Novel Technique for Configuration Transformation of 3D Curved Cables of Suspension Bridges: Application to the Dongtiao River Bridge

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Abstract:

Configuration transformation is an important issue during the construction stage of spatial suspension bridges with three-dimensional (3D) curved cables. Without fully considering this issue, the hangers could collide with the cable duct at the connection of the cable and girder, which can cause damage to the hangers and hamper the construction procedure. This paper proposes a novel technique using lateral bracing members (LBMs) to aid the configuration transformation during the construction stage of suspension bridges. The lateral displacement and rotation angle are investigated to ensure safety during the construction process. The limitations of the conventional configuration transformation techniques are acknowledged. In order to demonstrate its capability the proposed technique is applied to a suspension bridge ,the Dongtiao River Bridge, located in Huzhou, China. Based on the results, it can be concluded that the LBMs can provide an efficient, reliable, and economical solution to aid configuration transformation of 3D curved cables of suspension bridges during the construction stage.

Keywords: Configuration transformation; Lateral bracing members; Rotation angle; Spatial suspension bridges; Novel construction method

1. Introduction

Suspension bridges have been widely used to cross long spans. For most self-anchored or earth-anchored suspension bridges, the main cables are arranged in the vertical planes(Xu et al. 2017). Recently, three-dimensional (3D) curved cables (i.e., spatial cables) have been used in the suspension bridges. Suspension bridges with 3D curved cables are not only elegant but also significantly enhance the lateral stiffness and torsion resistance of the structure (Sun et al. 2016). Generally, the 3D system is formed by inclined hangers in transverse direction and cables are constructed spatially from the top of towers to the outside of the girder at the main span. For instance, the Yongjong Grand Bridge in Korea (Gil and Choi 2001; Gil and Choi 2002; Kim et al. 2002; Kim et al. 2006) and the new San Francisco–Oakland Bay Bridge in the United States (Sun et al. 2002; Sun et al. 2004) belongs to this type of bridge structure. In addition, this type of bridge has also been adopted in China, and many bridges of this type have been constructed, such as the Fumin Bridge in Tianjin (Sun et al. 2015; Xiong et al. 2017), the Qingdao Bay Bridge (Nie et al. 2011), the Liede Bridge in Guangzhou (Zhang et al. 2013), the Jiangdong Bridge in Hangzhou (Li et al. 2010; Zhang et al. 2010), the Jiangxinzhou Bridge in Nanjing (Li et al. 2013), and the Tianhe Bridge in Songyuan (CSCEC-6th-Bureau 2016; Huang et al. 2017; MingHao-technology 2016).

For suspension bridges with 3D cable, the construction process is generally more complicated than that of planar cable bridges because of the configuration transformation. For the 3D curved cable, the shape must be changed from plane configuration to the 3D curved profile during the construction process, which could cause the lateral displacement of main cables and the rotation of the hanger and cable bands. Thus, during the construction stage, the hangers can rub or collide with the cable duct at the girder and/or the pin plate at the cable band, which in turn could damage the hangers and hamper the construction process.

In order to solve this problem, several techniques were developed. For instance, during the construction stage of the Yongjong Grand Bridge, four groups of winches and hydraulic jacks were placed on the deck near the center of the main span, and the two main cables were moved outside to complete the cable shape change (Cho et al. 2001; Gil 2001; Yoon et al.

2001). For the Jiangdong Bridge, five pairs of temporary hangers anchored into the girder were used to shift the configuration of the cables (Ke et al. 2010). With respect to the Tianjin Fumin Bridge, the innovative rotatable cable clamp (Han et al. 2008) and hanger with spherical hinge base (Wu et al. 2008) were proposed to adapt to the lateral displacement and lateral torsional angle. The techniques of the rotatable cable clamp and spherical hinge base were also applied to Songyuan Tianhe Bridge, combined with the control technique of temporary hangers (Huang et al. 2017). In the new San Francisco–Oakland Bay Bridge, the cable bands were placed on the cable in a rotated position in accordance with the compensating camber, which could vary from 5 degrees to about 20 degrees (Nader et al. 2013). All these developed techniques could only be applied to one type of construction sequence (e.g., erecting cable after girder (ECAG)), and could not be applied to all types of suspension bridges. For instance, Dongtiao River Bridge in China was built according to a construction procedure named “erecting cable before girder (ECBG)”(Wang et al. 2016). It means that the main cables are constructed prior to erecting, and then the girder segments are lifted and suspended on the cables. Obviously, the aforementioned control techniques for configuration transformation can not apply to this type of bridge. To the best of the authors’ knowledge, right now there is no universal approach available to aid the configuration transformation of 3D curves using different construction procedures. In this paper, a novel technique is proposed to solve this problem.

To overcome the drawbacks, a novel lateral bracing-based method (LBM) is proposed in this paper. Specifically, the free main cables are pulled to the design position in the bridge’s transverse direction by using lateral bracing members. The effects of the main influencing factors on the configuration transformation for 3D curved cable systems are investigated, such as the type of span arrangement, construction procedure and hanger type. In order to demonstrate its capability, the proposed technique is applied to a suspension bridge with a 3D curved cable, the Dongtiao River Bridge, located in Huzhou, China. The benefit associated with the proposed technique is also investigated and compared with that of the traditional approaches.

2. Complexity of Configuration Transformation of 3D Curved Cables

Configuration transformation is a complex issue during the construction stage of 3D curved cable and should be investigated to ensure the safety and efficiency of the construction process. During the construction stage, first, the suspension cable is constructed as a free-hanging cable (FHC) in a vertical plane. At the final stage, the 3D cable becomes a fully loaded cable (FLC) within a spatial surface. During configuration transformation of the 3D curved cables from free-hanging state to fully loaded state, the following phenomena have been observed during the construction stages:

- The cables are displaced significantly in the transverse direction from the free-hanging to the fully-loaded position (Gil 2001; Yoon et al. 2001);
- The transverse displacement of cables from the initial to the final position can cause the change of lateral inclination of hangers during the construction process; namely, the lateral rotation angle of hangers continuously varies (Ke et al. 2010; Nader et al. 2013);
- The variation of hanger inclination may cause the cable to twist about its axis, which can affect cable safety and change the cable bands' lateral inclination (Cho et al. 2001; Nader et al. 2013); and
- The variation of the hangers' and cable bands' lateral inclination complicates the attachment of the hangers. When the laterally inclined hangers are attached and loaded, the hangers can rub or collide with the cable duct at the girder and the pin plate at the cable band. Then, the hangers can be subjected to bending action induced by the variation of hanger lateral inclination. The stress induced by bending would cause damage to the hangers. In extreme cases, the hanger may fail to be inserted into the girder (Ke et al. 2010).

3. Construction Assessment of Cable Configuration Transformation

The two control indicators, the main cable's lateral displacement and the hanger's lateral rotation angel, are defined to explore the complexity and intensity of the configuration transformation. The main influencing factors on the configuration transformation are also investigated in the following section.

3.1 Control indicators

To ensure safety during the construction stage of the 3D curved cable, the rotation angle of the hanger and lateral deflection should be controlled and be within a tolerant interval to ensure the safety and reliability of the hanger system. A lateral rotation angle of the hanger, $\Delta\theta$ (as shown in figure 2), is proposed to describe the variation of hanger lateral rotation:

$$\Delta\theta = \theta_F - \theta_C \quad (1)$$

where θ_F is the transverse inclination angle of a hanger in the final bridge state and θ_C is the transverse inclination angle of the hanger in the free cable state. When the lateral rotation angle exceeds the tolerant interval, the hangers can rub or collide with the cable duct, which could cause damage to the hangers, or even fail to connect to the girder. If the lateral rotation angle is within the allowable range, the aforementioned problem associated with the hangers installation does not exist and the configuration transformation of the 3D curved cable system can be simplified as the process with respect to the traditional planar suspension bridge.

Additionally, in order to measure the transverse displacement of the main cable during the construction process, a parameter related to the lateral displacement of the main cable is defined as:

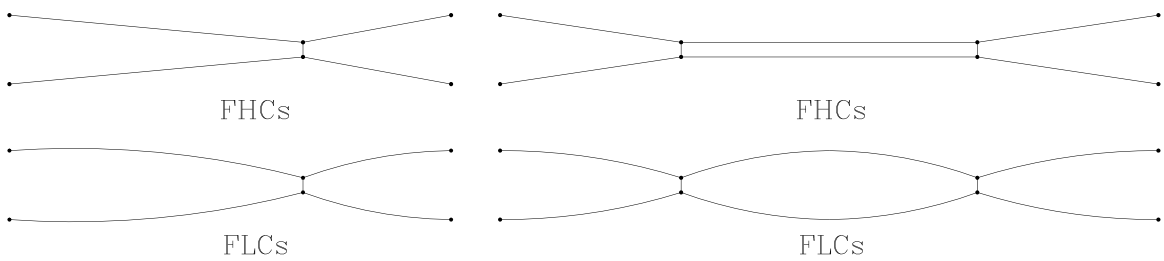
$$\Delta Y = Y_F - Y_C \quad (2)$$

where ΔY (as shown in figure 2) is the difference of the transverse displacement between FHC and FLC, which reflects the intensity of the configuration transformation; Y_F is the transverse coordinate of a cable node in the final fully-loaded state; and Y_C is the transverse coordinate of the cable node in a free cable state. These two performance indicators are related with each other. For instance, the lateral rotation angle factor is related to the lateral displacement factor, depending on the boundary conditions. The indicators are mainly affected by the span arrangement type, construction procedure, and hanger type, among others.

3.2 Factors affecting configuration transformation

3.2.1 Span arrangement type

The arrangement type of the span associated with the suspension bridge can be categorized into the following two types: (1) Single-pylon system(as shown in Figure 1 a)), such as the New San Francisco-Oakland Bay Bridge; and (2) Double-pylon system(as shown in Figure 1 b)), such as the Yongjong Bridge. The plan-view projection of the two FHCs within a single-pylon system are two oblique lines that intersect at a point, and the inclination direction is from the center to the outside of the girder. The plan-view projection of the two FLCs within a single-pylon system are two convex curves that intersect at the same point. Thus, the difference of the plan-view projection between the FHC and FLC is not significant. Additionally, during the configuration transformation, the lateral displacement of the main cables is not obvious.



a) Single-pylon system   b) Double-pylon system

Figure 1. Plan-view projection of Span arrangement By comparison, the plan-view projection of the two FHCs of the center span in the double-pylon system are two lines parallel to each other, and their directions are along the bridge axis. Accordingly, the plan-view projection of the two FLCs are two convex curves that can form an ellipse. Thus, the lateral difference between the FHC and FLC in the center span is relatively large, and the lateral displacement of the main cable is much larger than that associated with the single-pylon system during the construction process.

3.2.2 Construction procedure

The construction procedure of the spatial suspension bridge can be categorized into the following two types: (1) erecting cable after girder, which is employed in most self-anchored suspension bridges; and (2) erecting cable before girder, which is usually used in earth-anchored suspension bridges.

Erecting cable after girder

With respect to the “Erecting cable after girder” construction procedure, the girder is first supported at the temporary piers at its designed position, and the main cables are erected with predetermined unstrained lengths. One of the crucial construction steps is structural system transformation. The hangers are installed and pulled to their design positions by the jacks. Subsequently, the girder weight is transferred to the main cables, and the temporary supports can be removed when all the hangers are in their design positions.

During the transformation process of “erecting cable after girder,” as shown in Figure 2, the position of the FHL is ΔZ, which is higher than that associated with FLC as indicated in Figure 2. The extended rods are used to lengthen hangers to ensure that the hangers can connect tentatively with the girder. After the transformation, the extended rods can be removed.

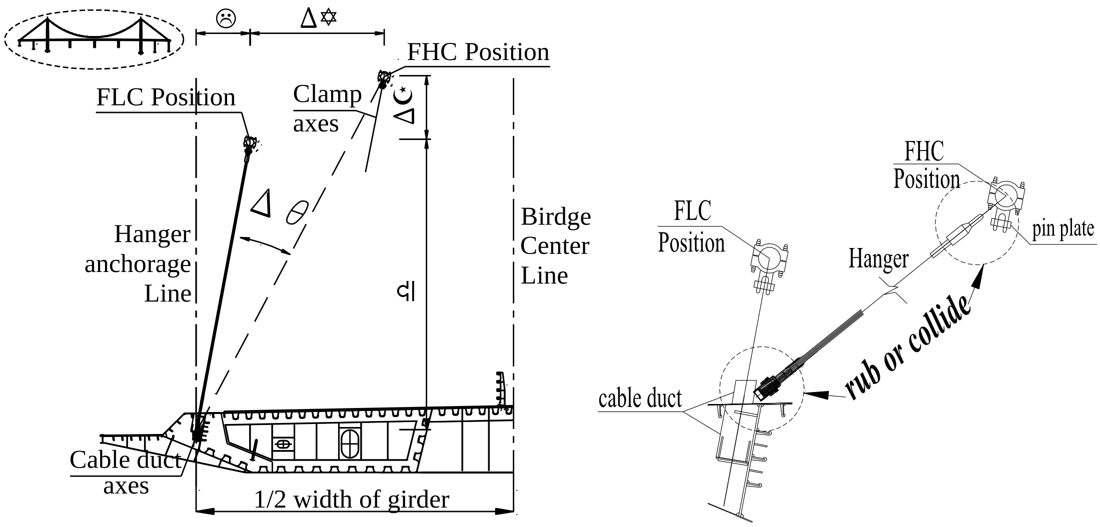


Figure 2. Lateral rotation angle of “Erecting cable after girder” method

Hence, the hanger’s lateral rotation angle with the “Erecting cable after girder” construction procedure, $\Delta\theta$, can be expressed as:

$$\Delta\theta = \arctan\left(\frac{d}{L}\right) - \arctan\left(\frac{d+\Delta Z}{L+\Delta Y}\right) \tag{3}$$

where L and d are the transverse and vertical projected length of the inclined hanger in the final bridge state, respectively; ΔY is the main cable's lateral displacement; and ΔZ is the vertical difference between the values associated with FHC and FLC.

Erecting cable before girder

The "erecting cable before girder" procedure would enable a construction sequence that is similar to a conventional earth-anchored suspension bridge, where the main cable is erected first and the girder is lifted and connected to the hangers. Generally, a moving crane is used to lift the prefabricated girder sections into the right location, where workpeople can attach them to previously placed sections and the hangers that hang from the main cables. This process is conducted to erect the whole length of the girder.

As stated previously, the position of the *FHC* is ΔZ higher than that associated with FLC. Hence, for the traditional planar suspension bridge, the girder segments need to be lifted with an additional height ΔZ in order to connect the girder with the hangers that hang from the FHC. However, for the suspension bridge with 3D curved cable, an additional extra height ΔH is needed to match ΔY, which is the lateral displacement for FHC as indicated in Figure 3.

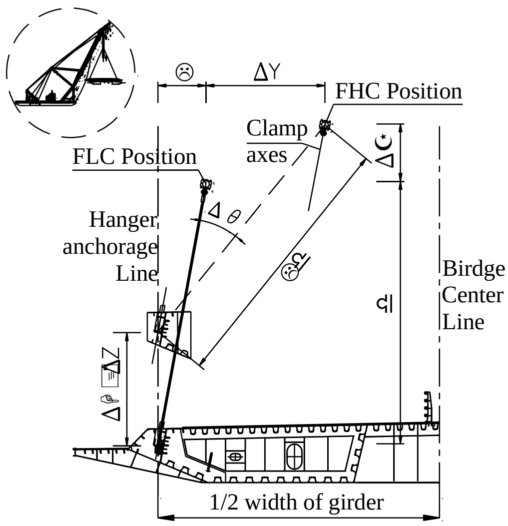


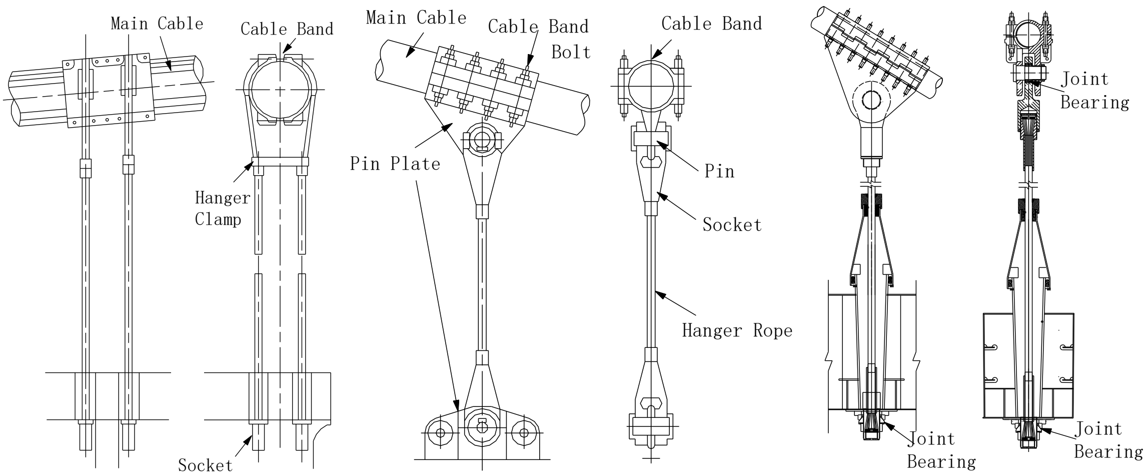
Figure 3. Lateral rotation angle of "Erecting cable before girder" method

Hence, this construction procedure would increase the hanger's lateral rotation angle, which can cause the bending of the hanger, especially for the short hanger at the center in the middle span. If the length $L_d \leq L + \Delta Y$, the hanger cannot be connected with the girder even if its lateral rotation angle is 90 degrees. The hanger's lateral rotation angle with the "erecting cable before girder" construction procedure, $\Delta\theta$, can be expressed as:

$$\Delta\theta_2 = \arctan\left(\frac{d}{L}\right) - \arccos\left(\frac{L+\Delta Y}{L_\mathrm{d}}\right) \quad (4)$$

3.2.3 Hanger type

The configuration transformation of 3D curved cable should ensure that the hanger can adapt to the lateral deformation. Different types of hangers have different adaptabilities. For the hanger with bearing connection (Figure 4a) as used in the Yongjong Grand Bridge and the new San Francisco–Oakland Bay Bridge, its transverse allowable rotation angle is up to ±10° (Ke et al. 2010). This can alleviate hanger installation problems to a certain extent.



a) Bearing Connection b) Plate Connection c) A Upgraded Hanger with Pin Plate Connection

Figure 4. Hanger Type

For hangers with a pin plate connection as indicated in Figure 4b), the transverse allowable rotation angle is usually less than ±3° (Ke et al. 2010). As shown in Figure 4c), in order to increase the transverse allowable rotation angle, two types of joint bearings are added on the upper and lower ends of the hanger, respectively (Li et al. 2010; Zhang et al. 2010). Even after the improvement, its allowable value is still less than ±6°(Li et al. 2010; Zhang et al. 2010). During the construction stage, the rotation angle could be easily larger than the threshold value, which could cause the hangers to rub or collide with the pin plate and the cable duct. Thus, a novel configuration transformation technique is needed to solve this issue.

4. Novel Technique: Lateral Bracing Method for Configuration Transformation

4.1 Structural component used within lateral bracing method

Figure 5 shows the elevation view of the lateral bracing members, which are employed to aid the configuration transformation of 3D curved cables during the construction stage. By pulling the main cables into the design position, the lateral bracings make the FHC's plan-view projection transformed from a parallel straight line into a polyline, which approaches the final 3D curve stage. The lateral bracings are situated on the cables by 2 temporary cable bands, which are used to support the main truss. Each temporary cable band has 3 card slots to restrain the lateral motion. When the main cables reach the target position, they are anchored with the temporary cable bands by using the bayonet lock. By using the lateral bracing members, the lateral displacement and rotation angle can be decreased accordingly.

The lateral bracing system consists of several key structural elements, namely, the main truss, the temporary cable band (Figure 6), bayonet lock, remote control winch, wire rope, and positioning steering wheel. The main truss works as an axial member to resist the main cable's restoring force in the transverse direction and also as a platform to install other components. The temporary cable band is adopted as a connector to connect the main cable to the wire rope, and also as a support for the main truss. The integration of the remote control winch, wire rope and positioning steering wheel, provides a traction system to tow the main cable into the design position. The lateral bracing is supported on the two main cables by the temporary cable bands.

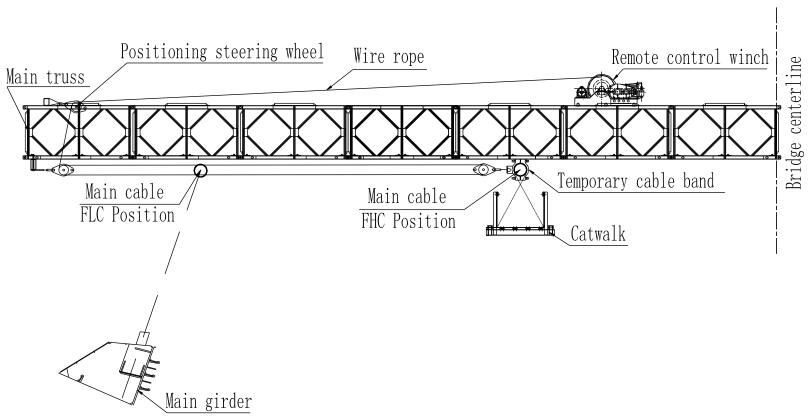


Figure 5. Half of lateral bracing between cables

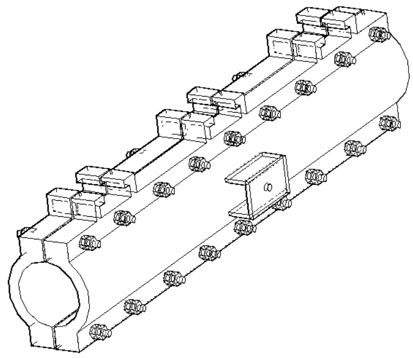


Figure 6. Structure scheme of temporary cable band

The lateral bracing plays an important role within the configuration transformation process and extra attention should be paid to this component. Based on the constraints of the lateral displacement and lateral rotation angle, the number and the installation position of lateral bracings could vary. The lateral bracing members should be placed in the critical positions where the associated effect on configuration transformation is the greatest, such as the center of the main span. Furthermore, the number of lateral bracing members should be determined to ensure that the lateral rotation angle of each hanger in any construction stage should be less than the tolerant limit.

Due to the girder-free characteristic, the LBM can be applied to different construction procedures whether erecting cable before or after the girder. Furthermore, relative to traditional control techniques shown in Table 1，the cost associated with the lateral bracing members is relatively small, and they are convenient to manufacture. Regarding the use of the bracing system, if the lateral rotation angles of the hanger exceed the transverse allowable threshold value of the hanger, the bracing system would be needed.

4.2 Construction steps

In the free cable state, the lateral bracings are lifted by crane and placed at the track groove of the temporary cable bands. Then, the main cables are pulled into the design position by the traction system. When the main cables arrive at the target position, they are anchored with the temporary cable bands by the bayonet lock. Thus, the cable’s plan-view projection is transformed from a parallel straight line into a polyline, which approaches the final 3D curve stage, as shown in Figure 7. Then, the girder sections can be attached with hangers easily. The movement of the main cable is achieved by using a pair of remote control winches located on the top of the main truss and a wire rope around the positioning steering wheel. The lateral restoring force of the main cable is balanced by the tension force in the wire rope. The tension force is resisted by the main truss. Namely , the tensile forces in the bracing system cables are offset by compression forces in the bracing system truss components. Once the girder is lifted completely, the lateral bracings are removed.

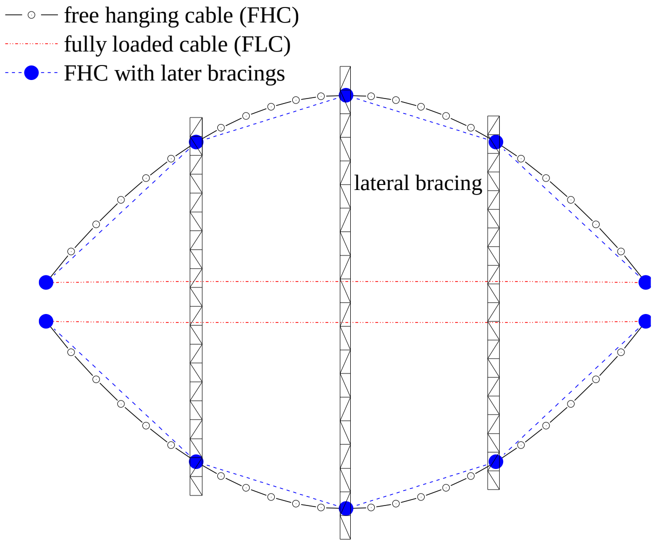


Figure 7. Principle scheme of lateral bracing

5. Illustrative Examples

In this section, the configuration transformation within three representative spatial suspension bridges is assessed considering the defined control indicators. The LBM is applied to a suspension bridge located in Huzhou, China. Through two case studies, the ability of the proposed configuration transformation method is assessed and the functionality of LBM is examined.

5.1 Case 1: Configuration Transformation in Three Typical Spatial Suspension Bridges using Traditional Methods

The configuration transformation of the 3D curve cables using traditional techniques is investigated in this section. Using the control indicators provided in section 3.1, the configuration transformation of three typical spatial suspension bridges is analyzed. The information of these three bridges is shown in Table 1. The effects of different factors on the configuration transformation are investigated.

Table 1. Three typical spatial suspension bridges

Bridge Name	Span arrangement (m)	Transverse sag (m) of main span	Control technique for Configuration Transformation
Fumin Bridge in China (Xiong et al. 2017; Sun et al. 2015; Sun et al. 2016)	157 + 86	4.472	rotatable cable clamp and hanger with spherical hinge connections at bottom end(Han et al. 2008; Wu et al. 2008)
Yongjong Bridge in Korea (Gil and Choi 2001; Gil and Choi 2002; Kim et al. 2002; Kim et al. 2006)	125 + 300 + 125	13.571	4 groups of winches and the hydraulic jacks(Kim et al. 2006; Yoon et al. 2001)
Jiangdong Bridge in China (Li et al. 2010; Zhang et al. 2010)	83 + 260 + 83	18.706	5 pairs of temporary hangers(Ke et al. 2010)

5.1.1 Effect of span arrangement type on configuration transformation

The influence of the span arrangement type on the configuration transformation is investigated and shown in Figures 8, 9, and 10 with respect to the three investigated bridges. Accordingly, the following conclusions could be obtained.

(1) Based on the outcomes of the illustrative examples, for the bridges with the similar mainspan length, the lateral displacement and rotation angle of the single-pylon system is significantly less than that of the double-pylon system. For example, the maximum lateral displacement and rotation angle of the Fumin Bridge is 2.775 m and 10.5°, respectively, while the maximum lateral displacement and rotation angle of the Jiangdong Bridge is 18.706 m and 61.198°, respectively;

(2) For the bridge with the double-pylon system, the lateral displacement and rotation angle in the center span is much larger than that of the side span. For example, the maximum lateral displacement and rotation angle of the center span in the Yongjong Bridge are 14.321 m and 56.260°, respectively; comparatively, the values of the side span are 2.313 m and 11.637°, respectively; and

(3) For the center span of the double-pylon system, the hanger's lateral rotation angle is proportional to the main cable's lateral displacement. For the single-pylon system and the side span of the double-pylon system, the rotation angle is still proportional to the lateral displacement near the tower. Nevertheless, the rotation angle is inversely proportional to the lateral displacement near the girder end.

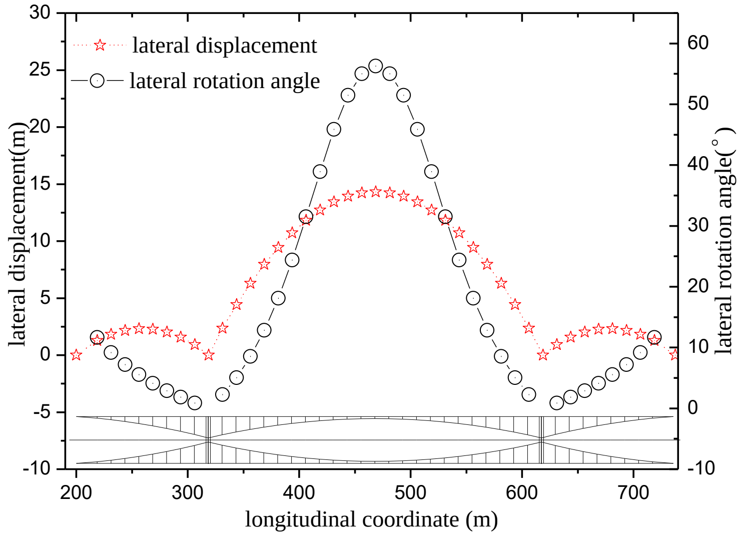


Figure 8. Lateral displacement and rotation angle of Yongjong Bridge in Korea

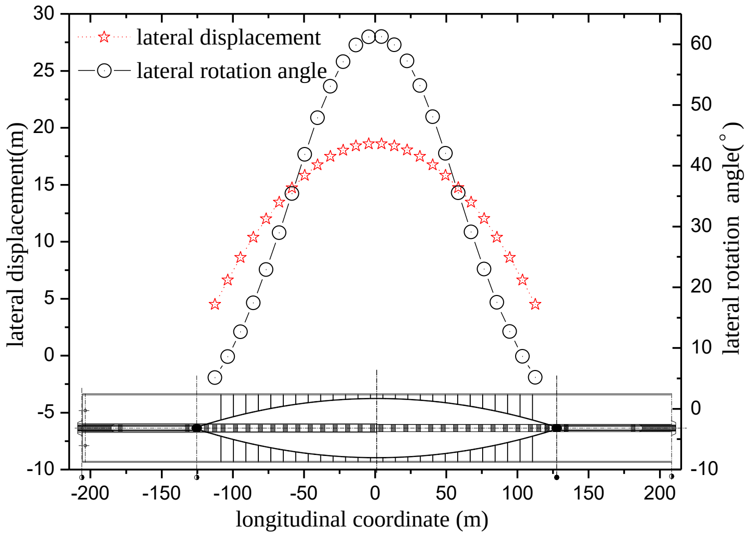


Figure 9. Lateral displacement and rotation angle of Jiangdong Bridge in China

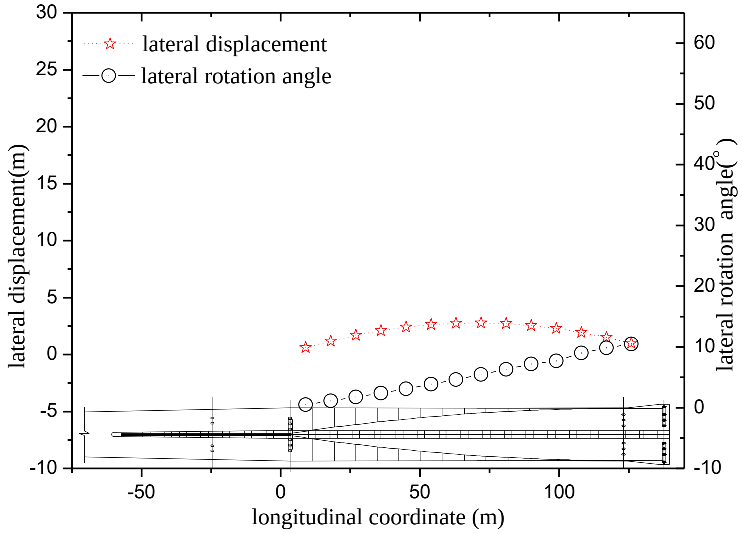


Figure 10. Lateral displacement and rotation angle of Fumin Bridge in China

5.1.2 Effect of construction procedure on configuration transformation

The effects of the construction procedure on the configuration transformation are also investigated as indicated in Figure 11 and 12, and relevant conclusions can be obtained.

(1). The lateral rotation angle with the "Erecting cable before girder" construction procedure is generally larger than that of the "Erecting cable after girder" procedure. This indicates that the "Erecting cable before girder" construction procedure is associated with a much more complex configuration transformation process;

(2). There is a trend of increasing difference of the hanger's rotation angle between the construction procedure with an increase of distance from the tower. The difference is most significant in the center of the mid-span, and the center portion is depended on the transverse sag and bridge width;

(3). At the center of the mid-span, the lateral rotation angle with the "Erecting cable before girder" construction sequence could exceed 90 degrees. This indicates that the hangers at the center may fail to connect with girder segments. Hence, a special control method for configuration transformation has to be adopted to meet the requirements.

Overall, the lateral rotation angles with the "Erecting cable before girder" procedure are much larger than those with respect to the "Erecting cable after girder" procedure. The traditional techniques listed in Table 1 are all related to cases where the girder is erected prior to the cable. In the case of the "Erecting cable before girder" construction procedure, these conditional techniques can not meet the requirements, and a novel technique is needed.

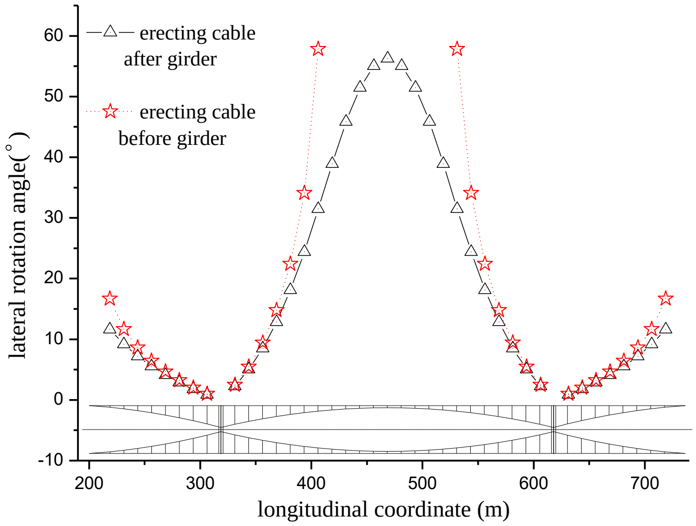


Figure 11. Lateral rotation angle for the FHC of the Yongjong Bridge

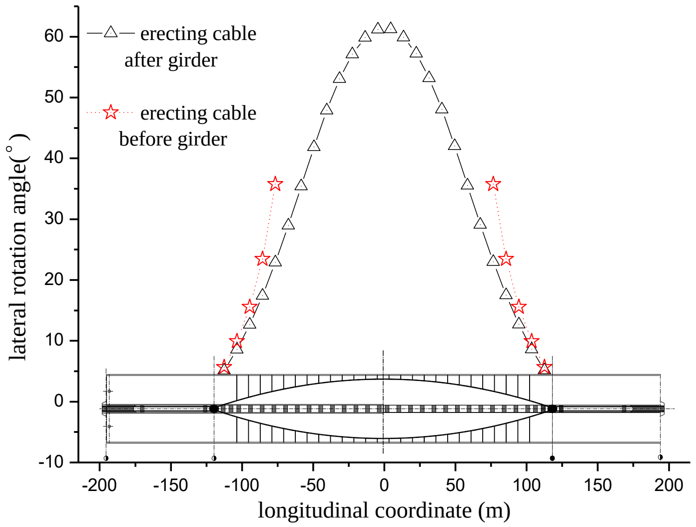


Figure 12. Lateral rotation angle for the FHC of the Jiangdong Bridge

5.2 Case 2: Implementation of Lateral Bracing Members to Solve Configuration Transformation in a Spatial Suspension Bridge

This section considers the innovative implementation of LBM within the Dongtiao River Bridge (Figure 13) for its configuration transformation. The main span of this bridge is a 228 *m* suspension bridge with 3D curved cables. In the free cable state, the FHCs are parallel to each other in two vertical planes; the distance between two cables is 16.02 *m*. In the finished state, the FLCs are two spatial curves, whose maximum distance is 31.364 *m* at the center of the bridge. The maximum lateral displacement of the cable is 7.672 *m* from the free cable state to the finished state. In order to avoid the interruption of the crossed channel, the "Erecting cable before girder" construction procedure is adopted for the construction of Dongtiao River Bridge. In this study, a detailed nonlinear finite element model (FEM) is employed to simulate the construction process. Pylons, girders, and lateral bracing members are modeled with the beam-column elements, and stay cables ,main cables and hangers are modeled with the elastic catenary cable elements. The gravity load and construction load were considered.

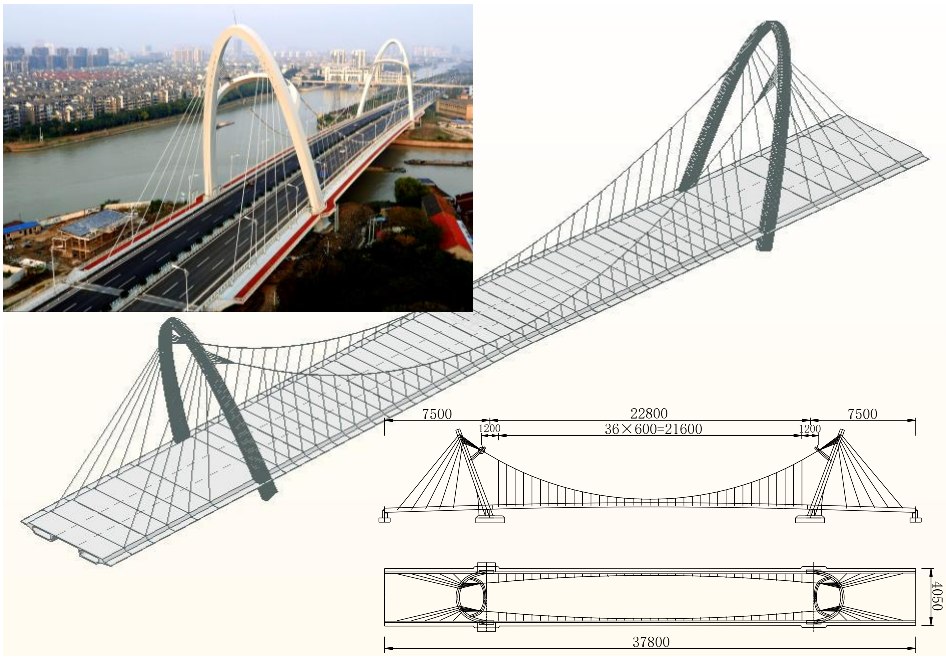


Figure 13. General view and layout of Dongtiao River Bridge (Dimensions are in cm. Photo provided to the first author by Mr. Chengshu Wang of Traffic planning and Design Institute of Zhejiang Province)

Figure 14 shows the lateral displacement of the main cable at the free cable state. This displacement is relatively large, ranging from 1.360 *m* to 7.686 *m*. The lateral rotation angle from No. 1 to No. 11 hangers is between 4.3° and 48.3°, and most of them have exceeded the allowed values (±6°). In addition, according to formula (4), the rotation angle from the No. 13 to No. 27 hangers in the center zone can be seen as infinite. This is due to the fact that $L_d \le L + \Delta Y$, which indicates these hangers cannot directly connect with the girder sections even if their lateral rotation angles reach 90 degrees. Hence, without any control measures, most of the hangers inevitably collide with the cable ducts or cable bands, which could lead to bending and cause structural damage. Hence, a novel control method for configuration transformation has to be employed.

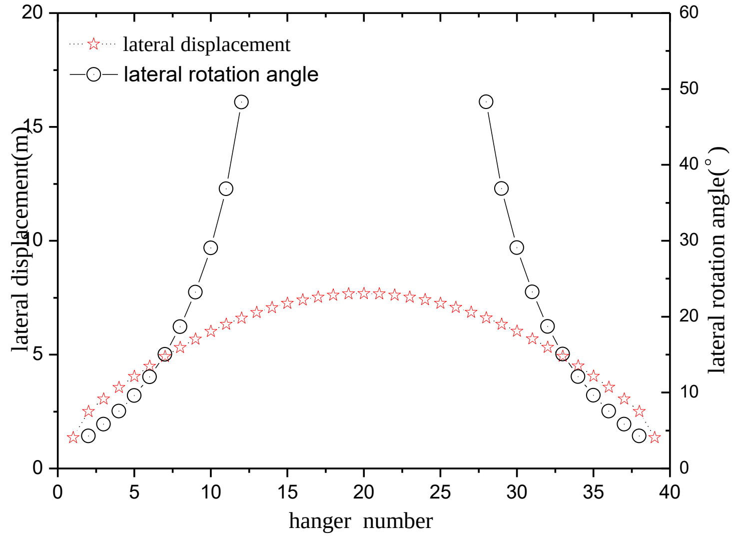


Figure 14. lateral displacement and rotation angle of Dongtiao River Bridge in a free cable state . Photo provided to the first author by .....

In the construction stage of Dongtiao River Bridge, a total of 40 construction stages are considered. When the pylon and the side span are constructed and anchored temporarily, the main cables and hangers of the mid-span and the stay cables of the side span are built. Before girder sections are lifted, three lateral bracings are installed at quarter points along the main cable, and then the main cables are pulled to the design lateral position, as indicated in Figure 15. After all the girder segments are lifted and attached to the hangers, the lateral bracings are removed by sequence. Then, the girder is completed by being welded together, and the bridge system is transformed into the final self-balanced state. Herein, the middle lateral bracing is associated with a section that is 900 × 1500 mm. The length is 34.12 m, and the weight is 10 ton. Herein, the main truss of the East and the West bracing is replaced by steel pipe, which could also fulfill all these goals.

Figure 15. Installation and application of lateral bracings (Photo taken by the first author)

5.2.1 Effect of lateral bracing on configuration transformation

The effect of the lateral bracings on the lateral displacement and rotation angle is shown in Figure 16 and Figure 17. For comparison, the effect of a previous scheme with a single lateral bracing that is placed in the center of the main span is also shown in these figures. The following conclusions can be drawn.

(1) With a single lateral bracing scheme, the maximum lateral displacement can be decreased to 1.885 m from 7.663 m. The hangers' lateral rotation angle is confined within an interval [-1.73°, 8.37°]. Hence, even if there is a single lateral bracing, the lateral rotation angles of all hangers decrease significantly, which indicates the efficiency of the LBM;

(2) Within the implementation plan, i.e., three lateral bracings are installed *at quarter points* along the main cable, the lateral rotation angles are restricted within a relatively narrow interval [0.12°, 4.89°], which is less than the allowed value ±6°. Therefore, the problem of configuration transformation is efficiently solved by the LBM. With the implementation plan, the establishment and adjustment of the construction procedure would not be restricted by the configuration transformation; and

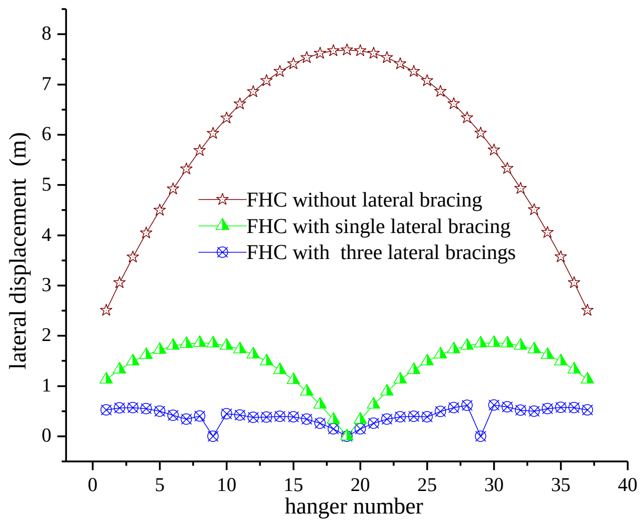


Figure 16. Lateral displacement of the main cable in a free cable state

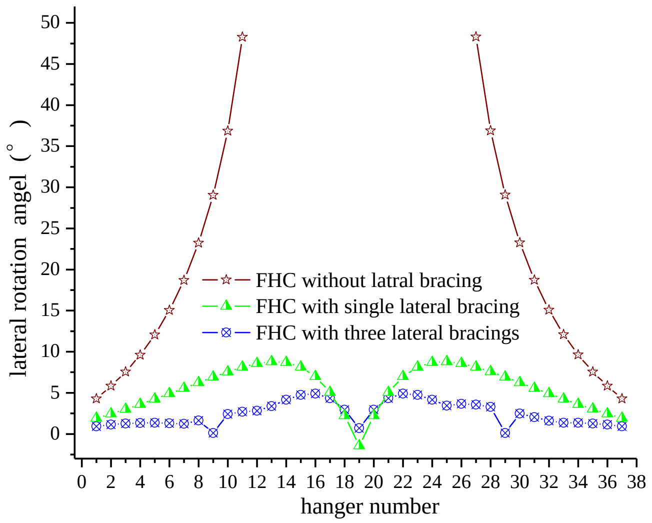


Figure 17. Lateral rotation angle of the hanger in a free cable state

The variation of the maximum lateral displacement and rotation angle during the construction process is shown in Figure 18. The following conclusions may be drawn:

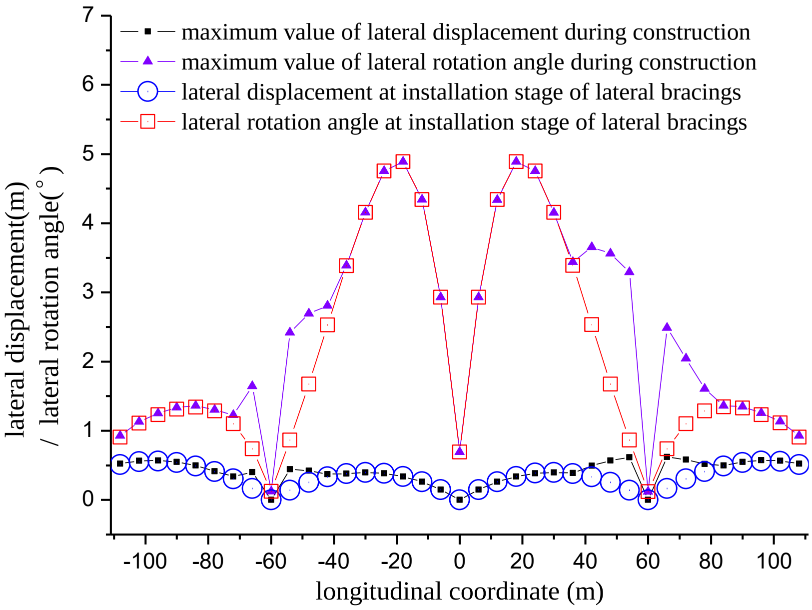


Figure 18. Variation of maximum lateral displacement and rotation angle during construction

(1). The maximum lateral rotation angle during the whole construction process is less than the tolerance limit. This ensures the smooth implementation of configuration transformation. The effective control effect can ensure that the installation process of hangers and girder sections will not be affected by the lateral rotation angle;

(2). The maximum lateral displacement and rotation angle occur at the construction stage of lateral bracings installation. Subsequent construction stages have a slight effect on partial hangers between the lateral bracings. This is mainly due to the rigid constraint characteristics of the lateral bracing, which allows for a larger margin of the construction error. Consequently, the LBM can ensure the highest degree of constructability, even if a variety of possible temporary changes occur during the construction process; and

(3). The LBM prevents the spatial suspension bridge from being affected by the lateral displacement and rotation angle and simplifies the construction process.

5.2.2 Effect of lateral bracing on construction process

The vertical deformation of the center node of the main cable during the construction process is shown in Figure 19. The effect of the lateral bracings on the vertical deformation is not obvious. The displacement of the center node of the main cable is reduced by 95 *mm*. Specifically, the main cable center is reduced by 333 *mm* under the self-weight of the middle lateral bracing and increased by 238 *mm* under the self-weight of the east and west lateral bracings. As shown in Figure 19, due to the measurement error and simulation error, there were some differences between the theoretical value and the measured value. However, these differences are less than 5 cm and can be neglected. Accordingly, the LBM could be adopted within the construction stage and simplifies the construction process of the spatial suspension bridge.

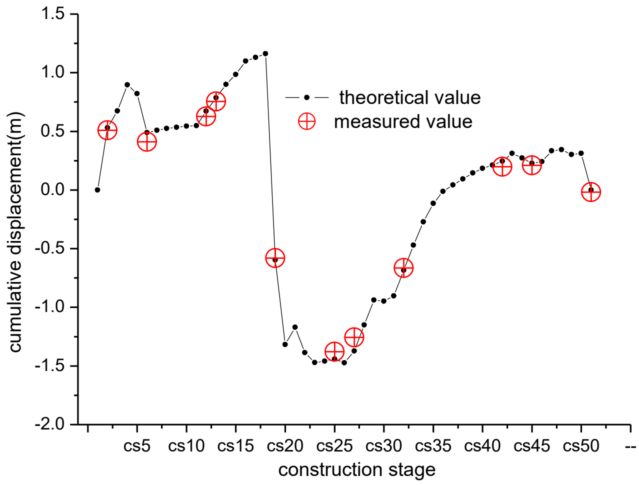


Figure 19. Center-node's vertical cumulative displacement curves of main cable during construction

Additionally, the force within the lateral bracing during the construction stage is assessed. The lateral bracing is mainly subjected to the axial force. The lateral bracings force measured in situ and analyzed by FEA is shown in Figure 20.

Due to symmetry, the East and West bracing bear nearly the same force. They are only under the compression force during the whole procedure of lifting girder sections, and it reached the maximum value 284 kN at the CS 25 (the 25^{th} construction stage). Based on the FEM, the theoretical force of the middle lateral bracing varies between 262 kN compression and 226 kN tension, which is basically consistent with the measured value. The maximum total stress of three lateral bracings is less than 25 MPa. In the lateral bracing, the axial force is directly applied along the transverse direction to control the FHC's shape. Compared with other methods, where force is applied along the oblique direction (Ke et al. 2010), directly applying force along the target direction can improve the control efficiency significantly. Therefore, due to the low stress level and large strength margin, the LBM could be easily and efficiently adopted within the construction stage.

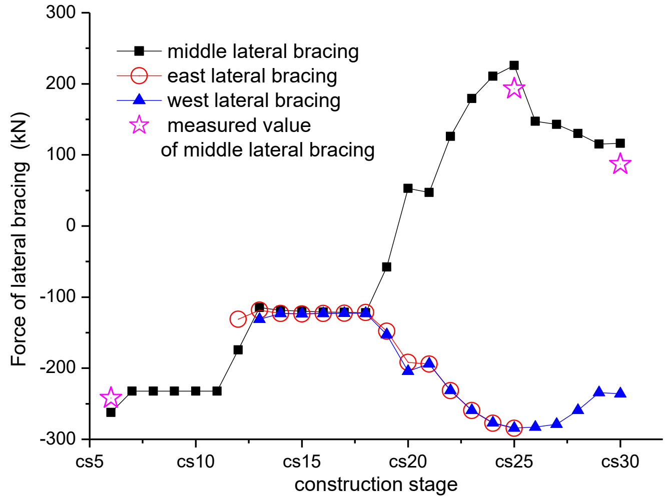


Figure 20. Force of three lateral bracings in hoisting (positive for compression)

6. Conclusions

This paper proposed a novel technique to aid the configuration transformation of 3D curved cables during the construction stage to ensure the safety and performance of suspension bridges. Specifically, an innovative control method named LBM is developed and first implemented in a real-world application to meet the challenges imposed by the unique bridge structural layout and the construction requirements. The effects associated with different paramteres, such as span arrangement and construction procedure, have been investigated. The presented illustrative example has demonstrated that the LBM can provide an efficient, reliable, and economical solution for the configuration transformation of suspension bridges with a 3D curved cable system.

The main conclusions can be drawn as follows:

1. During configuration transformation of the 3D curved cables from free cable state to final fully loaded state, the cables are displaced significantly in the transverse direction, and the lateral inclination of hangers continuously varies. The variation of the hangers' and cable bands' lateral inclination complicates the attachment of the hangers. The hangers can rub or collide with the cable duct at the girder and the pin plate at the cable band. The bending stress induced by the colliding would cause damage to the hangers, and in extreme cases, the hanger may fail to be inserted into the girder.

2. The configuration transformation of 3D curved cable is significantly affected by the type of span arrangement, construction procedure, and hanger type. Based on the outcomes of the illustrative examples, for the bridges with the similar mainspan length, the lateral displacement and rotation angle of the single-pylon system is considerably less than the double-pylon system. The lateral rotation angle with the “erecting cable before girder” construction procedure is generally larger than the “erecting cable after girder” process; particularly, the lateral rotation angle of hangers at the center zone of the mid-span of the double-pylon system with the “erecting cable before girder” construction process may exceed 90 degrees. The hanger with a bearing connection has a larger transverse allowable rotation angle than the one with a pin plate connection. This reduces the complexity of the configuration transformation.

3. Compared with the traditional methods, the LBM can be applied to any type of construction sequence (i.e., both ECAG and ECBG). The proposed method provides a larger margin for construction error, ensuring the highest degree of constructability. Overall, due to the efficient control effect on the lateral shape change and the insignificant influence on the vertical displacement, the LBM makes the construction process of the spatial suspension bridges flexible and convenient .

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