Accelerated Construction of Self-Anchored Suspension Bridge using Novel Tower-Girder Anchorage Technique

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Abstract:

The traditional construction methods (e.g., erecting cable after girder) of self-anchored suspension bridge, can interrupt traffic during the construction stage due to the installation of temporary supports. That severely limits the wide application of this type of bridges. Thus, this study proposes a novel tower-girder anchorage (TGA) technique for accelerated construction of self-anchored suspension bridges. By using the proposed TGA technique, the mid-span girder segments are hoisted and connected to the hangers, which subsequently avoids the interruption of traffic during the construction period. The proposed TGA technique would reduce the construction cost, time of erection, and demolition of temporary scaffolds. To ensure structural safety and performance during the proposed construction process, the force transfer mechanism and construction process of TGA technique are assessed. To this end, the devices for TGA and system transformation are designed. The constructability of TGA technique on accelerated bridge construction is evaluated by a real-world application: Dongtiao River Bridge in China. A finite element model is established to analyze the construction process. Simulation analysis and field test data are compared. The comparison demonstrates that TGA technique can safely and economically achieve accelerated construction of self-anchored suspension bridges.

Keywords: Self-anchored suspension bridge; Tower-girder anchorage; Accelerated construction; System transformation.

Introduction

Owing to the increased attention to the bridge landscape and aesthetics, self-anchored suspension bridges, which are associated with exquisite shape and lightweight configuration, have rapidly gained popularity in bridge engineering around the world (Li *et al.* 2013; Xu *et al*. 2016; Frangopol *et al.* 2017; Wang *et al.* 2018). Well-known examples are the Yongjong Bridge (Gil and Choi 2002), San Francisco-Oakland Bay Bridge (Sun *et al*. 2004), Pingsheng Bridge (Hu *et al.* 2006), Liede Bridge (Ke 2010), Qingdao Bay Bridge (Nie *et al.* 2011), Jiangdong Bridge (Shen *et al.* 2011), Taohuayu Yellow River Bridge (Wang *et al.* 2014), among others.

The self-anchored suspension bridges do not require huge earth-based anchors and can begenerally used as a feasible solution to cross the channel restricted by terrain and geology; sometimes, self-anchored suspension bridges have become the landmarks for many places (Li and Jia 2005; Xu *et al*. 2016; Zhang *et al*. 2013). The main cables of the self-anchored suspension bridges are anchored at both ends of stiffening girder, which carry the horizontal force resulting from the tensioned cable (Jung *et al*. 2015; Ochsendorf 1999). Due to the girder-based anchor, the girder would be constructed first on the temporary supports before erecting and anchoring main cables. This construction procedure is termed as “erecting cable after girder” (ECAG) method. The ECAG method has been the main construction method for self-anchored suspension bridge (Nie *et al*. 2011; Xu *et al*. 2016); however, the method inevitably interrupts traffic due to temporary supports under girders during the construction period. In 1915, German engineers built the first large-scale self-anchored suspension bridge over the Rhine River at Cologne (Mullins 1936). The most distinguished self-anchored bridge was the Cologne-Mulheim Bridge constructed in 1929, with the main span of 315 *m* and it was the longest suspension bridge in Europe when completed (Schleicher 1929). The Konohana Bridge in Osaka is the first large-scale, modern self-anchored suspension bridge (Tanaka *et al*. 1992). In 2001, Yongjong Bridge, the world's largest highway and railway bi-purpose self-anchored suspension bridge, is built as a three-span continuous double-deck bridge (Gil and Choi 2002). The new San Francisco-Oakland Bay Bridge, which is a single-tower self-anchored suspension bridge with a main span of 385 m, was opened in 2013 (Sun *et al*. 2004). The Taohuayu Yellow River Bridge has the main span length of 406 m and it and is the longest self-anchored suspension bridge in the world (Wang *et al*. 2014). The ECAG method was employed to construct all the aforementioned bridges. Bridges constructed using ECAG method have the disadvantages, such as extended construction time, higher cost, risk of assembling and removing temporary supports, among others. Thus, the ECAG method does not comply with the accelerated bridge construction (ABC) approach (Zhu and Ma 2010; Zhu *et al*. 2015) and has become the one of the main factors limiting the wide application of the self-anchored suspension bridge.

With the increasing demands for the ABC and novel structural construction methods (Deng *et al*. 2016; Tucker and Ibarra 2016; Dong 2018), it is crucial to explore and upgrade the erection scheme of self-anchored suspension bridges. Considering this issue, some construction technologies of the self-anchored suspension bridges for ABC are investigated. The representative methods are (1) Cable-stayed method (Zhong 2004): The deck sections are cantilevered out by using temporary cable stays. Only when the deck is completely erected, the main cable can be erected. After completion of the main cable, the cable stays are removed. This method was used for the construction of the Duisburg Bridge (Goolen 2006), E'gongyan Bridge, among others(Chen 2017); (2) Temporary ground anchor (Tian 2006): The caisson is used as temporary anchorages that can support the tension of the main cables by the steel wires between the caissons and end girders, while the design of side piers only needs to satisfy the force of the finalized stage of the bridge. Representative bridges built by this method include Zhuyuan Bridge (Sun *et al*. 2004) and the Soosan Bridge (He 2009; Liu 2004) in China; (3) Pier-girder anchorage method (An *et al*. 2007): A permanent side-pier and its foundation were used as a temporary anchorage to support the main cable. The construction of the Beijing-Hangzhou Canal Bridge adopted the combination of pier-girder anchorage method and temporary ground anchor method (Tian 2006); and (4) Tower-girder anchorage method: To resist the horizontal cable force, a compressive strut is needed in the side span from the end support to the basement of the tower(Goolen 2006). The temporary cable-stayed method and ground anchor method need a lot of temporary components and are associated with extended construction period and higher cost for assembling and removing temporary components. The pier-girder anchorage method cannot be directly applied to long-span bridge construction.

To overcome the aforementioned drawbacks, a novel Tower-Girder Anchorage (TGA) technique for accelerated construction of self-anchored suspension bridges is proposed in the paper. The TGA technique makes the bridge tower resist the horizontal force resulting from the tensioned main cable during the hoisting process of main girder. Once the final closure section is welded, the horizontal component of the main cable tension is transferred smoothly from tower to the main girder and the structure is transformed to a permanent system. This method has been successfully applied to Dongtiao River Bridge in China. The following sections depict the details of principle, anchorage devices, and structural system transformation of TGA.

Tower-Girder Anchorage Construction Technique of Self-Anchored Suspension Bridges

Basic Principle of TGA Technique

To eliminate traffic impacts under girder during construction period (Fig. 1b), TGA technique erects mid-span girder by hoisting segment method, such as the deck unit erection gantry (Fig. 1a). By using the TGA device, the side-span girder transfers the tension of main cables to the bridge tower. The bridge tower bears the horizontal component of main cable tension during the hoisting process of mid-span girder segments, to ensure the normal operation of traffic under the bridge. TGA technique takes full advantage of the enormous anti-push capability of the bridge tower to resist thehorizontal force during the construction stage.

The detailed construction process of TGA technique is shown in Fig. 1a. The side-span girders are erected on the temporary supports; the side-span girders are temporarily anchored at the bridge tower by the TGA device, as indicated in Fig. 1. The main cables are erected and anchored to the designed position at the side-span girder ends. The horizontal force resulting from the main cable is transferred to the bridge tower by side-span girders. During the erection process of the mid-span girder segments, the horizontal component of the main cable tension is undertaken by the bridge tower. Meanwhile, the bending state of the tower can be improved and regulated through the adjustment of the unbalanced horizontal force ΔH, as shown in Fig. 2, which is related with the magnitude of tension force within the hangers, number of tensioned side-span hangers, among others. When the main-span girder is hoisted in segments and connected to the hangers, girder segments are welded together. Finally, the structure is transformed from the temporary system to a permanent one.

The calculation scheme for TGA technique is shown in Fig. 2. The stress of the bridge tower is computed as:

$$\begin{cases} \sigma_{\min} = \min\left\{ \dfrac{N_1 + N_2 + G_1 + G_2}{A_1} - \dfrac{|H| \cdot h_1 - |\Delta H| \cdot h_2}{W_1}, \dfrac{N_1 + N_2 + G_2}{A_2} - \dfrac{|\Delta H| \cdot h_2}{W_2} \right\} \\ \sigma_{\max} = \max\left\{ \dfrac{N_1 + N_2 + G_1 + G_2}{A_1} + \dfrac{|H| \cdot h_1 - |\Delta H| \cdot h_2}{W_1}, \dfrac{N_1 + N_2 + G_2}{A_2} + \dfrac{|\Delta H| \cdot h_2}{W_2} \right\} \end{cases} \quad (1)$$

where N_1 = vertical force resulting from tensile force of the side-span cable; N_2 = vertical force associated with the tension force of the mid-span cable; G_1 = weight of the bridge tower below the main girder; G_2 = weight of the bridge tower above the main girder; A_1 = area of the I-I section; A_2 = area of the II-II section; H = horizontal force resulting from the cable tension; h_1 = height of the bridge tower below the main girder; h_2 = height of the bridge tower above the main girder; ΔH = unbalanced horizontal force of the middle and side span; W_1 = section modulus of the I-I section; and W_2 = section modulus in bending of the II-II section.

The TGA technique meets the construction requirements of the long-span self-anchored suspension bridge. Because the cross-section of the pier part within the bridge tower is the largest among all the pier column, it can be used as a temporary bearing structure to resist the horizontal force resulting from the main cable tension during the construction process. In order to enlarge the applicable span of self-anchored suspension bridge, the TGA technique transfers horizontal force to the pier part of tower through the side-span girder. TGA technique takes full advantage of the enormous anti-push capability of the pier part of the bridge tower. Furthermore, by using the TGA technique, the temporary bearing structure is transformed into an eccentric pressure member (Fig. 1a & 2); which could reduce the tensile stress as shown in Eq. (1). In addition, as the axial force of the tower during construction is much less than the design force, the flexural capacity would increase accordingly under the axial load. The axial force born by the side span girder during the construction process using the proposed method is comparable as that of the “erecting cable after girder” method. Therefore, in order to avoid buckling and compressive failure, the layout distance of temporary support of side-span girder can base on the traditional construction method (e.g., 2 to 4 times the hanger spacing).

Anchorage Device Design for TGA Technique

The device for TGA is mainly composed of two pairs of grille frames, i.e. anchored to the bridge tower and the side-span girder, force transmission braces (placed in between the grille frames), and the vertical displacement restraining device. Detailed configuration of the device for TGA is depicted in Fig. 3a. Two grille frames are anchored to the bridge tower and the side-girder with the perfobond leiste (PBL) board, U-shaped anchor bar, and pre-embed steel. Force transmission braces are composed of reaction frames and the jacks are installed. The vertical displacement restraining device is fixed on the bridge tower, which is used to ensure that the force transmission braces can smoothly transmit the horizontal tension of the side-span girder.

Structural System Transformation of TGA Technique

After all the girder segments are hoisted, the segments are welded to an integrated structure. As indicated in Figure 3b, jacks are installed at the closure segment to adjust the closure gap. These jacks are launched smoothly to transfer 40% horizontal force of cable tension to girder from bridge tower. Then, some other jacks are launched gradually to transfer the remaining 60% horizontal force of cable tension from reaction frames. After the reaction frames are uninstalled, the closure section is welded to make sure that the closure gap meets the welding requirement (20 mm) by correspondly unloading the jacks. Then, all the jacks are unloaded step by step until transferring the 100% horizontal force of cable tension to girder. The system transformation is then completed, namely, to transform the temporary system to a permanent one.. The detailed steps are outlined in Fig. 4.

Constructability Assessment of TGA Technique on ABC

The main requirements of ABC are to reduce the construction time, avoid traffic delays, reduce the expense of a temporary structure, and improve workers' safety during the construction process (Hartley *et al*. 2015). Traditional full scaffold method (Li *et al*. 2008) and incremental launching method (Chen 2006) belong to the method of erecting cable after girder and these construction processes are different from the TGA technique. The processes of two methods are shown in Fig. 5, and ABC performance evaluation associated with the two methods are listed in Table 1.

As shown in Table 1, the traditional “erecting cable after girder” method has the disadvantages of higher cost and longer construction period, meanwhile inevitably interrupts traffic during the construction period. The TGA technique is a novel solution to overcome these problems, which not only avoids the channel traffic obstruction under the bridge but also takes full advantage of the anti-push capability of the tower to reduce the construction time. Thus, the TGA technique can reduce the traffic interruption for both the channel and road traffic.

Engineering Application

Investigated Bridge

The Dongtiao River Bridge in Huzhou, China, a self-anchored cable-stayed-suspension bridge with a span of (75 + 228 + 75) *m* and a semi-floating structural system, is illustrated as an example in this study. The overall layout of the bridge is shown in Fig. 6. The main span of the bridge is a spatial cable suspension bridge with a rise-span ratio of 1/7 and the vector height is 44.5 *m*. The main cable is separated into 7 individual cables through the splay sleeve and anchored in the tower. In order to balance the horizontal force transmitted by the main cable on the bridge tower, the cable-stayed structure is adopted in the side span. The longitudinal spacing of the side cable is 10 *m*. The upper end of the side cable is anchored in the bridge tower, whereas, the lower end is anchored in the concrete box girder. The bridge tower is a steel structure and, the bridge tower comprises a monolithic arch structure. The stiffening girder is a steel-concrete composite girder which consists of steel box girded in the middle span and prestressed concrete box girder in the side spans. The girder height is 3 *m* and the width of the box girder is 41.6 *m*. The Dongtiao River has a busy navigation channel as shown in Fig. 7.

Construction Process

The main construction procedures of Dongtiao River Bridge are as follows: ① The tower foundation is constructed and the side-span concrete girder is constructed on the falsework; ② The tower segments are assembled by welding on the side span girder, then the tower is rotated to the designed position; ③ The TGA device is installed; ④ The cables andhangers of the mid-span and side span are erected; ⑤ The steel girder segments of the mid-span are hoisted and attached to the hangers; ⑥After all the girder segments are hoisted, the segments are welded to an integrated structure. Then, the temporary anchorage device is removed, and the bridge system is transformed into the final self-balanced state; and ⑦ the falsework supporting the side-span girder is removed, and the pavement is constructed. The detailed construction steps of hoisting mid-span girder segments are shown in Fig.6.

Finite Element Analysis

The finite element model of the investigated bridge was established using Ansys as indicated in Fig. 7a. The structural performance during the construction stage is assessed considering several performance indicators. The tower and girder are modeled using beam elements, whereas the main cables and hangers are modeled using a series of elastic catenary cable elements to account for geometric nonlinearity caused by cable sag. The segment of main cable, separated by two adjacent hangers, is modeled using the cable element. The connections between hangers and the girder are modeled using special rigid elements. The whole FE model, as shown in Fig. 7a, consists of 936 elements, 133 link elements, and 941 nodes.

A three-dimensional solid finite element model analysis is carried out for the temporary grille frame (Fig. 7b). The constraint conditions of the tower-girder temporary anchorage are indicated as follows: the bottom of the tower is consolidated, and virtual beam elements and rigid arms are arranged at the top of tower wall to transfer the relative displacement from the upper tower to the top of tower wall. The displacement boundary conditions are used instead of the force boundary conditions in the model.

Process of Hoisting Girder Segments by TGA Technique

The Q420qd steel is used for the TGA device. The mid-span girder segments (Fig. 9) have been successfully hoisted by TGA technique as shown in Fig. 8, which could avoid the interruption of the ship navigation during the construction period.

The variation trend within the construction steps of the horizontal thrust and axial force of TGA device is similar as shown in Fig. 10a. The axial force of the TGA device increases gradually and its maximum value is 17401.6 kN at construction step 29. After the completion of structural system transformation, the force of the TGA device is reduced to zero kN as the horizontal force is fully transferred from the bridge tower to the main girder. Similarly, with the hoisting of the main girder, horizontal thrust of the tower increases and the maximum value is approximately 43254.5 KN. Then, the horizontal thrust of the tower is reduced to 31356.5 kN.

As shown in Fig. 10b, the vertical reaction force of the tower increases gradually and reaches the maximum value of 101402.5 kN at the final construction step. Along with hoisting girder segments, the moment at the tower foundation changes gradually from the 166855.6 kN·m in step 1 to -161844.8 kN·m in step 27. The moment at the tower foundation is 24083.2 kN·m at the final construction step. The variations in steps 2-3 and 27-28 are due to the adjustment of the stay cables tension. The calculated moment and axial force of bridge tower is far less than the allowable value, and the load-bearing capacity of bridge tower satisfies the requirement.

The horizontal and vertical displacements at the top of tower are shown in Fig. 10c and Fig. 10d, respectively. The upward direction is defined as positive for vertical displacement. The direction toward the mid-span is defined as positive for horizontal displacement. The displacements associated with three points on the tower are selected (i.e., the top of tower, the highest point of stayed cable in side-span, and the lowest point of the branch cable in mid-span). As indicated, the variation trend of the horizontal and vertical displacement during the construction stage is similar. The maximum absolute value of displacement is in step 1 under the dead load of tower. At the final construction step, the horizontal and vertical displacements at the top of tower are 2.15 and -1.52 cm, respectively.

As indicated in Fig. 11, the maximum shear stress between TGA device and tower wall is 117 MPa, which is located at the junction point of grille frame and tower wall. The maximum Mises stress is 357 MPa and the Mises stress of the steel plate near the point is about 119 - 198 MPa. The Mises stress in the other locations is below 150 MPa. The results show that under the maximum horizontal thrust, the stress of TGA device is far less than the allowable value, and its strength satisfies the requirement.

Structural System Transformation

Based on the finite element analysis, the maximum axial force of TGA device is 17401.6 kN. Four sets of jacks of 5000 kN are arranged respectively in the anchorage device on both sides. Meanwhile, another 4 sets of identical jacks are arranged at the closure section as shown in Fig. 12. Structural system transformation is conducted with a total of 12 jacks together. The system transformation process is divided into 20 steps, in which the jacks at the closure segment are launched in steps 1-4, the jacks at the tower-girder anchorage are launched in steps 5-9, the closure gap is adjusted to meet the welding requirement in steps 10-14, and the system transformation is completed in steps 15-20 by welding the closure section.

The variation of forces for the permanent and temporary component during the construction process is shown in the Fig. 13. As indicated, the jacks at closure segment are gradually loaded to resist 8000 kN of the horizontal force; subsequently, the jacks at the tower-girder anchorage are gradually loaded to resist the remaining 10000 kN. Thus, at step 9, all the horizontal components of cable tension are transferred to the jacks from the reaction frames. Then, the jacks at tower-girder anchorage are gradually unloaded and all the horizontal component of cable tension are transferred to the jacks at the closure segment. Subsequently, the jacks at closure segment are unloaded.

Along with the loading and unloading process of jacks, the axial force of mid-span critical section increases twice. The first increment is due to the starting of the jacks at the closure segment, and the second increment is due to the unloading of the jacks at tower-girder anchorage. The axial force of TGA is gradually reduced to zero kN, which is due to that the horizontal force is transferred to jacks. The horizontal thrust of tower transferred from girder also reduces gradually to 0 kN. Since the force of the jacks at tower-girder anchorage is also transferred to the tower and the thrust value keeps unchanged in the steps 5-8 as shown in Fig. 13c.

The closure gap is adjusted to the welding requirement by unloading all jacks gradually. The field test data are shown in Fig. 13d. The closure gap width increases gradually to 45 *mm* due to the elastic compression of the girder in steps 1-5 and decreases gradually to 20 *mm* in steps 9-14 due to the unloading of jacks. The horizontal displacement of the side-span girder end is 18 *mm*.

Conclusions

A novel tower-girder anchorage (TGA) technique for accelerated construction of self-anchored suspension bridges is proposed in this paper. In general, the basic principle of anchorage device design and construction process of the TGA technique were investigated. The constructability of TGA technique on accelerated bridge construction is evaluated and has been successfully implemented on Dongtiao River Bridge in China. It was observed that for the construction of a self-anchored suspension, the TGA technique can be adopted as an efficient approach. The TGA technique transfers the horizontal force resulting from the main cable to the bridge tower by temporary TGA device during the hoisting of mid-span girder segments. Through the system transformation process, a permanent self-anchored system is finally completed. Since the TGA technique fully exerts the huge anti-push bearing capacity of the bridge tower, it can be applied to the accelerated construction of long-span self-anchored suspension bridges. Compared with the traditional methods, the TGA technique not only avoids traffic obstruction during construction but also reduces the construction cost and time significantly.

The feasibility and practicability of the TGA technique were highlighted and validated by the finite element analysis and field test. The results showed that the force variations of the tower and TGA device satisfied the code requirements during the hoisting girder segments process and the force transformation is smooth and safe during the system transformation process. Simulation analysis and field test data demonstrate that TGA technique can safely and economically achieve accelerated construction of self-anchored suspension bridges.

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Table 1. ABC performance evaluation associated with the two methods

ABC Performance	Traditional "erecting cable after girder" method	Tower-girder anchorage method
Traffic delays	Obstruct the mid-span and side-span traffic;	Eliminate impacts on mid-span traffic;
Temporary facilities	Lots of temporary supports or scaffolds;	Simple TGA device;
Onsite construction periods	Longer construction periods due to: 1. Erection and dismantlement of massive temporary facilities and 2. The catwalk and main cable can only be erected after the main girder is fully erected;	Shorter construction periods due to 1. Erection and dismantlement of simple temporary facilities and 2. The catwalk and main cable erection can be carried out simultaneously with the construction of the mid-span girder;
Construction cost	Higher cost, due to erection and dismantlement of massive temporary facilities.	Less cost, due to erection and dismantlement of simple temporary facilities.