure when the segment is being poured *in situ*. Therefore, the carriage must be incorporated into the finite-element model for construction simulation. In addition, all steps involved in each segmental construction process should be taken into consideration in the simulation analysis.

Table 1 A typical segmental erection process for the Yamen Bridge girder

Step 1	Move the carriage forward and set up forms at proper levels
Step 2	Set up reinforcement of the segment
Step 3	Erect and partially stress the stay cables (up to 25% of the required tension forces) attached to the carriage
Step 4	Cast 50% concrete
Step 5	Stress the stay cables for the second time
Step 6	Cast the remaining 50% concrete
Step 7	Stress the stay cables for the third time, up to 50% of the required tension forces
Step 8	Cure and prestress the segmental concrete
Step 9	Loosen the connection between the stay cables and the carriage, and then stress cable stays to the required values

The first objective of the simulation analysis is to reach a proper construction scheme during casting of segmental concrete, specifically in respect of the cable-tension times and the corresponding tension forces. A typical segmental erection process for the Yamen Bridge girder is illustrated in Table 1. The second objective of the simulation analysis is to determine the proper level to set up the forms for the new segment. This can be achieved by a simple backward analysis based on the prescribed elevation of the segment when completed. Finally, the whole process of structural responses, including deformation and internal forces, can be obtained through simulation analysis, which lays a theoretical basis for the following parameter identification and construction adjustments.

4.2 Analysis of creep and shrinkage effects of concrete

Due to the difference of concrete age between different segments of the girder, creep and shrinkage effects of concrete must be considered in detail through incremental finite-element analysis, in which characteristics of segmental construction techniques should be taken into consideration. The concepts of effective modulus and equivalent initial strains should also be employed in the analysis. The theoretical results obtained in Section 4.1 can then be modified based on the above calculation. It has been shown by finite-elament analysis that the effects of creep and shrinkage effects of the Yamen Bridge girder are not negligible. They have certain influences on the girder deflection and the cable forces as well. The maximum variations of the girder deflection and cable forces due to creep and shrinkage effects are approximately 25 mm and 90 kN, respectively [2].

4.3 Analysis of temperature effects

Grasping the regularity of temperature effects is of great concern to construction control of cable-stayed bridges during erection. There are three different kinds of effects, namely the effect of overall temperature difference, the effect of temperature difference between the girder and cables, and the effect of temperature gradient of the girder. Overall temperature difference has little influence on the structure due to nearly the same coefficients of expansion for the concrete and cable materials, while the remaining two factors have somewhat large influence on the bridge. For the Yamen Bridge, finite-element analysis shows that the maximum influence on the girder deflection and cable forces during a day may be up to about 80 mm and 70 kN, respectively, which are in good agreement with the results obtained from field measurements [2]. Clearly, modifications due to temperature effects are extremely important for determination of form levels and field measurements of cable forces.

5 Field Measurements during Erection

Field measurements during erection of a PC cable-stayed bridge generally include measurements of cable-stayed tensions, girder and pylon stresses, deck profile and pylon deformation, temperature of structural components and temperature effects, etc. Among them the measurements of cable forces and concrete stresses are the most important. They will be discussed below based on the field measurement practice during erection of the Yamen Bridge.

5.1 Field measurement of cable-stay tensions

During the erection of a cable-stayed bridge, the profile of the main girder and the structural internal force state are strongly related to the cable forces. It is, therefore, required that cable-stay tensions be measured at high accuracy and efficiency. The frequency domain method is now the most commonly used method for measurement of cable forces. The method consists of two steps. First, the random vibration signals of cables under ambient excitation are picked up by accelerometers attached to them. The signals are then analyzed in the frequency domain with the natural frequencies of the cables being identified. Second, the cable forces are deduced according to the relationships between tensions and frequencies of the cables, which should be determined in advance by theoretical analysis and field calibration. It is evident that the effectiveness of the frequency domain method depends mainly on the accuracy in both signal-pickup techniques and tension-frequency relationships of the cables.

After completion of each segment of the Yamen Bridge girder, the tensions of the cables corresponding to the first five segments at the cantilever ends were measured by the above method. The values were then compared with the theoretical predications for the purpose of parameter identification of the current construction stage.

5.2 Field measurement of girder and pylon stresses

At each erection stage the concrete stresses at critical sections along the girder and pylons must be monitored and reviewed so as to ensure the structural safety as construction goes forward. For the Yamen Bridge, strain gauges were embedded at 13 sections for stress monitor of the girder and pylons. It should be noted that only concrete strains can be measured directly based on the use of strain gauges. The strains must then be transformed into equivalent stresses by certain stress-strain relationships. How to separate the non-stress strains due to creep and shrinkage effects from the total strains in concrete becomes the critical issue for obtaining concrete stresses at certain accuracy.

In view of the above problem, a new method was proposed in the practice of the Yamen Bridge on the basis of the fact that the stresses at the neutral axis of the girder are only related to cable forces. The procedures of the method are briefly outlined as follows. First, the stresses along the neutral axis of the girder are calculated by use of the measured cable forces. Second, those stresses are then used to calibrate the corresponding stresses by field measurements, from which the creep and shrinkage coefficients of concrete can be identified. Finally, the above results can further be used to modify the measured stresses at upper and lower edges of the sections.

6 Parameter Identification during Erection

On the basis of simulation analysis and field measurements during erection of cable-stayed bridges, such parameters as girder segmental weights, elastic modulus of concrete, coefficients of creep and shrinkage of concrete, and temporary construction loads, etc., can be identified by the discrepancies between the actual structural responses and the theoretical predictions. It has been found through stochastic sensitivity analysis [3] that the errors of girder segment weights have the most important effects on the girder deflection and cable forces. For the Yamen Bridge, the discrepancies of the segmental weights range between 0.9% to 3.1% of the designed values [2].

7 Adjustments of Deck Elevations and Cable Forces

During the construction of a cable-stayed bridge, some discrepancies may occur between the actual state and the state of design expectation. Such discrepancies may arise from the errors of those material and/or loading parameters as stated in the previous section. Therefore, it is required that certain construction adjustments be performed timely during erection so as to control the discrepancies within an allowable tolerance. In this respect, there exists the so-called "double-control" issue, that is, both the deck elevations and the cable tensions are expected to be controlled at high accuracy. But, in fact, the requirements for deck-profile geometry and cable-stay tensions are frequently incompatible; it seems impossible to achieve both requirements simultaneously due to the influence of the other parameter errors. In view of the above considerations, the deck elevations of the Yamen Bridge were required to be controlled within close tolerance, while the cable forces could be turned over a suitable range to eliminate or reduce the effects of such errors as segmental overweights on the deck profile and the internal force state of the girder and pylons.

Since a cable-stayed bridge is a highly redundant structure, changing one cable tension will cause deflection and cable-tension changes throughout the whole structure. Therefore, in case a group of cables need to be adjusted, careful planning for the adjustment based on detailed analysis is absolutely necessary.

8 Results of Construction Control of the Yamen Bridge [2]

The closure tolerance and the corresponding discrepancies of elevation at the joints are listed in Table 2. After the closure of the main span, the deviations of segment elevations were controlled within the range of ±40 mm, showing that the geometric profile of the girder is in good agreement with the designed shape.

Table 2 Closure tolerance and elevation discrepancies at joints

Side	Side span		Main span	
	Closure tolerance (mm)	Elevation discrepancy (mm)	Closure tolerance (mm)	Elevation discrepancy (mm)
East	+2	-17	2	+16
West	-3	+20		

After completion of the main span, the measured stresses at different sections of the girder are given in Tables 3 and 4. The results obtained by theoretical identification are also listed in the tables for comparison. It is evident that the theoretical predictions basically match the measured values, and that the structure is safe with the compression stresses of the girder below the prescribed maximum value of 13.5 MPa. As for cable forces, they are distributed reasonably and mostly larger than the designed values due to the overweights of segments. The discrepancies of the cable forces are basically controlled within 6% of the prescribed values.

Table 3 Girder stresses after closure of the main span (East side, MPa)

Position		S1	M1	S15	M17
Upper	Measured	-9.68	-11.30	-7.07	-6.35
	Theoretical	-10.24	-10.73	-6.78	-3.82
Middle	Measured	-9.97	\	\	-6.42
	Theoretical	\	\	\	\
Lower	Measured	-10.68	-9.70	-8.42	-12.19
	Theoretical	-10.12	-9.44	-7.13	-9.32

Table 4 Girder stresses after closure of the main span (West side, MPa)

Position		S1	M1	S15	M17
Upper	Measured	-9.78	-8.44	-5.98	-2.64
	Theoretical	-9.58	-10.40	-6.71	-3.86
Middle	Measured	\	-9.87	\	-5.74
	Theoretical	\	\	\	\
Lower	Measured	-11.26	-9.72	-5.65	-7.35
	Theoretical	-11.07	-10.17	-7.41	-9.43

Note: S—side span; M—middle span; segments are numbered from the pylon location.

9 Concluding Remarks

Construction control plays an extremely important role during erection of cable-stayed bridges. Detailed simulation analysis and careful field measurements must be conducted throughout the whole construction process. The actual state of the structure should be monitored and compared with the theoretical expectation. On the basis of the above work, identification of the relevant parameters must be performed timely, so that effective schemes of construction adjustments can be worked out to avoid accumulation of the discrepancies of the structural response during erection. Fruitful results have been achieved in the construction control of the Yamen Bridge, indicating that the procedures presented in this paper are reliable and practical.

References

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