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Research Article

Coordinate Monitoring Technology in the Process of Incremental Launching Construction of Curved Steel Box Girder Bridge

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Based on the steel box girder curve incremental launching project of SW ramp bridge in Harbin East Third Ring Road, the geometric alignment and structural internal force of the steel box girder during the incremental launching process were monitored in the whole process. The curve incremental launching coordinate position control method was adopted, and the relevant parameters were modified according to the site construction situation and the initial stress conditions of the girders, and the corrected theoretical value was used as the control and evaluation basis of the monitoring value. The results showed that the original theoretical deflection value was −33.10 mm, the modified theoretical deflection value was −64.10 mm, and the actual monitoring value was −53.20 mm. The modified theoretical value agreed well with the monitoring value, and the error rate between the monitoring value and the theoretical value under each working condition was −17.82%~14.48%. The geometric alignment and internal force of the steel box girder met the monitoring requirements, ensuring that the steel box girder can meet the design requirements under various working conditions.

1. Introduction

The incremental launching method is a construction method in which jacks are applied to force the prefabricated beam along the axis of the bridge, and the beam passes through the top of each pier until it reaches the design position. When the surrounding geographical environment is complex and it is impossible to use the support method or lifting technology for construction, the incremental launching method can be used for the construction of concrete or steel box girder continuous girder bridge [1–9].

Leonhard and Ball [10] put forward the concept of incremental launching construction and applied it to the construction of continuous girder bridges. At present, many scholars have done a number of research and applications in the incremental launching method and the related construction monitoring. The High Moselle Bridge in Germany is currently the largest bridge project in Europe, and the incremental launching method was used in the construction of its superstructure [11]. Based on the railway construction of Western Express and SV Road Santacruz, Manish and Nitesh [12] proved that the incremental launching construction method can reduce the time and cost of the bridge construction. Tugela River Bridge on the Tugela River was built by Naidu through incremental launching method and balanced cantilever construction method [13]. Chacon et al. [14] conducted experimental research and numerical simulations on the bridge incremental launching process. According to the mathematical model, the strain, stress, and displacement of steel box girders were obtained to provide theoretical support for bridge incremental launching construction and monitoring. Based on the Xiamen-Shenzhen Railway, Zhang [15] researched the "zero damage" of structure in the incremental launching construction of prestressed concrete continuous box girder systematically. Through a great deal of research on the incremental launching construction technology of steel box girders, Wang [16] summed up a series of problems that should be paid attention to in the process of box girders' incremental launching construction. Dai et al. [17] used finite element software to model a steel box girder cable-stayed bridge in China. Also, the most unfavorable position of girder bridge was analyzed. Zhang et al. [18] analyzed the mechanical behavior of a long-span cable-stayed bridge. Furthermore, the stress state at the most unfavorable position of the section is studied emphatically. Ding et al. [19] designed a suitable construction scheme according to the structural characteristics and environmental conditions of Ji'nan Huanghe Railway road bridge, which provided a reference for the construction of large steel truss bridges. In addition, Fraternali [20] and Luciano et al. [21] provided reference for the follow-up analysis of construction monitoring.

At present, the incremental launching method is seldom used in the construction of the curved steel box girder bridge. Therefore, this paper proposed the initial condition correction technology based on the incremental launching project of the curved steel box girder of the SW ramp bridge in the East Third Ring Road in Harbin. The stress of the critical sections was expressed in the form of the whole construction process, which could provide a certain theoretical reference.

2. Project Overview

The SW ramp bridge in the East Third Ring Road in Harbin adopted a continuous steel box girder with a span of 29 m + 41.5 m + 40.5 m + 30 m, the horizontal curve radius is 103.5 m, and the maximum width of the bridge is 10.05 m. The total length of the incremental launching girder is 58.9 m, which is composed of three segments of girders, and the lengths of each segment are 22.9 m, 16 m, and 20 m, respectively. The weights of each segment are 80 t, 56 t, and 70 t, respectively. The cross section of the steel girder is a box shape with a single box and single chamber. The height of the middle span steel girder is 2.1 m. The width of the cantilever is 2.175 m. The U-shaped stiffeners are set on the top and bottom, respectively. The plane arrangement chart of the bridge types and cross section chart of the steel girders are shown in Figures 1 and 2, respectively.

The project planned to lift the curved steel box girder to the designated position for construction. However, due to the influence of high voltage line in the construction area, some segments cannot be lifted. Therefore, the following scheme was chosen. (1) Pushing the box girder segment located near the high voltage line onto the temporary support pier. (2) Pushing it to the designated position. The new construction scheme is different from the conventional scheme, resulting in the difficulty and risk of construction. Thus, in the process of incremental launching construction, the whole process must be monitored.

3. Monitoring Technology

3.1. Coordinate Control of Curve Incremental Launching Process. Considering the limited length of single incremental launching of the steel box girder, three temporary piers and two ordinary temporary supports were set up in the curve incremental launching process. Ten fixed points of displacement reference were set up, and six moving points were set at the front, middle, and rear positions of the bridge section. The incremental launching trajectory was drawn by AutoCAD software. The tangent direction at the moving

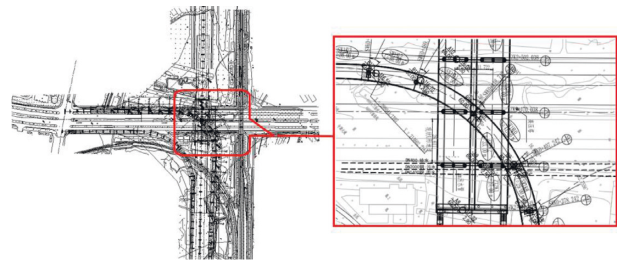


Figure 1: Plane arrangement chart of the bridge types.

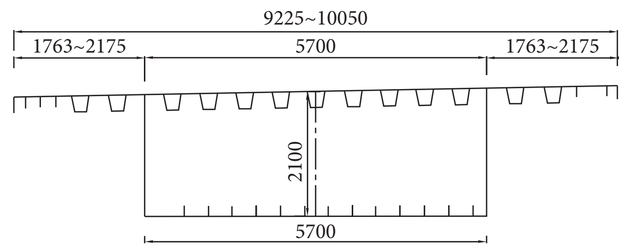


Figure 2: Cross section chart of the steel girders.

fixed points of the trajectory and the radial direction of the steel box girder were taken as the incremental launching direction and the rectifying deviation direction, respectively. The moving path of the corresponding girder is shown in Figure 3. The maximum length of single incremental launching was 350 mm, and there were 57 incremental launching steps in the whole process. Due to space limitations, this article shows one of the drawings (Figure 3).

According to different conditions, control points were selected at both ends of each steel box girders. In the whole process of construction, the coordinate of each control point corresponding to each stroke was calculated. The coordinates were used to monitor and control the actual jacking construction process to ensure accurate movement of the beam along the track line. The flowchart of incremental launching displacement control is shown in Figure 4.

3.2. Monitoring Condition. According to the construction scheme of the steel box girder of East Third Ring Road in Harbin, under the premise of ensuring the safety and reliability of the structure, the worst conditions during the incremental launching construction process were divided into three working conditions, and the specific content of each working condition and the location map of the steel box girder are shown in Table 1 and Figure 5, respectively.

3.3. The Initial Condition Correction Method. Due to transportation, construction, or supporting conditions, the initial condition of the girder is a non-zero stress state in practical engineering. The influence of the above factors is not considered in the finite element software analysis process, resulting in a large error between the simulated value and the monitoring value. Therefore, it is necessary to modify the theoretical simulation results to make the simulation values reflect the actual situation more accurately.

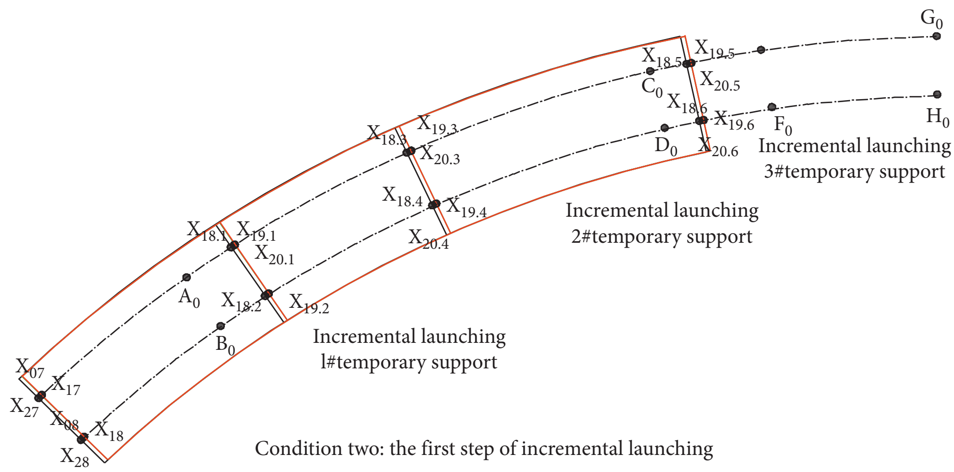


Figure 3: Schematic diagram of curve incremental launching.

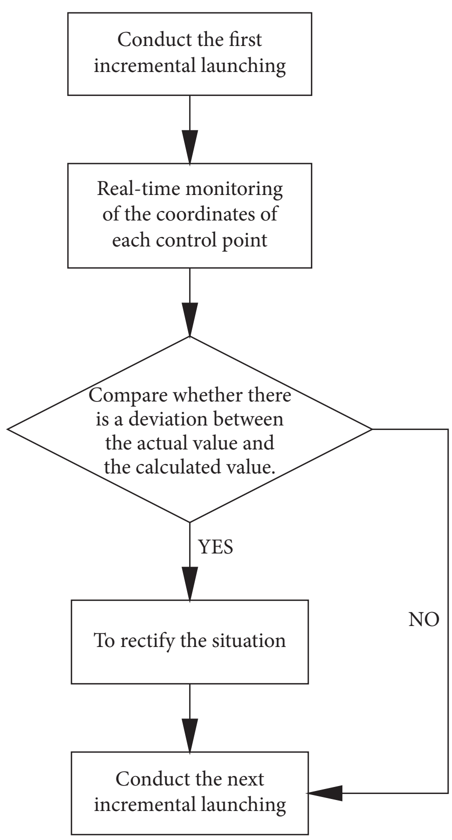


Figure 4: Flowchart of incremental launching displacement control.

3.4. Correction of the Theoretical Deflection Value. In condition 2, it was necessary to connect segment three (S3) with the whole segment (segment one and segment two, S1 and S2) and then start the incremental launching, as shown in Figure 6. At this time, the end of segment three was in the maximum cantilever state, that is, the worst stress state, so the deflection value of the end of segment three needed to be monitored to ensure the safety of incremental launching construction.

Therefore, MIDAS/Civil was used to simulate and analyze the steel box girder, focusing on the force state of the steel box girder when the lifting jacks. However, in condition 2, an unpredictable situation occurred on the construction site because the operator did not cut the temporary steel pier (as shown in Figure 6) under the end of the steel box girder at the same time during the construction. The girder end was subjected to uneven forces and downward tensions, resulting in considerable errors between the theoretical and monitored values.

Since the situation was not considered in the finite element analysis, it is necessary to correct the additional deflection of the steel box girder based on the theoretical value. The correction method adopts the bending moment equation, the deflection equation, and the stress calculation formula, as shown in equations (1)–(4), respectively.

$$M(x) = \frac{1}{2}qx^2 + F(l - x), \tag{1}$$

$$EIw'' = -M(x), \tag{2}$$

$$M = \sigma \cdot W_z, \tag{3}$$

$$\sigma = E \cdot \varepsilon, \tag{4}$$

where $M(x)$ is the bending moment (kN·m); x is effective length (m); l is the length of the cantilever segment of the steel box girder (m); q is combination value of the uniformly distributed load (kN/m); F is the tension caused by temporary steel piers (kN); E is the modulus of elasticity (MPa); I is the moment of inertia of cross section (m^4); w is the deflection (mm); W_z is the bending section coefficient (m^3); σ is the stress (MPa); and ε is the strain ($10^6\ \mu\varepsilon$).

Substituting the maximum value of the actual tensile strain into (4), the stress value in this state can be determined, and then the relevant design parameters were substituted into (1)–(3) to calculate the theoretical value of deflection correction which was −64.10 mm.

Table 1: Classification and content of working conditions.

Construction status	Specific contents
Condition 1	S1 and S2 were hoisted to the top of the temporary pier at the same time, and after welding to form a whole, the ordinary temporary support was removed, which was in the state of a beam with simply supported ends
Condition 2	After connecting S3 to the whole segment, the incremental launching began, and the ends of the S3 were in the maximum cantilever state
Condition 3	Sections one, two, and three were jacked 19.9 m to the specified position under incremental launching, and the front end of section one was in the maximum cantilever state at this time

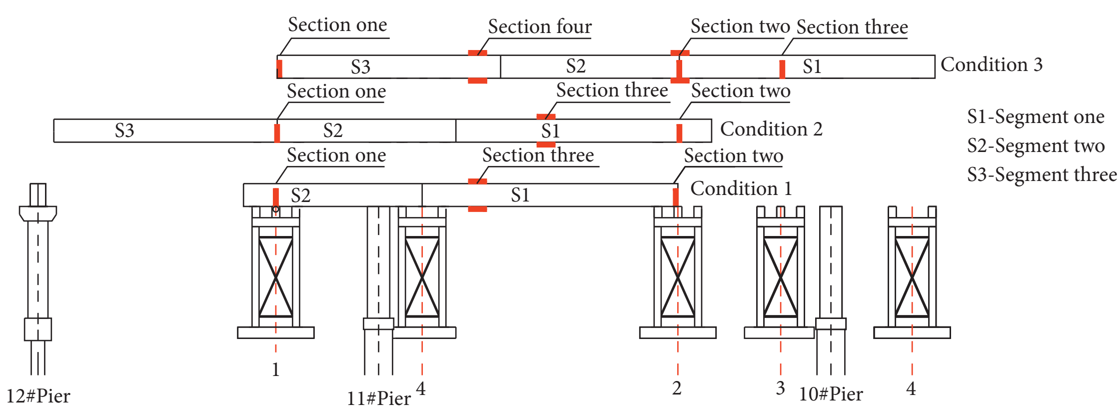


Figure 5: Schematic diagram of the position of steel box girder under various working conditions. 1-no.1 Incremental launching temporary pier, 2-no.2 Incremental launching temporary pier, 3-no.3 Incremental launching temporary pier, 4-Ordinary temporary pier.

3.5. Correction of the Relationship between Temperature and Strain. The steel box girder was affected by direct solar radiation and atmospheric environment in the natural environment during the incremental launching process, so the temperature effect existed in the bridge structure. Although the finite element analysis of the temperature field can accurately reflect the temperature distribution of the cross section of the actual engineering steel box girder, the temperature distribution curve is complicated, which is not conducive to the calculation and analysis of the actual monitoring process. Therefore, the monitoring value was corrected based on the changes in real-time temperature and strain, and the strain value monitored at the standard atmospheric temperature of 25°C was used as the benchmark. After multiple days of monitoring, it was found that the strain value increased by about 100 $\mu\varepsilon$ when the temperature increased by 1°C on average. Therefore, the actual monitoring value was modified accordingly based on the relationship between temperature and strain in this monitoring.

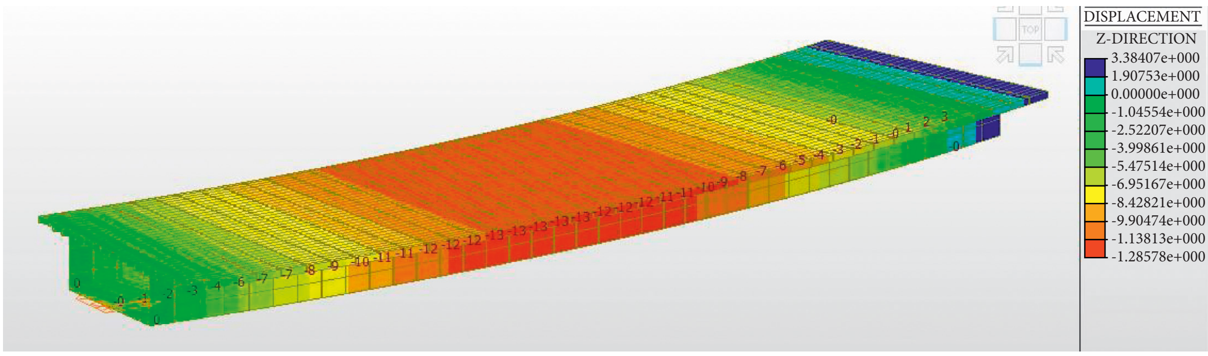
3.6. Correction of Theoretical Stress Value. The correction principle of the theoretical value of stress is that each working condition is subdivided into two states: (1) the state before incremental launching; (2) the state when the jack starts to lift. For example (condition 1), before incremental launching, the bottom of the girder was supported by ordinary temporary support, and the steel box girder can be regarded as an integral continuous girder. When the jack started to lift, the steel box girder was lifted and separated from the ordinary temporary support, and the girder can be regarded as a simply supported beam.

Figure 6: Temporary steel pier under cantilever end of the steel box girder.

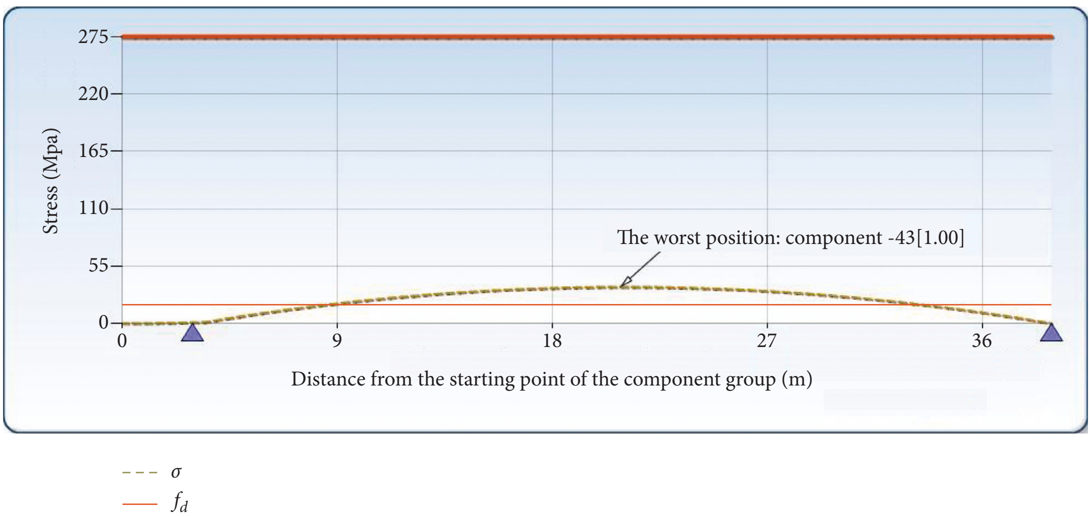
Because the steel girder was in the elastic stage during the incremental launching process and the internal forces were linearly proportional, based on the finite element software simulation results, the simulated internal forces were discounted and calculated to eliminate the effect under the continuous girder state, and the theoretical monitoring control values of key section can be obtained.

3.7. Design of Monitoring System

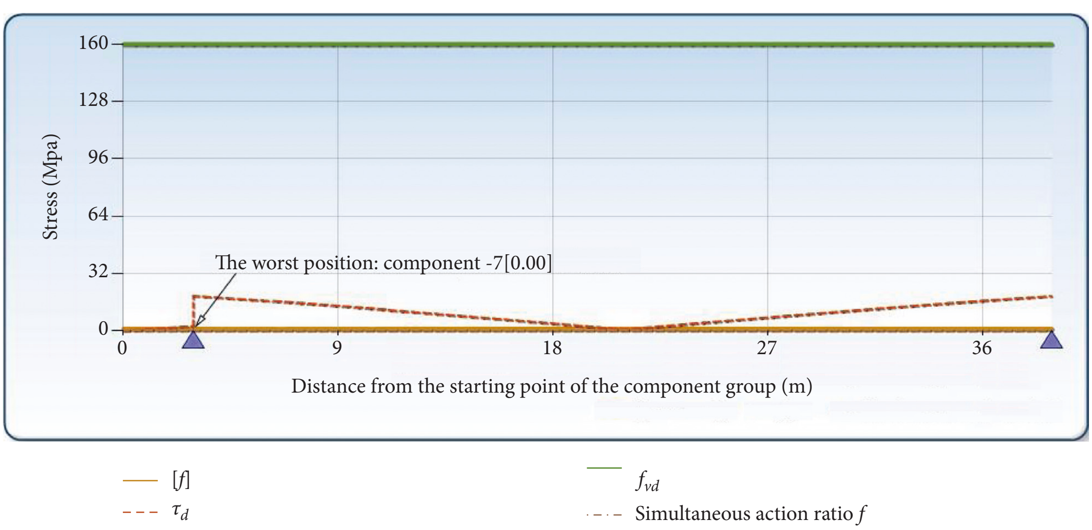
3.7.1. Monitoring Parameters and Basis. The finite element analysis software MIDAS/Civil was used to simulate and analyze the continuous steel box girder. The structural stress and deformation results under various working conditions were obtained, including the deflection and stress value of



(a)



(b)



(c)

Figure 7: Finite element model diagram of the steel box girder. (a) Deflection diagram of steel box girder. (b) Bending normal stress envelope diagram of flange plate of bending member. (c) Envelope diagram of the stress of web of bending member.

the section at the disadvantageous position of the steel box girder. The finite element model diagram of the steel box girder of incremental launching construction is shown in Figure 7.

To ensure that the geometric alignment and stress of the steel box girder can be effectively controlled in the process of monitoring, the deviation limits of internal force and deflection under various working conditions are determined as

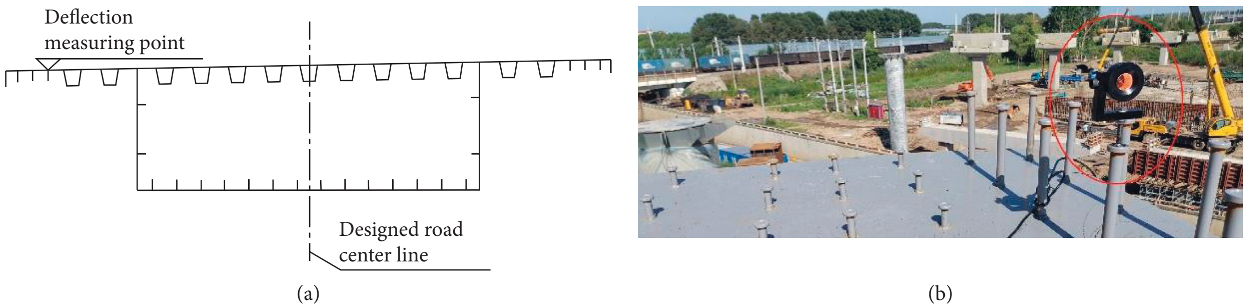


Figure 8: Cross-sectional layout drawing of the deflection measuring point of the steel box girder. (a) The layout of the cross-sectional survey points. (b) Object picture of measuring-point arrangement.

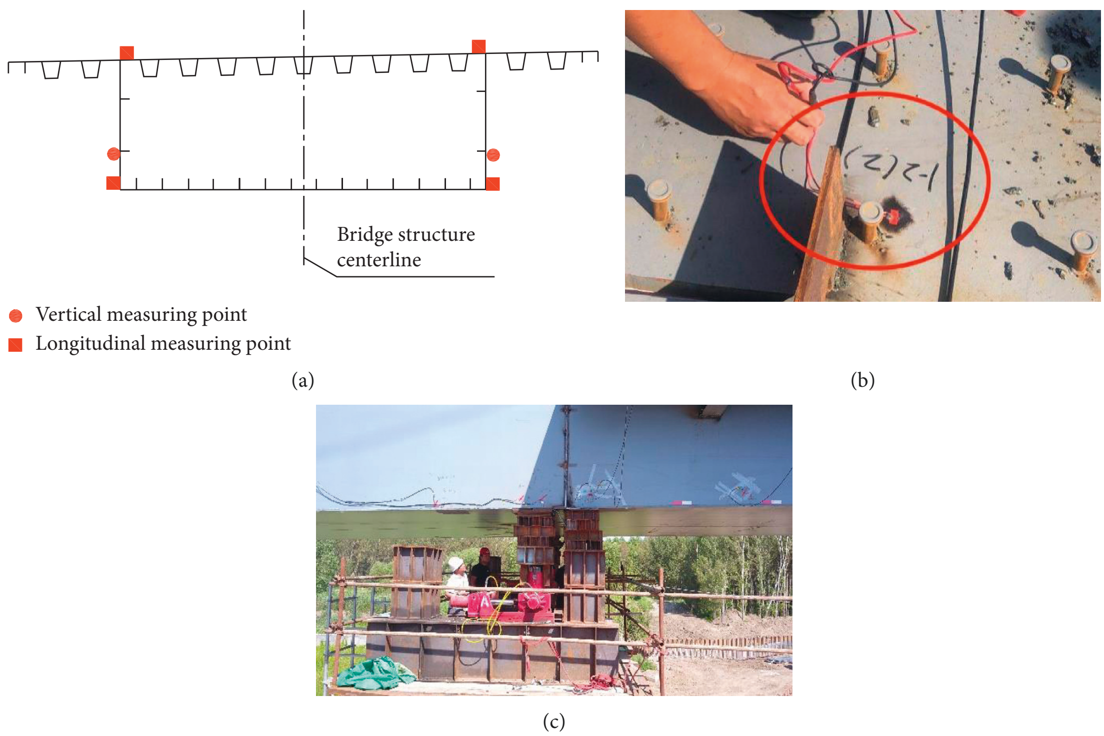


Figure 9: Layout drawing of stress measurement points. (a) The layout of the cross-sectional survey points. (b) Longitudinal survey points on the beam top. (c) Survey points on both sides of the web.

the basis of safety control in the process of construction [22]. To achieve the purpose of monitoring, the real-time monitoring value and theoretical calculation value were compared and analyzed.

3.7.2. Measuring Point Arrangement. With the progress of the incremental launching construction progress, the applied force system of the structure was in a constant change state which led to the constant change of the geometric alignment and the internal force of the steel box girders which were mainly monitored during this process [23]. The focus of the geometric alignment control was the change of the deflection of the steel box girders during this process. And stress control was based on real-time monitoring of key sections in the steel box girder to ensure that the structure was within the safe and controllable range.

3.7.3. Deflection Measuring Points. The prisms were arranged at the top slab surface of the front, middle, and end of the steel box girder segments, as shown in Figure 8. During the incremental launching process, real-time monitoring of the elevation changes of the cantilever end, the supporting abutment, and the control section of the middle span of the steel box girders was used to calculate the deflection and compare it to the theoretical value.

3.7.4. Stress Measuring Points. Forty-six stress measuring points were arranged. The layout of the measuring points is shown in Figure 9. The vertical and longitudinal stress measuring points are arranged on both sides of the web and roof of the steel box girder. They are used to monitor the variation trend of compressive stress and bending normal stress of steel box girder web during jacking. The results were

Table 2: Comparison of deflection monitoring value and theoretical value of steel box girder.

Construction status	Incremental launching status	Comparison value	Deflection (mm)
Condition 1	After lifting jacks	Theoretical value	12.86
		Monitoring value	8.50
		Limitation value	±20.00
Condition 2	Temporary steel pier unloaded incompletely	Theoretical value/modified theoretical value	−33.10/−64.10
		Monitoring value	−53.20
		Limitation value	±66.67

Note. The theoretical correction value in the second condition is the deflection value corrected according to the method in Section 3.4.

Table 3: Stress monitoring value and theoretical value of key sections of steel box girder.

Construction status	Incremental launching status	Section location and measuring point layout	Theoretical value (MPa)	Monitoring value (MPa)	Error rate (%)	Strength limit (MPa)
Condition 1	The moment of lifting jack	Vertical measuring point of section 1	25.81	21.21	−17.82	160.0
		Vertical measuring point of section 2	21.56	18.58	−13.82	160.0
		Longitudinal measuring point of section 3	23.80	22.87	−3.91	275.0
Condition 2(1)	Temporary steel pier unloaded incompletely	Vertical measuring point of section 1	85.99	93.73	9.00	160.0
Condition 2(2)	The moment of lifting jack	Vertical measuring point of section 1	75.99	75.39	−0.79	160.0
		Vertical measuring point of section 2	22.48	24.72	9.96	160.0
		Longitudinal measuring point of section 3	6.56	7.51	14.48	275.0
Condition 3	Before lowering down	Vertical measuring point of section 1	38.50	33.37	−13.32	160.0
		Vertical measuring point of section 2	36.63	34.40	−6.09	160.0
		Longitudinal measuring point of section 2	31.45	27.40	−12.88	275.0
		Vertical measuring point of section 3	34.70	29.25	−15.71	160.0
		Longitudinal measuring point of section 4	34.91	30.48	−12.69	275.0

Note. Error rate = (monitoring value − theoretical value) × 100%/theoretical value.

recorded by JM3813 strain gauges. Based on the stress-strain relationship of steel, the stress of key sections was obtained.

3.8. Implementation Effect and Analysis

3.8.1. Deflection Monitoring of Steel Box Girders. The values of deflection of the steel box girders under some working conditions were compared with the theoretical values, as shown in Table 2. By the situation of the construction site and the data in the table, the values of deflection were all in the control range of the theoretical values, which meant that the geometric alignment of girders met the safety design. Among them, because the practical construction load was much smaller than the set value in the finite element analysis, the actual test values were also smaller than the theoretical ones.

3.8.2. Stress Monitoring of Steel Box Girders. According to the monitoring data of the construction site, the stress monitoring values and theoretical values of each key section of steel box girders under different working conditions are shown in Table 3. By combining the data in the table and the situation of the construction site, the error rate between the test values and the theoretical ones under each working condition was −17.82%~14.48%, and the values of deflection were all in the range of the margins, which met the demands of the monitoring and control, that is, stress monitoring could monitor the incremental launching process effectively under various working conditions to ensure the safety and reliability of the structure. Among them, due to the influence of the temperature and the acceleration generated by the dynamic load during the incremental launching construction progress, there was a certain error between the test values and the theoretical ones, which were normal.

3.8.3. Whole Process Expression of Key Section Stress. The coordinate system was established with the incremental launching length as the x-axis and the stress monitoring value of the key section of the steel box girder as the y-axis.

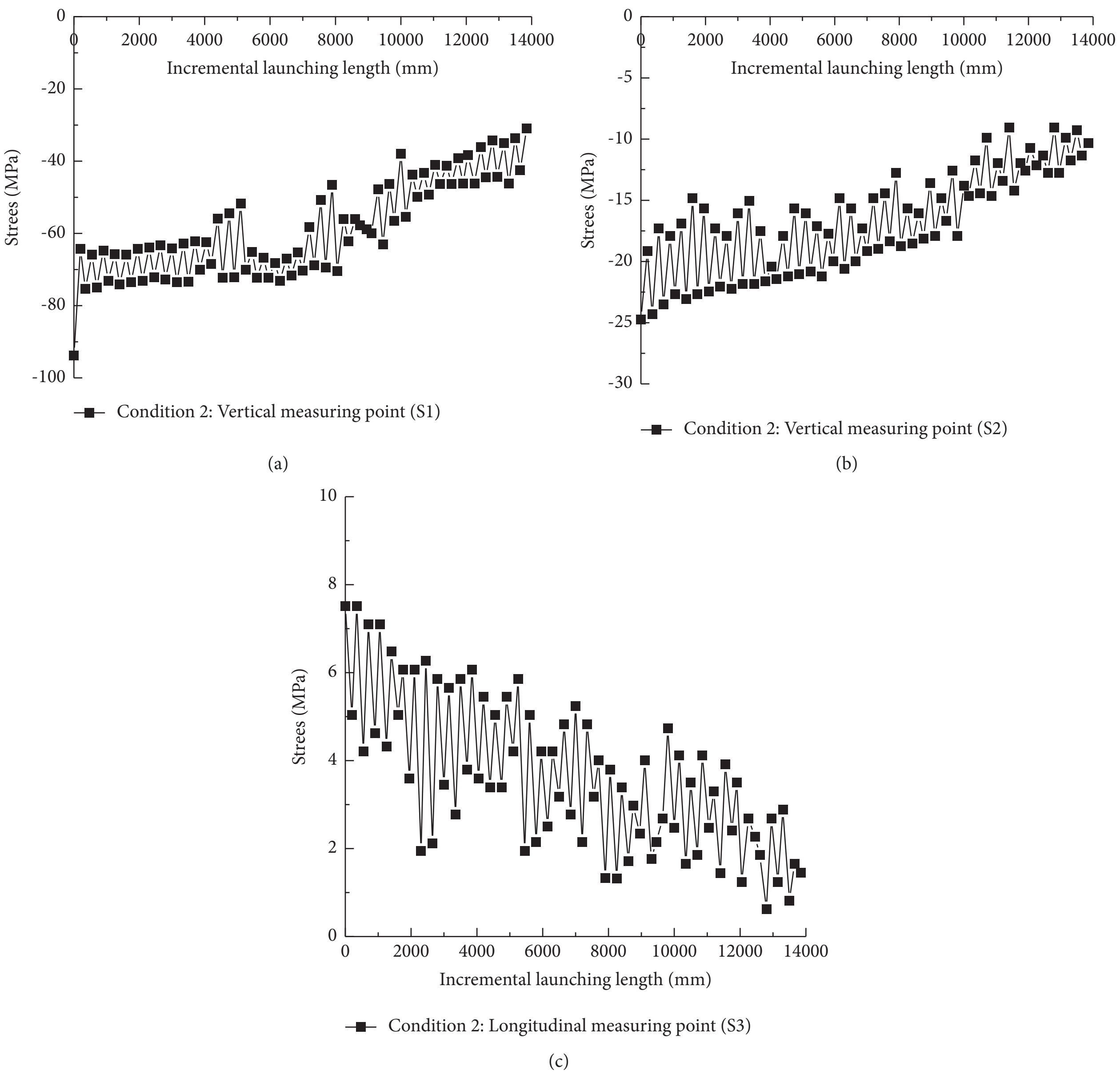


Figure 10: Stress-incremental launching length curve of each key section. (a) Section 1 (S1). (b) Section 2 (S2). (c) Section 3 (S3).

By placing the construction site monitoring data in this coordinate system, the whole process of stress variation with the length of the jacking was obtained. Due to limited space, only the stress curves for condition 2 are shown in Figure 10.

It could be seen from Figure 10 that the measured stress in each critical section of the steel box girder in condition 2 tends to decrease with increasing incremental launching length. Based on the whole process curves of the stress of each key section, the real-time force changes of the steel box girders could be clarified and compared with the theoretical calculation values. The result showed that the development trend of the two was relatively consistent. In addition, due to the influence of the factors such as disturbance in the launching process, various internal forces of the girders were changed, which in turn caused the fluctuation of the stress curve, but the peak stress was all in a safe and controllable range.

4. Conclusions

(1) During the incremental launching process of the steel box girder, the geometric shape and internal force of the structure met the expectations. Also, the critical components monitored were in a linear elastic state, which met the design requirements.

(2) The curved shape coordinate control method, initial condition correction, and whole process expression of stress in the key section were proposed. The stress state in the incremental launching was analyzed and modified. During monitoring the deflection in condition 2, the theoretical value of deflection before correction was −33.10 mm. To conform to the actual construction situation, the theoretical deflection value was modified to −64.10 mm, and the actual

monitoring value was 3.20 mm, which agreed well with both. Furthermore, the error rate between the stress monitoring value and the theoretical value under various working conditions ranged from −17.82% to 14.48%, indicating that the correction method was reasonably reliable.

(3) The strain monitoring value fluctuates to a certain extent due to the influence of temperature change and lifting dynamic load, but it met the relevant design requirements. The strain gauges used in this project provided reliable performance and ensured monitoring accuracy during the incremental launching process.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

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