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Optimization of the Construction Sequence for Temporary Supports of Ultra-Wide Steel Box Girder Self-Anchored Suspension Bridge

Fangdao SUN[a], Zhengwu DONG[a], Liang XU[b], Yuhan ZHAO[b], Peilin QIAN[b] and Wei WANG[b,1]
[a]*CCCC Second Harbor Engineering Company Ltd., Wuhan, 430040 China*
[b]*School of Civil Engineering, Changchun Institute of Technology, Changchun 130012, China*

Abstract. This article takes the Lecheng Bridge in the Boao Lecheng Pilot Zone of Qionghai City, Hainan Province as the engineering background. Using MIDAS Civil bridge specific analysis software，a simulation model of a super wide steel box girder self anchored suspension bridge is established. According to four different support removal schemes, the relatively best support removal sequence of self-anchored suspension bridge is explored. The analysis results indicate that the support of the mid span cast-in-place section should be removed after the suspension rod is tensioned, therefore, various schemes for dismantling the support have little impact on the stress of the main beam during the completion stage. Only during the construction process, it has a certain impact on the deformation and stress of the main beam; After the tensioning of the suspension rod is completed, some of the main beams at the cable tower detach from the support, which is beneficial for removing the mid span support. After adopting the above construction plan, the structural stress state of the bridge is good. It can provide reference for the construction of such Bridges in the future.

Keywords. Self anchored suspension bridge; bridge construction; finite element method; ultra wide steel box girder

1. Introduction

The main characteristic of Self-Anchored Suspension Bridges (SAS) is that the main cables are not anchored to the ground but are instead anchored at both ends of the main girder. Therefore, the large anchoring devices used in traditional earth-anchored bridges are no longer needed, making the structural configuration lighter and more streamlined [1]. Due to their excellent aesthetic effect, strong adaptability, and good economic performance, they have rapidly developed in the country in recent years [2-3].

The sequence of removing the main girder supports of a self-anchored suspension bridge has a significant impact on the main cable profile [4], main girder profile, and

1 Corresponding Author: Wei Wang, 16695496@qq.com

tower displacement. It is a very important aspect of construction control. The purpose of the study is to ensure that the suspension bridge reaches a reasonable final state after the supports are removed [5].

Currently, many scholars both domestically and internationally have conducted extensive research on scaffold removal construction techniques. In terms of construction optimization, numerous scholars [6-8] have proposed methods such as cable force calculation optimization and construction uncertainty analysis.

In recent years, the application of computer simulation in bridge construction has become increasingly widespread, gradually evolving from initial bridge stress analysis to construction monitoring, temporary structure analysis, structural health monitoring, and formwork removal. Using computer finite element analysis software such as Midas Civil and Ansys can effectively improve design efficiency, verify the feasibility of construction plans, or identify design flaws in construction plans in advance, thereby saving costs. Lee [9] and others used finite element analysis to verify the impact of structural changes on the temperature behavior of the towers of long-span suspension bridges. Chawit, Ayubirad M S, and others [10-11] established a finite element dataset of live load-bridge interaction through parametric finite element simulation, which more accurately predicts the structural response to damage field inputs. Bas [12] and others proposed a more effective improvement plan by comparing the structural health monitoring data generated by finite element models of inclined and vertical hangers; Geng et al. [13] used finite element models for simulation analysis to obtain a new construction scheme for towers and main cables, and proposed monitoring and control methods for the construction. In terms of bracket removal, Mei et al. [14-15] established finite element models to analyze the force changes in brackets under different removal methods, determining the most reasonable timing for bracket removal and the sequence for system transition.

Extensive research has been conducted on the overall load-bearing performance and stability analysis of ultra-wide steel box girder self-anchored suspension bridge on both a domestic and international scale. Nevertheless, there are relatively few reports on the safety and stability of the construction procedure of ultra-wide steel box girder self-anchored suspension bridges. Construction simulation is typically performed via finite element software, wherein loads are applied individually over numerous load increments. Each load stage incorporates the calculation findings from the preceding load step, facilitating precise simulation of the construction process through this methodology. This article, in conjunction with the main bridge of the Boao Lecheng Pilot Zone in Qionghai City, Hainan Province, proposes different temporary support removal sequences based on the conditions of each construction stage. It uses large-scale finite element software to simulate and analyze the temporary support removal process, calculating and analyzing the impact of different temporary support removal sequences on the structural forces [16]. It proposes a reasonable temporary support removal sequence to ensure the safety of the structure during construction.

2. Overview of Temporary Scaffolding Construction for Bridges

2.1. Project Overview

Lecheng Bridge is located in the northern part of the Boao Lecheng Pilot Zone in Hainan Province. It is a single-tower self-anchored suspension bridge. The overall structural layout of the bridge is shown in Figure 1. The main bridge adopts a single-tower self-anchored suspension bridge design, with a span arrangement of (35+2×130+35) m. The bridge is divided into three parts: the steel main beam, the steel-concrete composite section, and the concrete main beam. The total length of the steel main beam is 184mThe main tower is a spatial diamond-shaped irregular tower. To meet the design requirements of the tower, the main beams within 24.5 meters on both sides of the tower are constructed using prestressed concrete with a composite section. The total length of the steel main beam is 184mThe main tower is a spatial diamond-shaped irregular tower. To meet the design requirements of the tower, the main beams within 24.5 meters on both sides of the tower are all made of prestressed concrete.

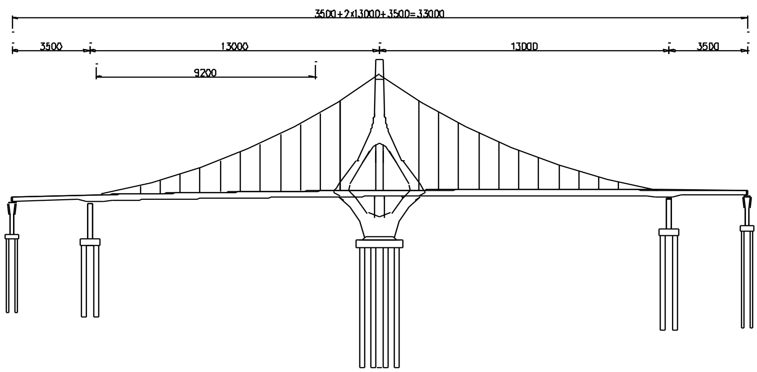


Figure 1. Overall structural layout of the bridge (unit: *cm*)

The overall layout of the entire bridge includes 8 temporary piers, 2 assembly platforms, and 2 gantry cranes. The temporary pier columns use Ø800×10mm steel pipes, the horizontal and diagonal braces use φ426×6mm steel pipes, the crossbeams use 3HN800×300mm section steel, and the longitudinal beams and spacers are processed from Q345 plates. The overall layout is shown in Figure 2. The steel main beam in the suspension cable area has a standard beam section width of 36m. It is a flat streamlined fully welded.to-height ratio of B/H=12. The bottom surface is a flat slope, and the steel box girder is shown in Figure 3. This paper studies the optimal dismantling sequence of the supports to ensure uniform stress on the superstructure and reasonable load distribution on the substructure, with the beam end anchorage designed accordingly.

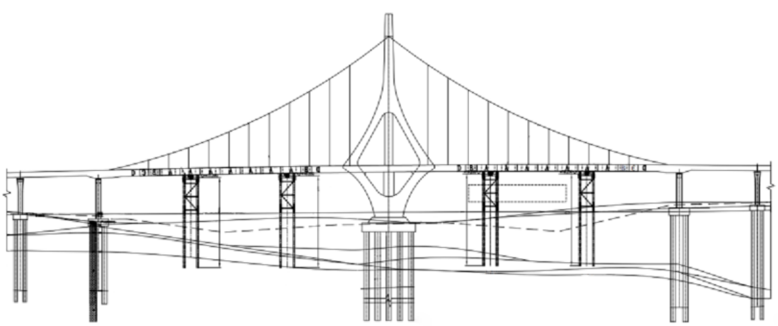


Figure 2. Temporary pier layout plan (unit: m)

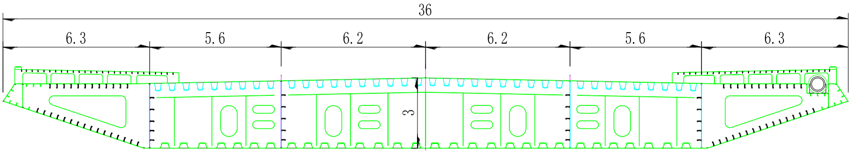


Figure 3. Section of steel box girder(unit: *m*)

2.2. Temporary Support Removal Plan

Due to the special structure of self-anchored suspension bridges, the main beam must be completed before the hangers. The main beam is generally constructed using full scaffolding or temporary piers. During the hanger tensioning process, the scaffolding or temporary piers need to be gradually dismantled. The author proposes four scaffolding dismantling schemes for simulation calculations.

Plan 1:

First, tension the tie rod to the design value, then remove the support (the sequence is from the mid-span to the side spans), in the order of: temporary pier 1 and 3 → temporary pier 2 and 4, with the pier numbers corresponding to the axis numbers, as shown in Figure 2. The advantage of this plan is that the self-weight of the main beam can be jointly supported by the tie rod force and the auxiliary piers.

Plan 2:

First, tension the tie rod force to the design value, then remove the supports (in the order from the side span to the middle span), with the sequence being: temporary pier No. 2 and No. 4 → temporary pier No. 1 and No. 3. The pier numbers correspond to the axis numbers, as shown in Figure 2. The advantage of this plan is that the tie rod force and the auxiliary piers can jointly bear the self-weight of the main beam.

Plan 3:

After the main beam is closed, the support frame will be removed (in the order from the mid-span to the side spans). First, remove temporary piers No. 1 and 3, then tension the tie rods to the design value. All temporary loads on the main beam during subsequent construction will be borne by the auxiliary piers. The advantage of this plan is that the structural forces are clear.

Plan 4:

After the main beam is closed, the support frame will be removed (in the order from the side span to the mid-span). First, remove temporary piers 2 and 4, then tension the tie rods to the design value. All subsequent temporary loads on the main beam during construction will be borne by the auxiliary piers. The advantage of this plan is that the structural forces are clear.

3. Numerical Simulation Analysis

3.1. Construction of Numerical Models

This paper uses the finite element analysis software MIDAS Civil to establish a full-bridge spatial calculation model of the Lecheng Bridge, simulating the construction process of the bridge and calculating the stress state of the bridge at each construction stage. The geometric parameters used in this model are based on the design drawings and relevant specifications. The structural model uses beam elements to simulate the main girder, main cable, and bridge tower. The model is divided into 1176 elements and 1290 nodes. The cross-section of the model is relatively complex, with a total of 12 main girder cross-section models, 42 main tower cross-section models, a 0.25m solid circular cross-section for the main cable, and a 0.0652m solid circular cross-section for the hangers.

The steel box girder and supports use elastic connections, while temporary piers, bridge piers, and auxiliary piers use elastic supports to simulate the bearing constraints of the bridge. The connections between the main girder and temporary piers, the main girder and auxiliary piers, the main cable and the main girder, and between the bridge towers are all simplified to general elastic connections. The auxiliary piers are connected rigidly; the main tower and the piers, the hangers and the main beam, and the main cables and the tower are set with primary and secondary constraint relationships; the spatial calculation model of the entire bridge is shown in Figure 4.

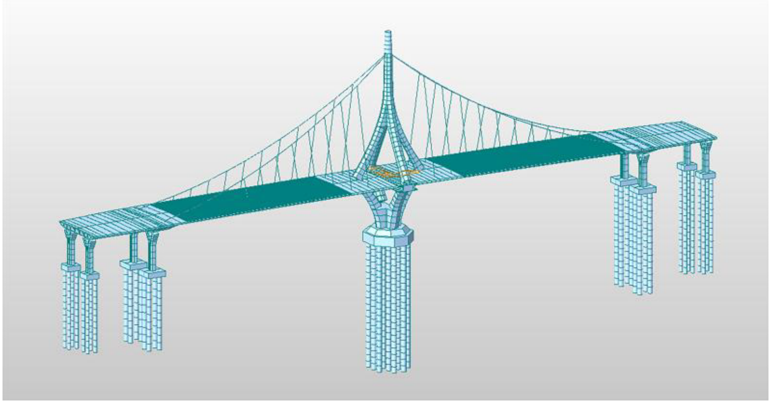


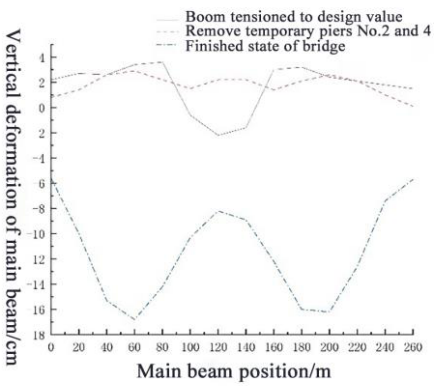
Figure 4. Stereo model of full bridge

3.2. Numerical Result Analysis

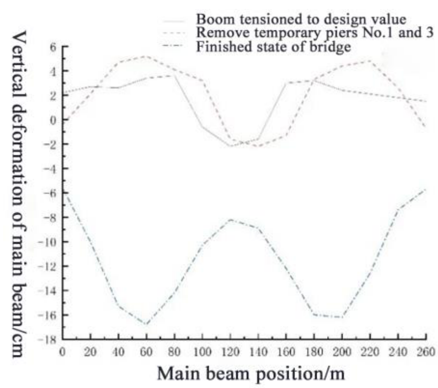
Through the calculations of various bracket removal schemes mentioned above, we now analyze and compare the deformation of the main cable, the vertical deflection of the main beam, and the stress of the main beam when reaching the target state under different bracket removal schemes, in order to determine the optimal bracket removal scheme suitable for this bridge.

To analyze the internal forces and deformations of the main beam under the four schemes, the completion of the main beam closure is taken as the initial state. The calculated results of the main beam bending moments and deformations for the four schemes are shown in Figures 5 and Figure 6, with the coordinate origin in the figures being the center of the auxiliary pier No. 10, and so on.

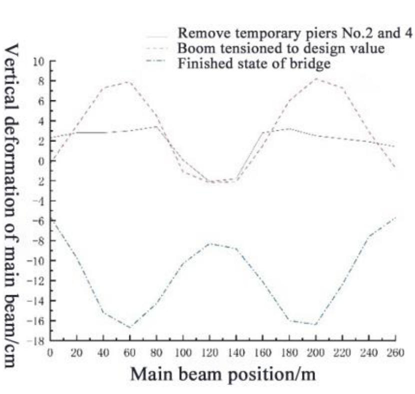
From the above vertical deformation diagram of the main beam, it can be seen that when the supports are removed in four different ways, the deformation of the main beam varies significantly with the order of support removal in the early stages, but the difference becomes smaller in the later stages. The four different methods of support removal can be broadly categorized into two main approaches. The first method involves tensioning the hangers and then removing the supports. In Scheme 1 and Scheme 2, the maximum vertical deformation occurs at the midpoint of the main span during the bridge construction phase, with a maximum vertical displacement of 16.8 cm. In the first demolition method, the vertical deformation of the main beam in the first and third stages shows very little difference. The vertical deformation amplitude of the main beam in the first stage ranges from -2.2 to 3.6. In the second stage, the vertical deformation amplitude of Scheme 1 ranges from -2.2 to 5.2, while the vertical deformation amplitude of Scheme 2 ranges from 0.1 to 2.9.The vertical deformation of the main beam in the third stage fluctuates significantly between -16.8 and -5.6.The second method of dismantling is to first remove the scaffolding and then perform the rod tensioning, as in Scheme 3 and Scheme 4.The maximum vertical deformation in both Scheme 3 and Scheme 4 occurs at the midpoint of the main span during the bridge construction phase, with the maximum vertical displacement in Scheme 4 being 16.7 cm. In the second demolition method, the vertical deformation of the main beams in the three stages of Scheme 3 and Scheme 4 are very similar. In the first stage, the vertical deformation amplitude of the main beams ranges from -2.1 to 3.5, and in the second stage, it ranges from -2.2 to 8.2, with a relatively large fluctuation range. The vertical deformation of the main beam in the third stage ranges from -16.7 to -5.6, which fluctuates more significantly compared to the first and second stages. In summary, when selecting Scheme 2 for demolition, the amplitude of the vertical deformation of the main beam is relatively small.



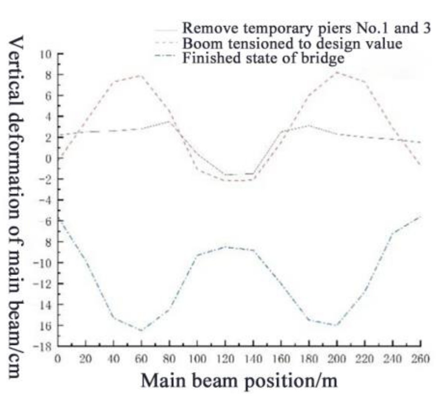
Plan 1



Plan 2

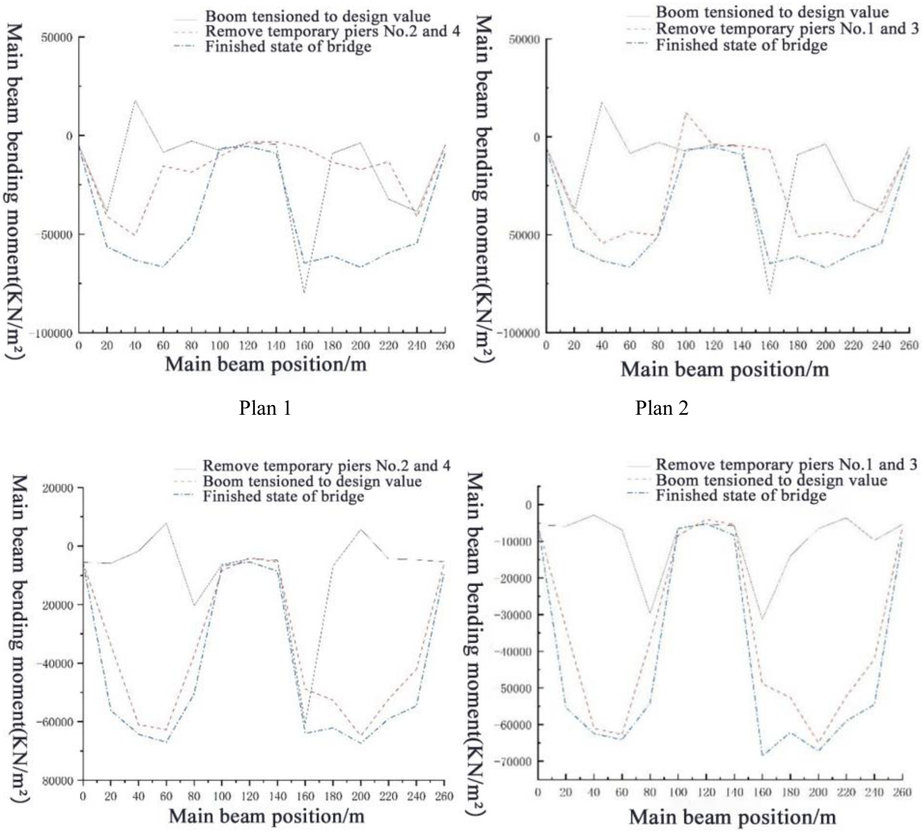


Plan 3



Plan 4

Figure 5. Vertical displacement of main beam in four schemes



Plan 1 Plan 2

Plan 3 Plan 4

Figure 6. The bending moment of the main beam of four schemes

From the above main beam stress diagram, it can be seen that in the four scaffold removal schemes, the section stresses are almost identical during the bridge construction phase. However, before the bridge is completed, during the cable tensioning process with different scaffold removal sequences, the section stresses of the main beam near the tower show significant differences. The stress in the first phase of Scheme 1 and Scheme 2 almost overlaps, with a large range of stress fluctuations, and the stress variation amplitude is between -39×10^3 KN/m² and 18×10^3 KN/m². The main beam moment changes have significant abrupt values. The stress variation amplitude in Scheme 3 is between -5300 KN/m² and -32×10^3 KN/m², while in Scheme 4, it is between -4800 KN/m² and -21×10^3 KN/m². The peak values of the positive and negative moments of the main beam in Scheme 3 and Scheme 4 are relatively smaller compared to Scheme 1 and Scheme 2.In the second phase, the stress fluctuations of Scheme 2 are significantly milder than those of Schemes 1, 3, and 4, and the peak values of the positive and negative bending moments of the main beam are relatively smaller. The maximum bending moment peak is approximately -41×10^3 KN/m², and the bending moment variation range is -41×10^3 KN/m² to -3500 KN/m². The bending moment variation range of Schemes 3 and 4 is much greater than that of Schemes 1 and 2, and the bending moment sudden change value of Scheme 1 is significantly larger compared to Scheme 2. Therefore, choosing Scheme 2 for bracket removal is more reasonable.

Due to the fact that the hangers were not tensioned during the removal of the supports in Scheme 3 and Scheme 4, the self-weight of the main cable was entirely borne by the continuous beam, resulting in significant internal forces and deformations in the main beam. Therefore, it is recommended to adopt Scheme 2 for the removal of the bridge supports.

Figure 7 shows the deformation of the main cable during the bridge construction phase under various different bracket removal schemes. From the figure, it can be seen that the main cable deformations in Scheme 1, Scheme 3, and Scheme 4 almost overlap, while the main cable deformation in Scheme 2 is the smallest.

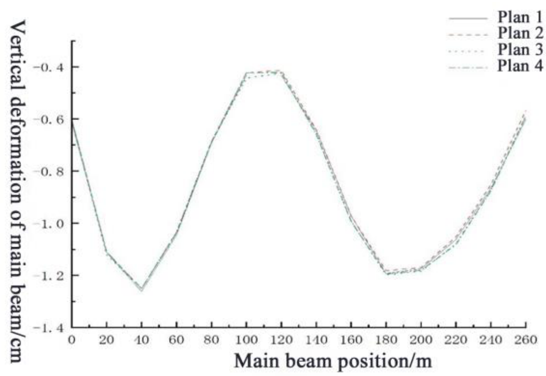


Figure 7. Deformation of main cable in bridge formation stage

Based on the above analysis, after the tensioning is completed, the main beam of the self-anchored concrete suspension bridge first detaches from the support position, located near the tower. Figure 8 shows the deformation of the concrete main beam in Scheme 2 at various stages of support removal. From the figure, it can be seen that after the cables are fully tensioned, the vertical deflection at the mid-span of the main beam is positive. Indicates that after the cable tensioning is completed, the main beam in the mid-span section detaches from the support.

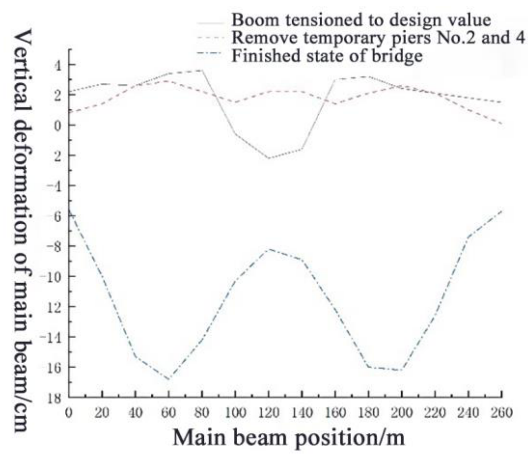


Figure 8. The vertical deformation of the main beam in the two stages of the scheme

4. Conclusion

This paper, based on the Lecheng Bridge project, studies the optimal problem of the bracket removal scheme for ultra-wide steel box girder self-anchored suspension bridges. Using finite element software for bridge structures, a full-process model of the construction of Lecheng Bridge was established. The deformation of the main cable, the vertical deflection of the main beam, and the stress of the main beam were analyzed and compared from three different scaffold removal methods after the removal of the self-anchored suspension bridge's ultra-wide steel box girder. The following conclusions and recommendations were obtained:

(1) Tensioning the tie rod allows the self-weight of the cast-in-place section at mid-span to be transferred to the tie rod and main beam together, thereby reducing the internal force and deformation of the main beam. It is recommended to dismantle the supports of the cast-in-place section at mid-span after the tie rod is tensioned.

(2) The internal force of the main beam in the initial stage is caused by its self-weight and is mainly borne by the supports. As the tie rods are tensioned, it will lead to a redistribution of the internal force in the main beam.Due to the removal of the temporary supports at the initial stage, the main beams of the side spans experienced vertical downward deflection, which caused corresponding deformations in the main beams of the intermediate spans. After the tensioning of the hangers, the main beam near the tower first experienced upward deflection. As the tension force increased, the main beam in the middle span gradually experienced upward deflection.

(3) For concrete self-anchored suspension bridges, the order of scaffold removal should be determined based on the deformation of the main beam, the stress of the main beam, and the deformation of the main cable after the hangers are tensioned. According to the above conclusions, the optimal order for scaffold removal is to start from the mid-span and proceed symmetrically towards the side spans.

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