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FINITE ELEMENT SIMULATION ANALYSIS OF STEEL TRUSS ARCH BRIDGE JACKING CONSTRUCTION

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ABSTRACT

In this study, a spatial model of a steel truss arch bridge was established using the finite element software Midas/Civil to simulate and analyze the jacking construction process. The stress performance of the guide beam and main structure at each jacking stage was obtained. The results showed that in the first stage of jacking, the maximum stress and deflection values of the main girder were observed. The maximum stress on the upper edge of the main girder was 34.9 MPa, and on the lower edge, it was -60.4 MPa. The maximum deflection was -35.88 mm. The maximum stress in the guide beam occurred during the jacking process and was -53.2 MPa, corresponding to the cross-section at the root of the guide beam. The maximum deflection of the guide beam occurred in the maximum cantilever state and was -30.79 mm. During the arch rib jacking process, the maximum stress was -49.4 MPa. Both the maximum stress and deflection values were within the allowable range, indicating that the structure was in a safe state. This study provides a reference for similar bridge jacking construction projects.

KEYWORDS

Steel truss arch bridge, Jacking construction method, Simulation analysis, Simulation analysis, Construction phase

INTRODUCTION

Bridge construction methods can be divided into many types, including cantilever construction (basket construction method), support construction, hoisting construction, jacking construction method, rotation construction, etc [1-3]. Bridge construction methods are usually chosen based on factors such as local topography, bridge usage, and construction costs. In recent years, the jacking construction method has been widely used in bridge construction, especially in cases where the terrain is complex, there are navigation requirements under the bridge, and it is not suitable to install supports under the bridge [4-6].

In simple terms, the jacking construction method involves selecting a construction site on one side of the abutment, where the prefabrication (assembly) of the main girders, main arches, and other components takes place. After the prefabricated structure is completed, jacking equipment such as hydraulic jacks are used to push or pull the structure gradually towards the designated position [7]. Temporary facilities such as temporary piers, steel guide beams, jacking sliding tracks, and traction equipment are set up along the jacking direction. The method of pushing or pulling the

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prefabricated structure to the specified position is known as the jacking construction method [8].

Among various types of bridges, steel truss arch bridges are widely used due to their high stiffness and aesthetic appearance [9-12]. However, research on the temporary facilities setting in integral jacking construction is mostly focused on girder bridges, with less attention paid to beam-arch composite structure bridges. For large-span beam-arch composite structures, there can be localized stress concentration due to their own weight [13-15]. Existing research lacks comprehensive understanding of the stress characteristics and deformation states and laws of temporary components and main structures during the jacking process. This study focuses on the simulation and analysis of the construction process of a steel truss arch bridge using the integral jacking construction method, aiming to investigate the stress performance of the guide beams and main structures at each jacking stage.

ENGINEERING BACKGROUND INTRODUCTION

This article takes a steel truss arch bridge as the engineering background. The main bridge structure adopts a lower deck steel truss arch beam structure with a main span of 106 m and a total width of 38 m. The roadway width is 24 m, accommodating six lanes in both directions. The main beam is a structure that bears the combined forces of the main longitudinal beam, steel cross beam, and secondary longitudinal beam. The bridge deck consists of orthotropic plates. The height of the beam at the bridge's centerline is 2.565 m, and the steel material used is Q345qC.

The arch ribs of the main bridge are in the form of steel trusses, with upper and lower layers of arch ribs. The upper and lower arch ribs are connected by vertical and diagonal struts to form a whole. Two trusses are arranged horizontally to enhance lateral stability. The upper arch rib has a span of approximately 142 m and a rise of 23.5 m. The lower arch rib has a span of approximately 103 m and a rise of 20 m. The net rise of the truss arch is 19.288 m, with a rise-span ratio of 1:5.5. There is a height difference of 3.5 m between the tops of the upper and lower arch ribs.

The bridge uses parallel wire suspension rods, with 30 suspension rods installed. The lower end of the suspension rods is anchored to the corresponding lug plate of the main longitudinal beam and cross beam. The upper end of the suspension rods is anchored to the lug plate on the transverse partition plate inside the arch rib's box structure. There are reinforcement ribs set on both sides of the lug plate, which serve as the main force transmission components. The weight of the bridge's dragging steel structure is 3816 t, the weight of the suspension rods is 10.7 t, the weight of the arch assembly support is 123.1 t, the weight of the guide beam is 83.8t, and the length of the guide beam is 25 m. The construction of this project adopts the continuous multi-point jacking method using dragging, as shown in Figure 1. The elevation and cross-section layouts of the bridge are shown in Figure 2 and Figure 3, respectively.

Fig.1 – Steel truss arch bridge completion effect picture

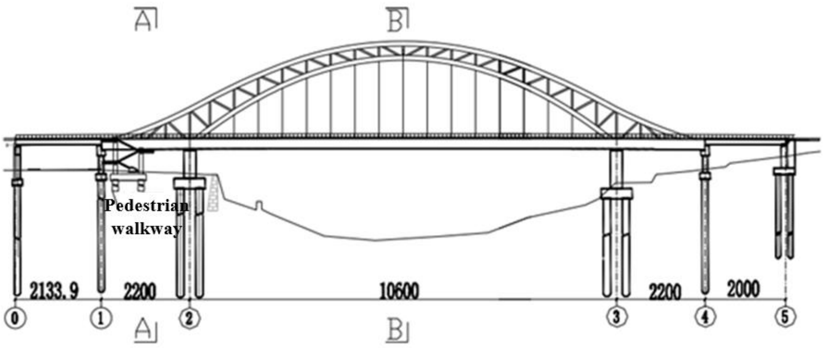


Fig.2 – Elevation layout diagram of the bridge

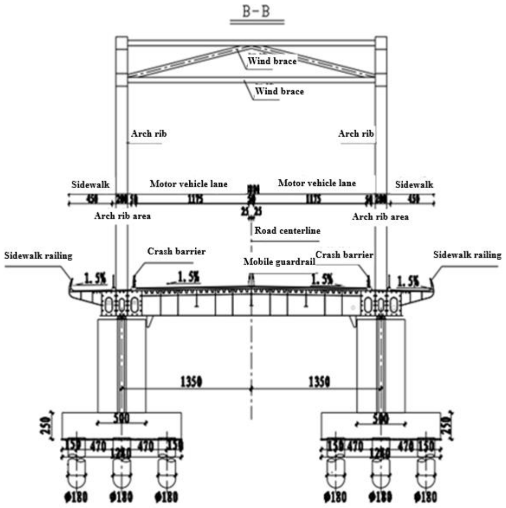
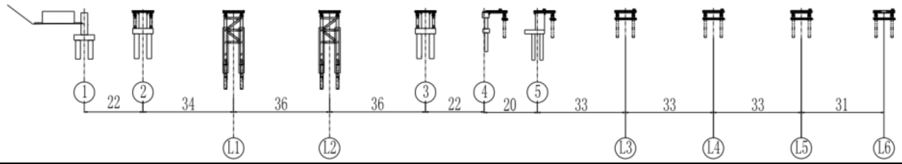


Fig.3 – Cross-sectional layout

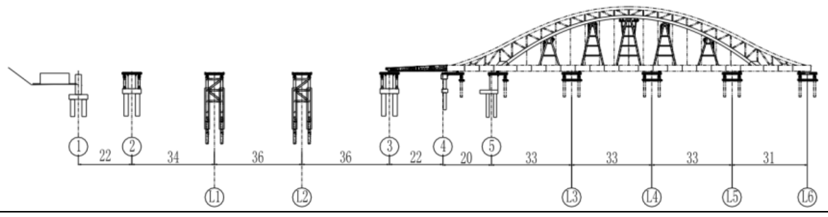
INTRODUCTION OF INTEGRAL JACKING CONSTRUCTION PROCESS

Due to the requirement for navigable waterway underneath the bridge, it is not possible to install supports in the river. Therefore, the main bridge of this steel truss arch bridge adopts the integral jacking construction method. The main construction steps are as follows, as shown in Table 1 to Table 8.

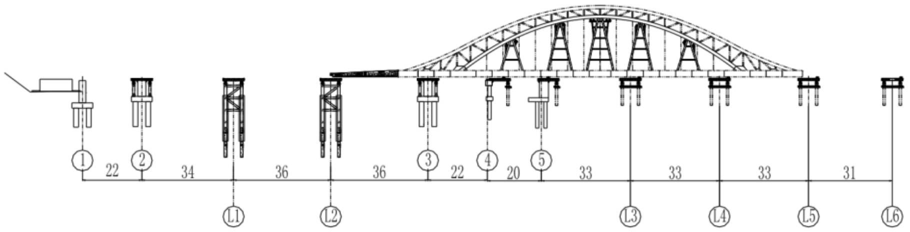
Tab. 1 - Top-down construction process step one

Step one	Construction preparation
Construction schematic	
Content description	1. Set up two temporary support piers, L1 and L2, between piers 2 and 3. 2. Install sliding beam tracks on the temporary support piers and arrange the installation of horizontal and vertical jacks for adjustment purposes. Conduct testing and adjustment of the top pushing equipment.

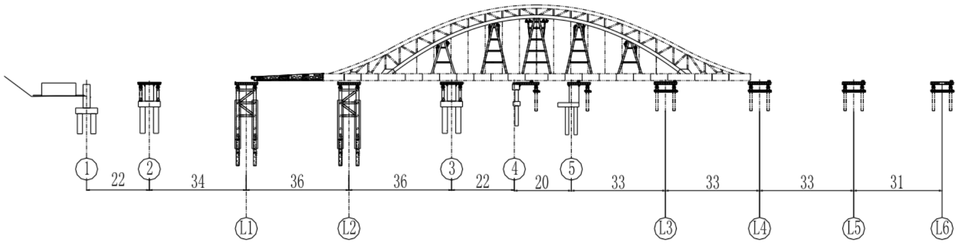
Tab. 2 - Top-down construction process step two

Step two	Assembly of beam arch structure
Construction schematic	
Content description	1. Assemble the steel box girder structure, arch ribs, suspension rods, and guide beams at the assembly site. 2. After installing the suspension rods, apply a certain amount of prestressing force as required. 3. Install the pier top pushing and alignment systems and adjust them accordingly. Once the top pushing system is ready, perform the necessary tests and adjustments.

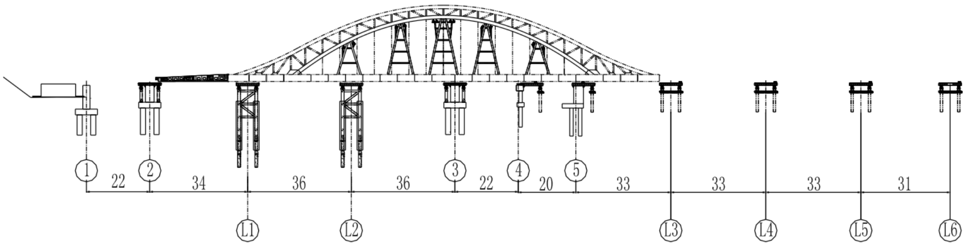
Tab. 3 - Top-down construction process step three

Step three	The jacking operation is in progress
Construction schematic	
Content description	1. Start the pulling device and drag the steel beam forward by 33.75 m. 2. Activate the vertical jacks to detach the steel beam from the sliders. Move all the sliders back to the starting position of the pulling device. 3. The rear cantilever is 26.96 m.

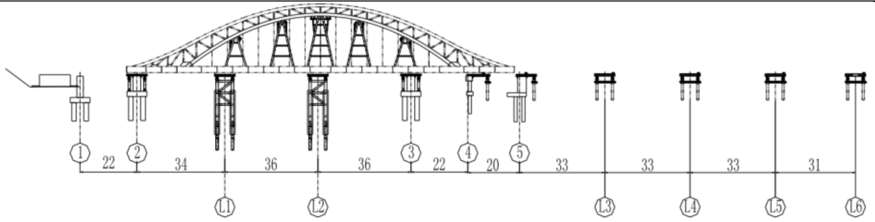
Tab. 4 - Top-down construction process step four

Step four	The jacking operation is in progress
Construction schematic	
Content description	1. Start the pulling device and drag the steel beam forward for 33 m. 2. Activate the vertical jack to separate the steel beam from the sliders; move all the sliders back to the initial position of the pulling device. 3. The tail overhangs for 26.96 m.

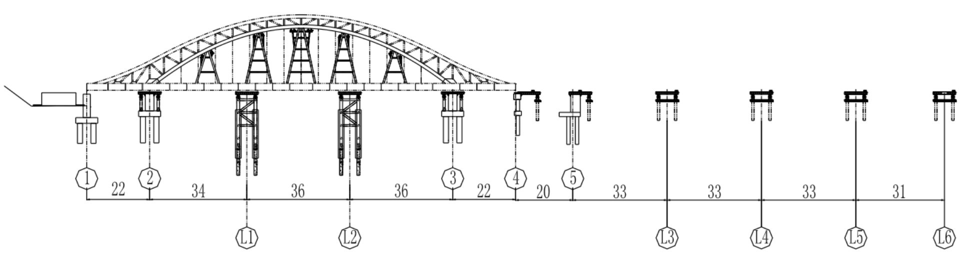
Tab. 5 - Top-down construction process step five

Step five	The jacking operation is in progress
Construction schematic	
Content description	1. Start the pulling device and drag the steel beam forward for 33.75 m. 2. During the dragging process, dismantle the steel guide beams section by section. 3. Activate the vertical jack to separate the steel beam from the sliders; move all the sliders back to the initial position of the pulling device. 4. The tail overhangs for 26.96 m.

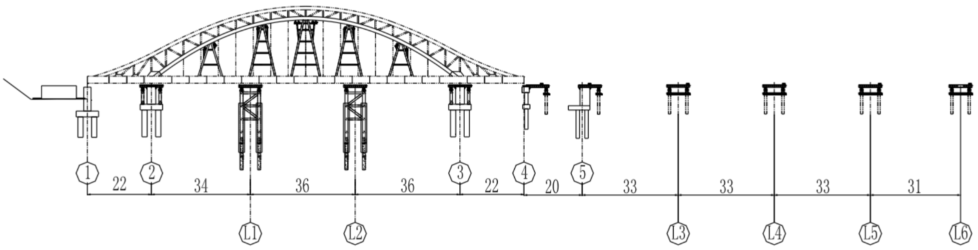
Tab. 6 - Top-down construction process step six

Step six	The jacking operation is in progress
Construction schematic	
Content description	1. Start the pulling device and drag the steel beam forward for 33 m. 2. During the dragging process, dismantle the steel guide beams section by section. 3. Activate the vertical jack to separate the steel beam from the sliders; move all the sliders back to the initial position of the pulling device. 4. The tail overhangs for 10.5 m.

Tab. 7 - Top-down construction process step seven

Step seven	The jacking operation is in progress
Construction schematic	
Content description	1. Start the pulling device and drag the steel beam forward for 17.25 m. 2. Drag the steel beam into its final position.

Tab. 8 - Top-down construction process step eight

Step eight	The jacking operation is in progress
Construction schematic	
Content description	1. Activate the vertical jack to separate the steel beam from the sliders and use the three jacks to adjust the final position of the steel beam. 2. Dismantle the dragging sliders layer by layer to complete the overall placement of the beam.

FINITE ELEMENT MODULE METHOD

Model Overview

The model consists of 1389 nodes and 1728 elements of various types. The finite element model can be seen in Figure 4. The beam and the arch share a joint. The main beam and pier are connected by general support.

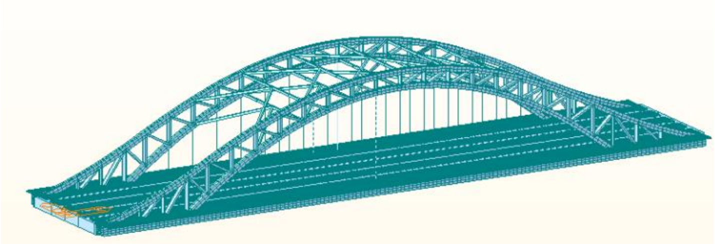


Fig.4 – Calculation model of a steel truss arch bridge

Division of construction conditions

According to the construction process, the analysis is divided into 34 construction stages, with each stage advancing the structure by 5 m. The main construction stages include the steel truss beam jacking stage and the maximum cantilever stage. Each construction stage activates the corresponding structural groups or boundary groups based on the actual conditions. The analysis simulates the stress and deformation of the main structure in each construction stage. Please refer to Table 9 for detailed description of each construction stage.

Tab. 9 - Calculation and analysis of load conditions explanation

Construction phase	Top push distance	Construction phase	Top push distance
1	Before top push	18	The top push distance is 80 m
2	Top push starts, with a push distance of 0 m	19	The top push distance is 85 m
3	The top push distance is 5 m	20	The top push distance is 90 m
4	The top push distance is 10 m	21	The top push distance is 95 m
5	The top push distance is 15 m	22	The top push distance is 100 m
6	The top push distance is 20 m	23	The top push distance is 105 m
7	The top push distance is 25 m	24	The top push distance is 110 m
8	The top push distance is 30 m	25	The top push distance is 115 m
9	The top push distance is 35 m	26	The top push distance is 120 m
10	The top push distance is 40 m	27	The top push distance is 125 m
11	The top push distance is 45 m	28	The top push distance is 130 m
12	The top push distance is 50 m	29	The top push distance is 135 m
13	The top push distance is 55 m	30	The top push distance is 140 m
14	The top push distance is 60 m	31	The top push distance is 145 m
15	The top push distance is 65 m	32	The top push distance is 150 m, and the top push is completed
16	The top push distance is 70 m	33	Remove the girder, temporary pier, and arch assembly bracket
17	The top push distance is 75 m	34	Completed Phase 2 pavement

ANALYSIS OF OVERALL JACKING CALCULATION RESULTS

Stress calculation result

The stress values during the jacking process are crucial for the safety of the structure, especially when using the integral jacking construction method, as the structure's self-weight can lead to stress concentration. The materials used in the bridge structure are all Q345 steel, so it is necessary to verify whether the stress in the structure is within the allowable range. Finite element software is used to perform simulation analysis on the structure and determine the construction stage and location with the highest stress.

(1) Main beam stress calculation results:

The upper and lower stress analyses of the main beam are performed separately for the maximum construction stages of the front and rear cantilevers. The stress envelop diagrams for the upper and lower edges of the main beam can be seen in Figure 5 to Figure 8. Detailed analysis results can be found in Figure 9 to Figure 10. The stress values are given in MPa, with "+" representing tension and "-" representing compression.

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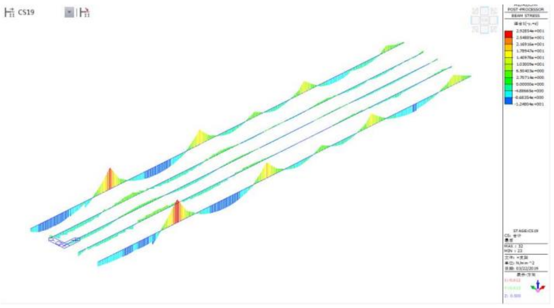

Fig. 5 – Maximum envelope stress diagram of the front cantilever of the main girder

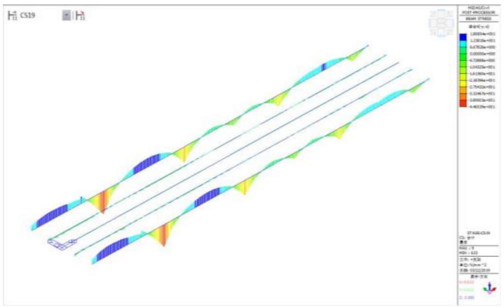

Fig. 6 – Maximum stress enveloping diagram of front cantilever main beam

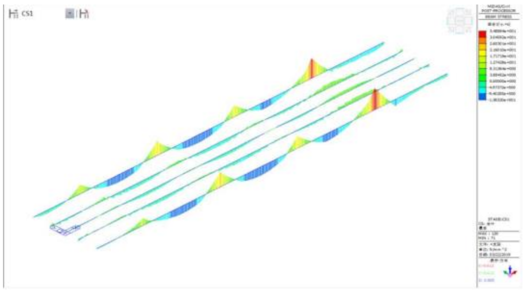

Fig.7 – Maximum stress enveloping diagram of rear cantilever main beam

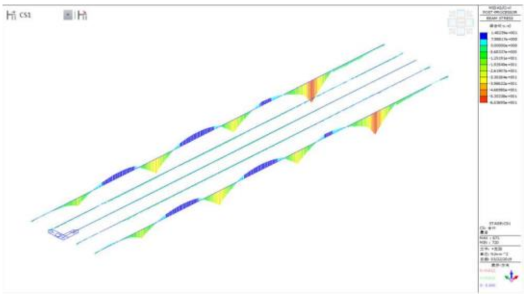

Fig.8 – Maximum stress enveloping diagram of the lower surface of the rear cantilever main beam

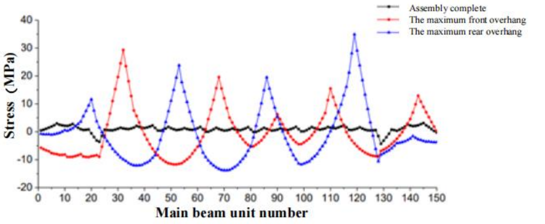

Fig.9 – Stress diagram of the upper surface of the main beam

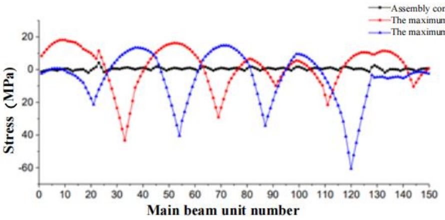

Fig.10 – Stress diagram of the lower surface of the main beam

From Figure 5 to Figure 8, it can be observed that the maximum stress in the rear cantilever of the main beam occurs in the first construction stage of the jacking process, when the rear cantilever has just left temporary support L6. Therefore, the maximum stress is generated at the end of the main beam. The maximum stress in the front cantilever of the main beam occurs in the 19th construction stage of the jacking process, when the main beam has been pushed out approximately 85 m and the front end is in a maximum cantilever state.

From Figure 9 to Figure 10, it can be seen that during the maximum construction stage of the front cantilever, the maximum stress on the upper edge of the main beam is 29.3 MPa, and the maximum stress on the lower edge is -44.7 MPa. During the maximum construction stage of the rear cantilever, the maximum stress on the upper edge is 34.9 MPa, and the maximum stress on the lower edge is 60.4 MPa.

The steel used in this structure is Q345 steel. It can be concluded that the overall stress of the structure during the jacking process is within the allowable range and the structure is safe and stable.

(2) Guideway stress calculation results:

The maximum stress in the guideway during jacking occurs in the 11th construction stage (with a cumulative jacking distance of approximately 45.75 m), and the maximum stress value is 53.2 MPa. The maximum stress stage and stress distribution in the guideway during the jacking process can be seen in Figure 11 to Figure 12.

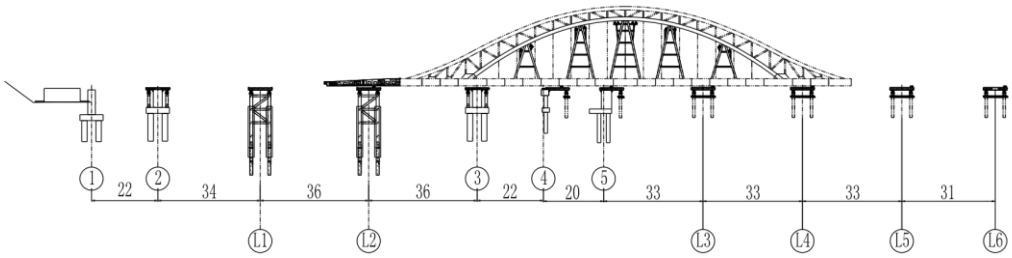

Fig.11 – Schematic diagram of the maximum stress stage of the guide beam

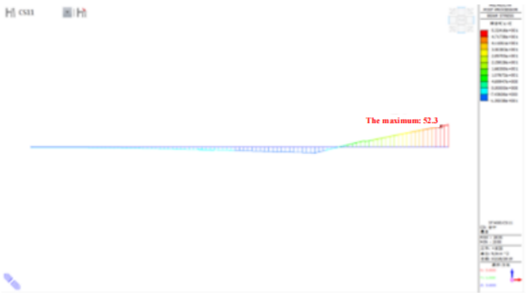

Fig.12 – Envelope diagram of maximum stress in the guide beam

From Figure 11 to Figure 12, it can be seen that during the overall jacking process, the maximum stress in the guideway occurs at the section where the guideway is connected to the main beam. This indicates that measures should be taken to strengthen the connection between the guideway and the main beam during the jacking process.

(3) Arch rib stress calculation results:

The maximum stress in the arch rib during jacking occurs in the 33rd construction stage. At this stage, the jacking is completed, the temporary piers are removed, and the arch rib assembly supports are dismantled. The maximum stress point is located at about 1/4 of the span from the lower arch ribs and at the arch foot, with a maximum stress value of -48.9 MPa.

The stage with the maximum stress and the stress distribution in the arch rib during the jacking process can be seen in Figure 13 to Figure 14.

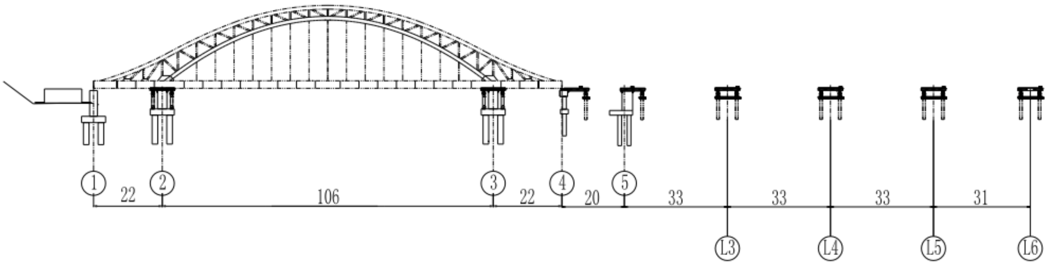

Fig.13 – Schematic diagram of the arch rib under maximum stress phase

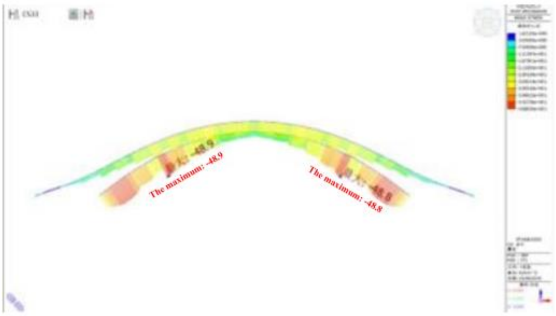

Fig.14 – Envelope diagram of maximum stress in the arch rib

Based on the above calculation results, it can be concluded that under the overall simulation analysis, the maximum stress in the arch rib during jacking is -48.9 MPa, which is within the allowable stress of the material. Therefore, the internal forces in the arch rib structure during the jacking process are well within the acceptable range.

Displacement calculation results

The displacement calculation in top-down construction is as important as stress calculation as it can also reflect the structural behavior. Through simulation analysis of a steel truss arch bridge during the top-down construction process, displacements at the front and rear ends of the guideway, as well as at the front and rear ends of the main beam, were calculated at each construction stage. The maximum displacement at the front end of the guideway is -30.79 mm, occurring in the 7th construction stage, while the maximum displacement at the rear end of the guideway is -8.14 mm, occurring in the 10th construction stage. As for the main beam, the maximum displacement at the front end is -13.14 mm, occurring in the 10th construction stage, and the maximum displacement at the rear end is -35.88 mm, occurring in the 1st construction stage. Please refer to Figure 15 to Figure 16 for more details.

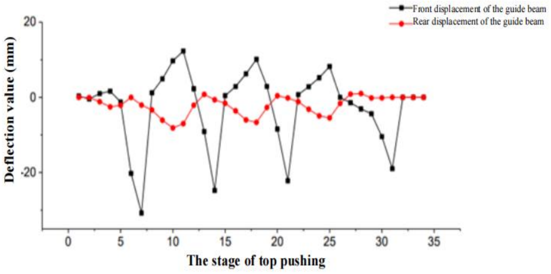

Fig.15 - The comparison of deflection between the front end and root of the guide beam

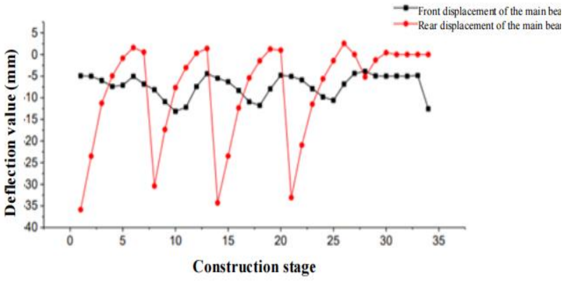

Fig.16 - The comparison of deflection between the front end and rear end of the main beam

From Figure 15, it can be observed that the front end of the guideway initially lifts during the 8th, 15th, and 22nd construction stages. After reaching a certain height, the upward trend gradually becomes gentler, and then it starts to descend, showing a noticeable regular pattern. The maximum deflection of the guideway occurs at the front end when it is in the maximum cantilever state, which happens during the 7th construction stage (with a cumulative jacking distance of 25 m), with a deflection value of -30.79 mm. The maximum deflection at the base of the guideway is -8.14 mm, occurring during the 10th construction stage. As for the main beam, the deformation at the front end is relatively stable, showing regular fluctuations. The maximum deflection occurs during the 10th construction stage (with a cumulative jacking distance of 40 m), with a deflection value of -13.14 mm.

The maximum deflection at the rear end of the main beam is -35.88 mm, occurring during the 1st construction stage. This is because, at the beginning of the jacking process, the rear end of the main beam loses temporary support, resulting in the maximum cantilever length and, consequently, the maximum deflection value.

Calculation results of reaction force at the top of temporary pier

During the top-down construction process of the bridge, a total of 6 temporary piers were installed, including 2 in the water (L1 and L2) and 4 on land (L3 to L6). The reaction forces at the top of these temporary piers are important data that reflect the bridge's structural behavior, and it is essential to calculate these forces.

(1) Maximum Reaction Force during Top-down Construction

According to the simulation calculation results, the maximum reaction force occurs during the 14th construction stage (with a cumulative jacking distance of approximately 62 m) at temporary pier L3# in the water. The magnitude of this reaction force is 6193.9 kN. The construction stage and the distribution of reaction forces are shown in Figure 17 to Figure 18.

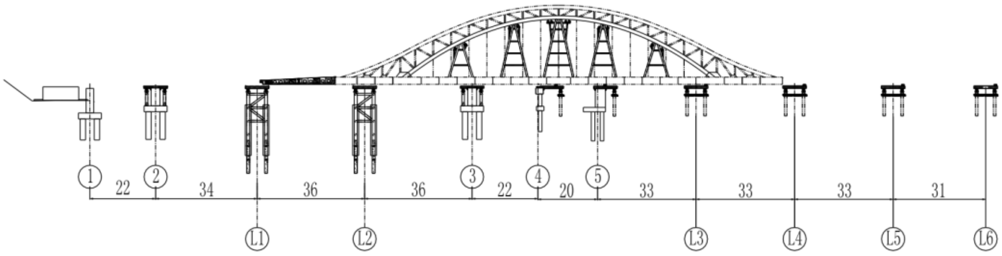

Fig.17 – The temporary pier reaction during the top-down construction phase

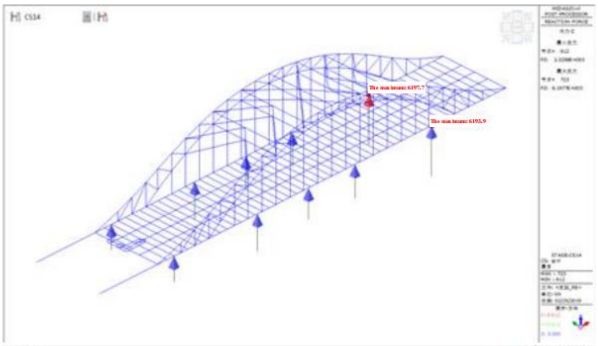

Fig.18 – The maximum reaction force result during the top-down construction process

(2) The reaction force at temporary pier L1# in the water

The maximum reaction force at temporary pier L1# occurs during the 25th construction stage (with a cumulative jacking distance of approximately 116 m). The magnitude of this reaction force is 5226.8 kN. The construction stage and the distribution of reaction forces are shown in Figure19 to Figure 20.

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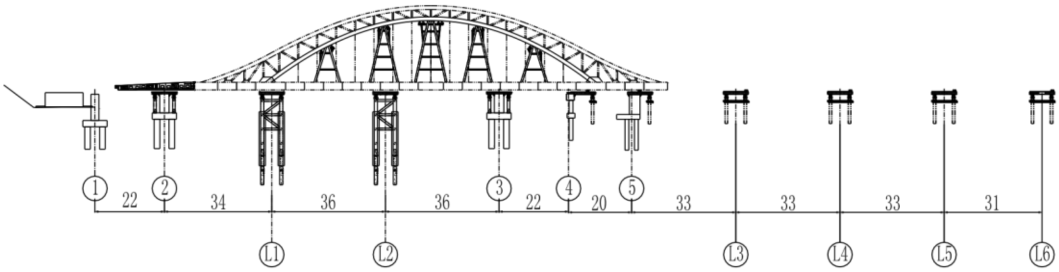

Fig.19 – L1# temporary pier's maximum reaction force occurs during the top-down construction phase of the launching process

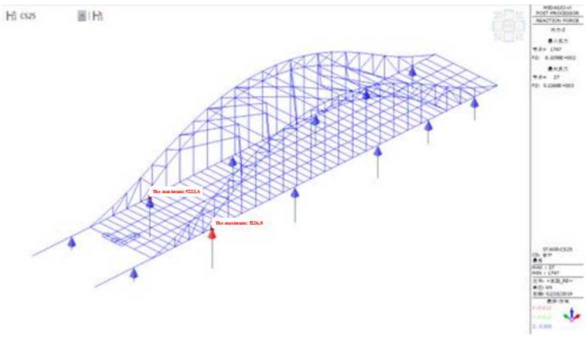

Fig.20 – The maximum reaction force of temporary pier L1# during the top-down construction process

(3) The reaction force at temporary pier L2# in the water

The maximum reaction force at temporary pier L2# occurs during the 17th construction stage (with a cumulative jacking distance of approximately 75 m). The magnitude of this reaction force is 5349.4 kN. The construction stage and the distribution of reaction forces are shown in Figure 21 to Figure 22.

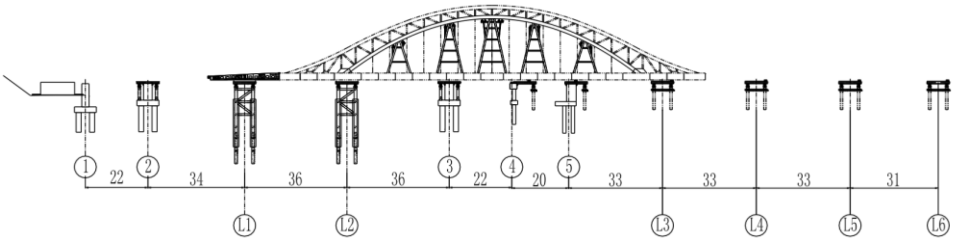

Fig.21 – The construction phase during which the maximum reaction force of temporary pier L2# occurs during the top-down construction process

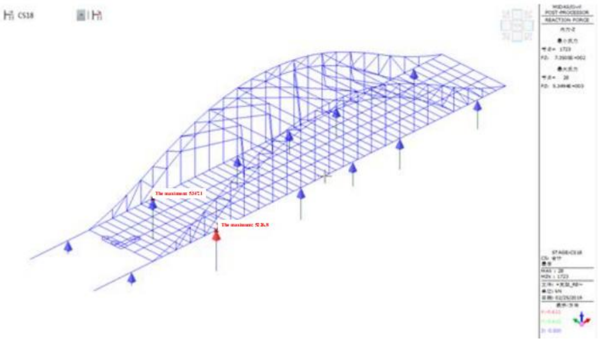

Fig.22 – The maximum reaction force of temporary pier L2# during the top-down construction process.

CONCLUSION

The study utilized the finite element software Midas/Civil to establish a spatial model and conduct a simulated analysis of the overall top-down construction process of a steel truss arch bridge. This analysis enabled the assessment of the structural performance and load distribution of the guide beam and main structure at each stage of the construction. The following conclusions were drawn:

(1) The maximum cantilever stage of the front end of the main beam occurs during the 19th stage of top-down construction (with a pushing distance of 85 m). The maximum stress on the upper flange is 29.3 MPa, while the maximum stress on the lower flange is -44.7 MPa. In the maximum cantilever stage of the rear end of the main beam, the maximum stress on the upper flange is 34.9 MPa, while the maximum stress on the lower flange is -60.4 MPa. At this stage, the rear cantilever has just left temporary support pier L6, resulting in the highest stress concentration due to the maximum cantilever length.

(2) The maximum stress on the guide beam during the top-down construction process occurs during the 11th construction stage (with a cumulative jacking distance of approximately 45.75 m). The maximum stress value is -53.2 MPa, and it corresponds to the cross-section at the base of the guide beam.

(3) The maximum deflection at the front end of the guide beam occurs during the maximum cantilever state, which is the 7th construction stage (with a cumulative jacking distance of 25 m). The maximum deflection value is -30.79 mm. The maximum deflection at the root of the guide beam is -8.14mm, occurring during the 10th construction stage.

(4) The maximum reaction force on the top of the pier during the top-down construction process occurs during the 14th construction stage (with a cumulative jacking distance of approximately 62 m), at temporary pier L3.

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