Article no. 32

THE CIVIL ENGINEERING JOURNAL 3-2023

# MONITORING AND ANALYSIS OF CANTILEVER JACKING OF HIGH SLOPE PRESTRESSED CONCRETE CONTINUOUS BOX GIRDER

*Zhe Zhang, Quansheng Sun, Chao Zhang and Xiaoqian Li*

*School of Civil Engineering and Transportation, Northeast Forestry University, Harbin 150040, China; sunquansheng@nefu.edu.cn*

## ABSTRACT

Due to the rapid development of the transportation industry and economy, an increasing number of bridges have been unable to meet the demands of traffic. Demolishing and rebuilding bridges can lengthen the construction period, waste a lot of resources, and increase construction costs. Based on the lifting renovation project of the old Harbin Dongsan Ring Expressway viaduct, this paper combines finite element analysis and on-site testing to analyze the construction process. The bridge alignment, elevation, and deviations were monitored during the construction process, and a correction system was developed to address such issues. Structural analysis was conducted to evaluate the internal forces when uneven jacking occurred. The construction process described in this paper can effectively solve the jacking problems of urban continuous bridges with large tonnage, high slopes, and heights. The successful implementation of the jacking retrofitting project has verified the reliability of the measures taken.

## KEYWORDS

Bridges, Structural analysis, Finite element methods

## INTRODUCTION

The construction of bridges around the world has a history spanning thousands of years. In the past century, the construction technology of concrete bridges has undergone multiple transformations and advancements. With the rapid development of China's economy and construction industry, urban transportation is transitioning from traditional ground transportation to three-dimensional transportation. Creating more transportation resources within limited space has become an important goal of urban planning today; therefore, urban expressway bridges have been widely constructed and applied as a type of spatial architecture. However, this transformation of urban transportation structures has also brought some challenges. The issue of rebuilding existing bridges is becoming increasingly prominent, leading to a serious waste of social and economic resources. To avoid unnecessary construction, lifting and renovating existing bridges has become an effective solution. This method can maximize the utilization of existing bridge structures and save socio-economic resources. Lifting renovation technology improves the deck of existing bridges to adapt to new traffic needs without the need for complete demolition and reconstruction. This method has significant advantages, one of which is that it reduces engineering costs. Compared to comprehensive reconstruction, lifting renovation can significantly reduce investment and save construction time. Secondly, the lifting renovation can maximize the preservation of the original bridge structure and historical value while reducing the impact on the environment. This method has been widely applied in the renovation of urban expressway bridges, providing sustainable solutions for urban development. The top lifting renovation technology for bridges was first used domestically in the 1950s and was mainly used for the construction, displacement, and setting of railway bridges. With the development of hydraulic technology, in September 2003, computer-controlled hydraulic synchronous jacking technology was first applied to the integral jacking of bridges[1]. As a newly developed bridge renovation technology, jacking has the characteristics of high economic efficiency, efficiency, and environmental friendliness, and has been widely applied in the renovation projects of urban expressway bridges, with good application prospects [2]~[6]. The common jacking methods used now include: sleeper-filled support method, bridge deck steel rail method, end integral jacking method, saddle bracket method, steel girder method, steel butterfly beam method, steel casing method, and hydraulic jacking method. The abbreviation of programmable logic controller is PLC, which is a kind of digital operation electronic system specially designed for application in industrial environment. It uses a programmable memory to store instructions for performing logical operations, sequential control, timing, counting, and arithmetic operations within it, and controls various types of mechanical equipment or production processes through digital or analogue input and output. This project adopts a PLC multi-point synchronous displacement jacking system, integrates digital monitoring transmission, hydraulic transmission control, and computer digital signal processing technology. It combines mechanical equipment systems with traditional bridge structure analysis technology, and uses multiple sets of jacks to achieve balanced, safe, and efficient bridge jacking [7]. The lifting system used is shown in Figure 1.


*Fig. 1 - PLC multi-pump group multi-point displacement synchronization system*

Figure 1 shows a PLC-controlled multi-point synchronous displacement control system for pump groups, which utilizes a closed-loop control system with variable frequency speed regulation. The flow rate of the oil pump is continuously adjusted by changing the frequency of the power supply to alter the speed of the hydraulic motor. With advanced electronic control equipment and displacement and pressure detection systems, precise control of the jack during synchronous lifting is achieved.

Bridge jacking, as a key technology in bridge renovation and maintenance, has achieved some successful practices in the displacement and jacking of building structures both domestically and internationally. Wu proposed the overall process principles of "divided lifting, synchronous control, and partial rotation angle displacement lifting", and elaborated on the key technologies such as synchronous lifting parameters, partial rotation angle displacement lifting, and construction monitoring[8]. The Golden Gate Bridge in the United States underwent repair and strengthening work using jacking technology in 2002, greatly improving its seismic resistance and load-bearing capacity [9]. A range of techniques based on jacking precast units have been developed in the UK since 1967. Thomson introduced the development and application of the tunnel jacking method, which can avoid traffic interruption. "Zhao, Y analyzed the contact behavior and stress distribution characteristics between the main beam and the supporting beam, and monitored and analyzed the induced stresses of the upper structure and support structure[10]. This article investigates the mechanical characteristics of a high-slope continuous beam during cantilever jacking through a combination of jacking tests and finite element analysis using the extended finite element method. Construction monitoring of bridge alignment, elevation, and lateral displacement is performed, and a correction system for lateral displacement is developed. The article also analyzes the internal forces of the structure in cases of uneven jacking caused by mechanical or human factors.

## CANTILEVER JACKING PROJECT TEST

### Project profile

The Harbin Dong San Huan Expressway lifting renovation project adopted the jack-up renovation construction of the old bridge on Huagong Road. The upper structure adopts a simple supporting continuous small box beam, and the bridge pier adopts a cap beam column pier. The bridge deck is arranged in two spans, with both the left and right spans arranged in the following span configuration: 4×30m+3×40m+3×30m+3×30m. The starting pile number of the bridge is K40+392.5, and the ending pile number is K40+812.5. The total length of the bridge is 420m. The section between K40+512.5 and K40+632.5 spans the railway, with a length of 120m. The load level of the bridge is urban A level, and seismic measures are designed according to a seismic fortification intensity of 7 degrees. It was completed in 2012. This paper takes the left span 3×30m continuous small box girder as the research object, and the bridge layout is shown in Figure 2. The main beam of the upper structure is 1.6m high, and the width of a single span bridge deck is 23m. The specific geographical location of this project is shown in Figure 3.

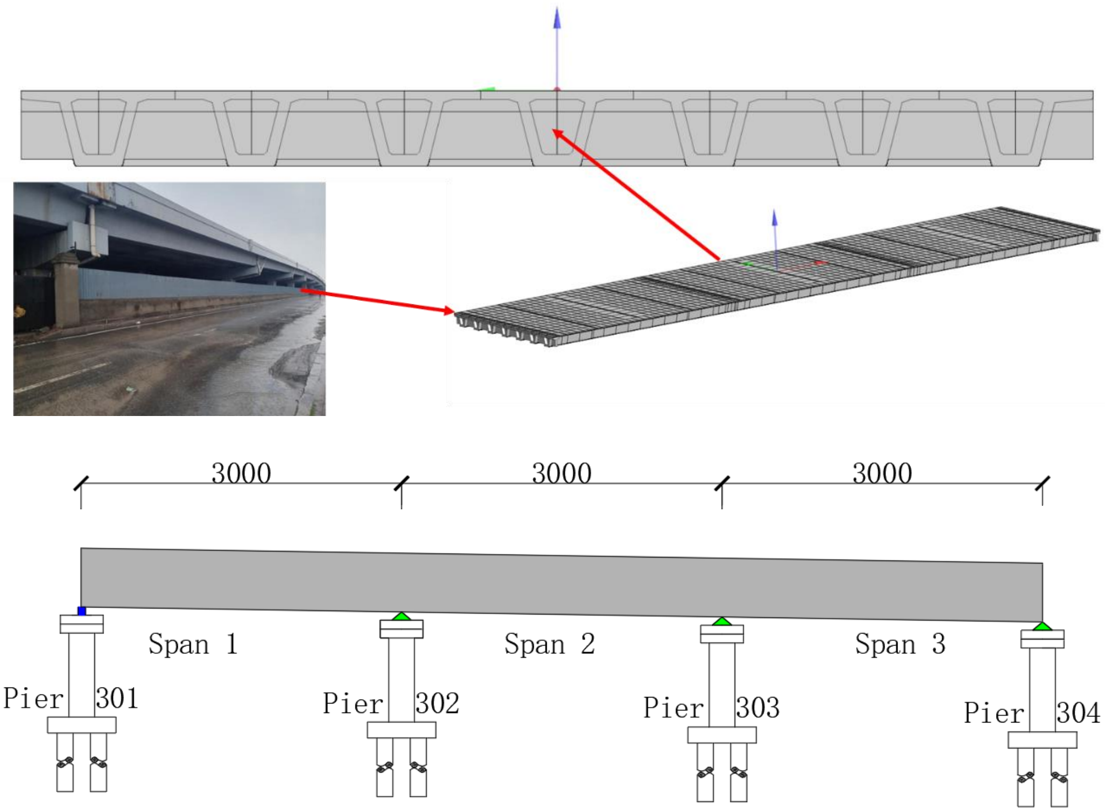



*Fig. 2 - Bridge layout (Units: cm)*

DOI 10.14311/CEJ.2023.03.0032

*Fig. 3 - Geographical Location Map of the Project*

Due to the construction needs of Harbin East Third Ring Expressway, the bridge needs to complete the transformation from the approach bridge to the viaduct through the leveling and jacking stage, upgrade to the new design elevation, and connect with the new viaduct. According to the design requirements and the actual situation of the bridge, the project has the following characteristics:  Large lifting weight, with a single span lifting weight of 4400 tons, requiring a large number of lifting equipment, limiting devices, and monitoring equipment;  Large lifting area, requiring high precision control of multi-point synchronous lifting equipment within a single area of 2000m$^2$;  Large lifting height, with a maximum lifting height of 6.897m, requiring multiple temporary shims placement and lifting cycles;  Design involves rotational lifting, and the bridge undergoes length changes in the projection direction, which results in secondary internal forces. According to the analysis of the overall drawing of the East Third Ring Road, the heights of each support point of the bridge need to be adjusted as shown in Table 1.

*Tab. 1 - North approach bridge lifting height (Units: m)*

| Pier fulcrum | lifting height | Pier fulcrum | lifting height |
|---|---|---|---|
| 301# | 4.197 | 302# | 5.097 |
| 303# | 5.997 | 304# | 6.897 |

## Finite element model

According to the design drawings of the original bridge, a finite element three-dimensional spatial calculation model of the original bridge was established using the finite element analysis software Midas Civil to conduct structural simulation analysis. The 3x30m prestressed concrete continuous box girder was divided into 598 nodes and 921 elements for the entire bridge, and the model is shown in Figure 4.

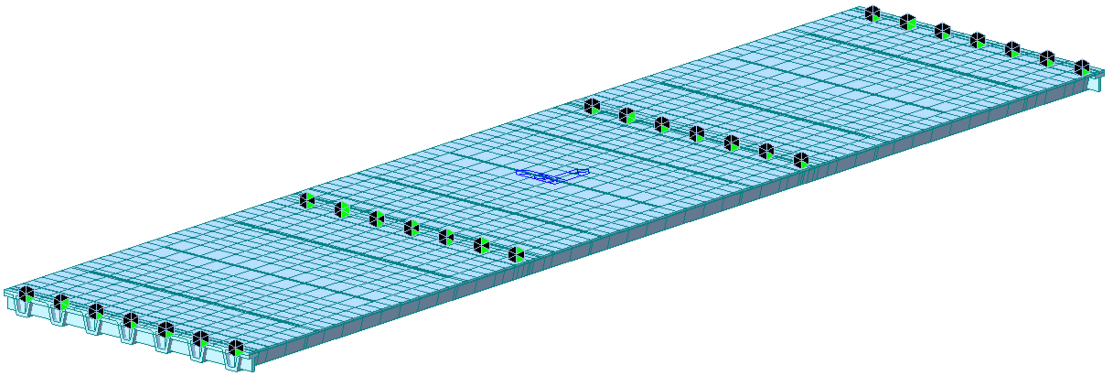


*Fig..4 - Diagram of finite element model*

The material and structural parameters used in the finite element software simulation of the original bridge state are all based on the data provided when the bridge was completed. At the same time, the impact of the overall weight of the structure, permanent load in the second phase, shrinkage and creep, non-uniform settlement, and temperature load on the theoretical model were considered. The node forced displacement was used to simulate the on-site jacking construction process, and the jacking simulation of the model structure was completed during the construction phase. The material parameters are shown in Table 2.

*Tab. 2 - Main material parameter table*

| materials | volumetric weight（kN/m3） | elastic modulus（MPa） | poisson ratio |
| --- | --- | --- | --- |
| C50 | 26.0 | 3.5×104 | 0.2 |

## Cantilever lifting test

For the sake of economic and construction difficulty considerations, the column-breaking jacking method was used for jacking construction, while retaining the upper structure, cover beams, and some pier columns of the original bridge. The bridge was first rotated at the same angle and then jacked up to the target height at the same displacement. At the higher part of the pier, cast-in-place corbel beams were used for jacking, while cover beams were used for jacking at the lower part of the pier. Steel distribution beams were used for cantilever jacking at the original bridge abutment. The jacking arrangement is shown in Figure 5, and the jacking process is shown in Figure 6.

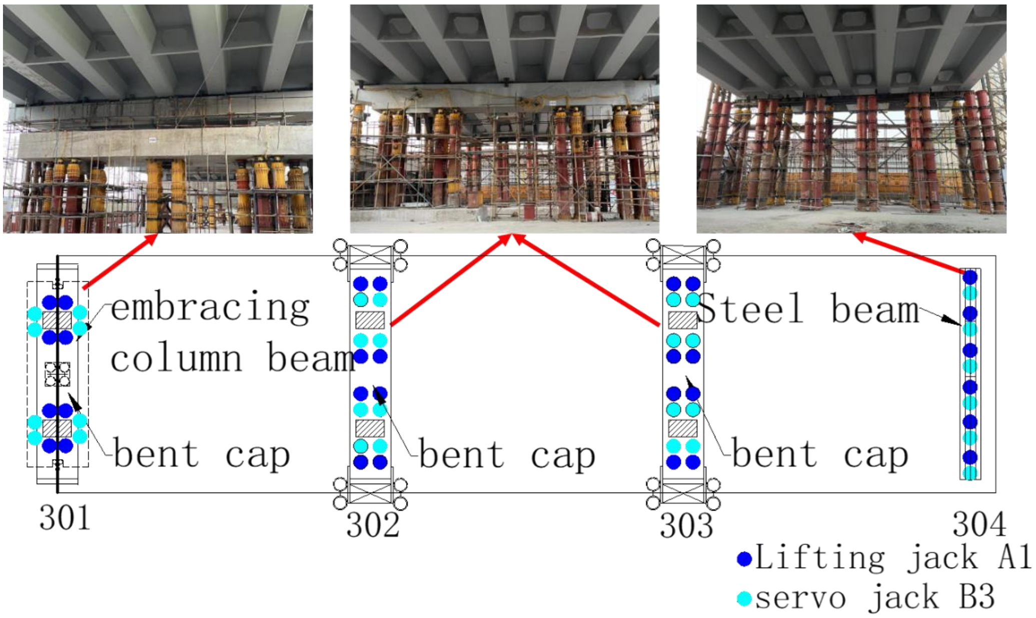



*Fig. 5 - Lifting device layout ( Units : cm )*

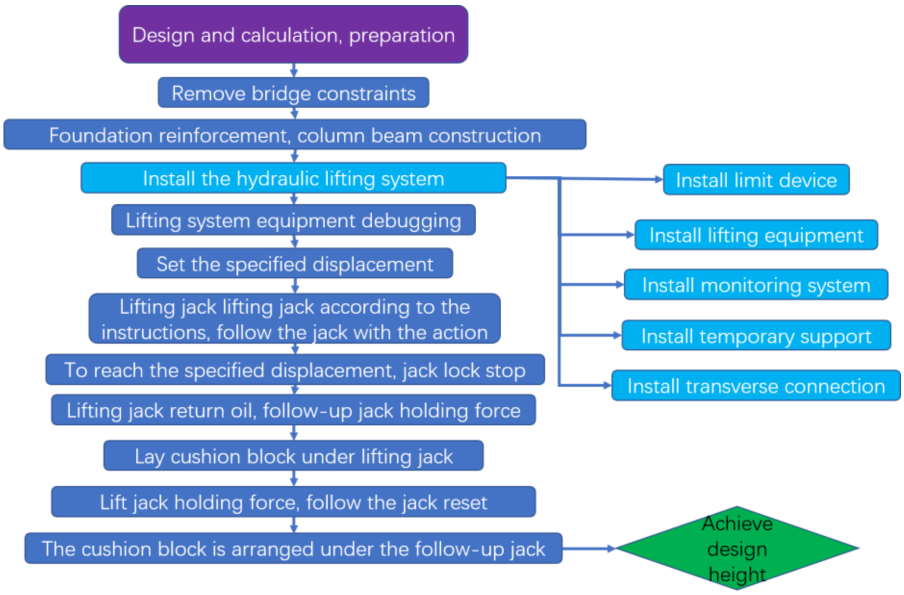



*Fig. 6 - Lifting construction flow chart*

From Figures 5 to 6, it can be seen that the jacking process adopts the combination of jacking jacks and follower jacks, using small displacements and multiple cycles as the jacking method. By increasing the number of steel support pipes, the purpose of lifting the bridge is achieved.

The bridge lifting process adopts a PLC multi-pump group multi-point displacement synchronous system, which integrates technologies such as displacement sensors, digital transmission, hydraulic control, and computer signal processing[11]. It can realize dual-loop control of force and displacement to ensure the safety of the structure. During the cantilever rotation and lifting of the bridge, the concentrated force on the lifting point exceeds 1500kN, and internal force analysis of the lifting bridge is required[12]. In order to prevent the deviation of the lifting system caused by vibrations during the lifting construction process due to construction equipment, passing trains, and natural factors, multiple limiting systems are used in this project. When the height of the original pier is low, a lateral limiting bracket is used in combination with a skew bridge for limiting; when the height of the original pier is high, a column-beam and limiting bracket are used for limiting, as shown in Figure 7.

*a) cantilevered end*

*b) bent cap*

*c) embracing column beam*

*Fig. 7 - Lifting and limiting device installation diagram*

As shown in Figure 7, the jacking process utilizes a combination of transverse Beray beam, anti-torsion limiting frame, cover beam limiting frame, and concrete column-beam limiting system. Beray beam and various types of limiting frames are connected by circular steel column flanges. The stability, safety, and reliability of the limiting system are ensured by presetting the connection between the foundation and the structural foundation.

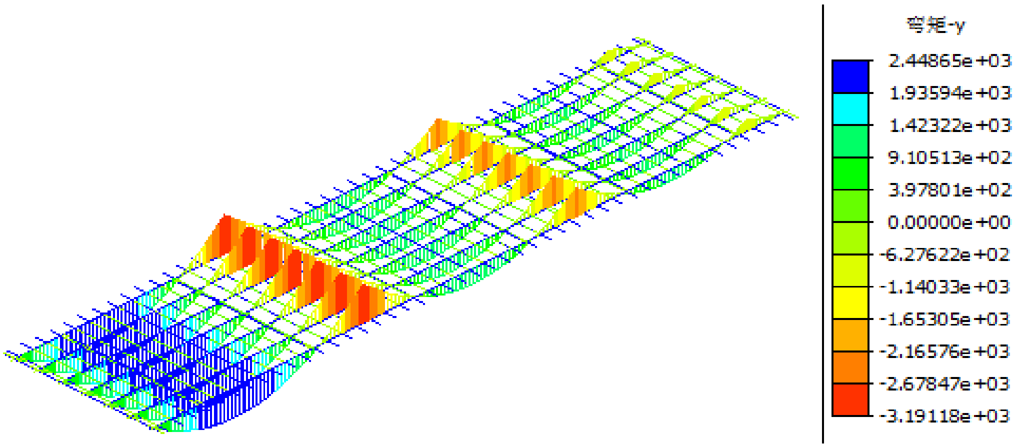
This study considers the three stages of cantilever rotation and lifting, namely, condition 1, where the boundary system of the original bridge is transformed from the 304 bridge abutment to the steel distribution beam; condition 2, where the bridge is rotated and lifted at the same angle; and condition 3, where the bridge is lifted vertically with the same displacement. The experimental conditions are shown in Table 3.

*Tab. 3 - condition (Units: m)*

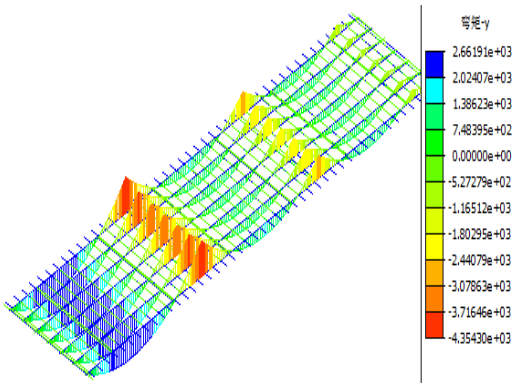
| Pier / condition | 301 | 302 | 303 | Steel beam |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0.0357 | 0.0714 | 0.1 |
| 3 | 0.1 | 0.1 | 0.1 | 0.1 |

The internal force diagrams for each condition were obtained by analyzing each stage of the bridge lifting construction using the Midas Civil finite element analysis software, as shown in Figure 8.

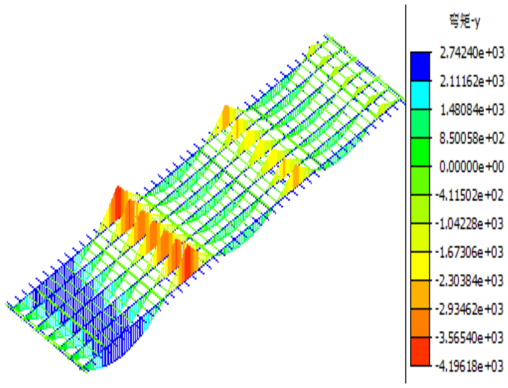
DOI 10.14311/CEJ.2023.03.0032




*a) Condition 1, the internal force diagram of the original bridge system*




*b) Condition 2, synchronous rotating jacking internal force diagram*




*c) Condition 3, synchronous displacement jacking internal force diagram*

*Fig. 8 - Main girder jacking internal force diagram of each stage*

From Figure 8, it can be seen that during the jacking phase of the bridge, due to the transformation of the structural system, the main beam at the steel distribution beam produces a maximum negative bending moment of -1305kN·m. The main beam is under tension and exhibits tension on the upper surface of the structure. Since the tensile strength of concrete is much lower than its compressive strength, to prevent cracking of the upper part of the main beam under tension, carbon fiber plates are used to reinforce the cantilever jacking position of the main beam to bear some of the surface tensile stress. The reinforcement design of the main beam is shown in Figure 9 [13]~[15].

*Fig. 9 - Carbon fiberboard active reinforcement diagram*

The maximum internal forces and their locations of the main beam under different working conditions were recorded based on Figure 8, as shown in Table 4.

*Tab. 4 - Internal force of main beam*

| internal force / condition | maximum positive moment | | maximum negative moment | |
|---|---|---|---|---|
| | position (m) | bending moment (kN/m) | position (m) | bending moment (kN/m) |
| 1 | No.1 spans 12m | 2448.65 | 302 pier top | -3191.18 |
| 2 | No.1 spans 12m | 2661.91 | 302 pier top | -4354.30 |
| 3 | No.1 spans 12m | 2742.40 | 302 pier top | -4196.18 |

According to Table 4, the maximum negative bending moment and positive bending moment during the synchronous rotation lifting and synchronous displacement lifting processes occur at span 1, 12m and pier 302, respectively. Furthermore, the lifting process has a relatively small impact on the positive bending moment of the structure, but a significant impact on the negative bending moment of the pier top. In order to study and evaluate the mechanical behavior of the bridge structure during the lifting process, the top section of pier 302 was selected as the testing section, and HY-65B digital strain gauges were used to measure the stress of the bridge structure. The layout of the strain measurement points is shown in Figure 10.

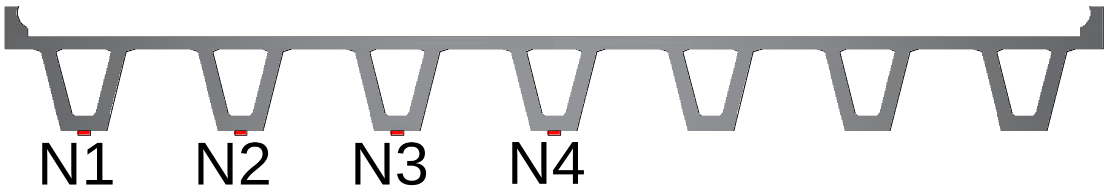
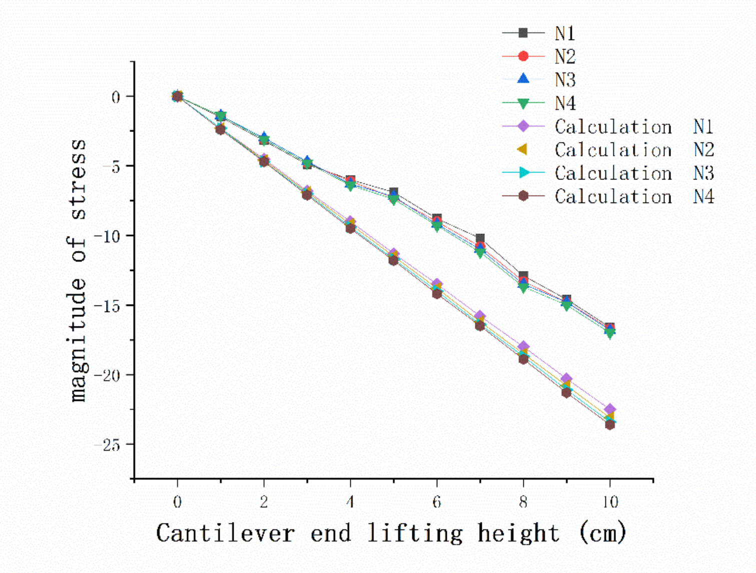



*Fig. 10 - Measurement point layout*

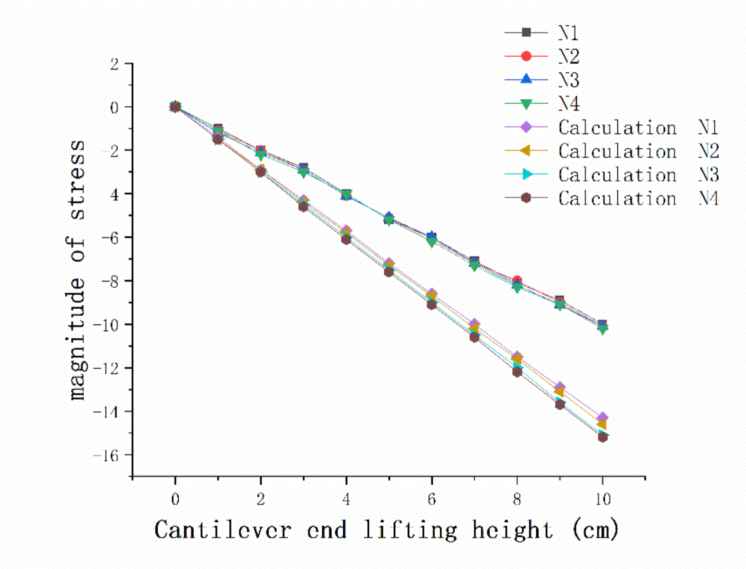
## Test result analysis

Stress and strain are key data that reflect the structural loading conditions. Monitoring the lifted bridge, the stress conditions of the structure during the lifting process can be reflected by the theoretical values and measured strain values at each measurement point. According to the superposition principle, the stress data of the main beam caused by the lifting can be obtained from the difference of stress values at each stage of the theoretical model, as well as the measured strain data, as shown in Figure 11.

DOI 10.14311/CEJ.2023.03.0032




Synchronous rotation lifting




synchronous lifting displacement

*Fig. 11- Measured and theoretical strain value*

Based on Figure 11, it can be seen that the stress of the cross section at the top of pier 302 is proportional to the lifting stroke during the two lifting stages, and the data at each measuring point is balanced, indicating that the structural integrity is relatively good. The experimental verification coefficient ranges from 0.58 to 0.80, and the sectional stress shows linear changes. The measured values of each section are smaller than the theoretical calculated values, and the maximum verification coefficient is 0.80, indicating that the structure is in a reasonable control state during the lifting process. The maximum stress change of the cross section at the top of pier 302 during the synchronous rotation lifting process is -17; the maximum stress change during the synchronous displacement lifting process is -10.2, indicating that the synchronous rotation lifting process has a greater effect on the internal force of the main beam than the synchronous displacement lifting stage. The linear relationship between the theoretical calculation values and the measured values is good, indicating that the finite element model can well reflect the stress status of the structure during the lifting process.

## JACKING CONSTRUCTION MONITORING AND ANALYSIS

The lifting process was monitored by using a total station for point layout. In order to address the issue of top lifting deviation caused by construction factors, mechanical vibration, external loads, etc., this study analyzed the influence of top lifting deviation on the structure during the construction process using a finite element model.

### Lifting construction monitoring

To accurately understand the stress situation of the jacking beam and ensure the smooth progress of the jacking project, in the cantilevered rotating jacking process, the linearity and deviation of the beam are monitored. Measurement points are set up at the top of the pier, on the side of the beam, and at the cantilever jacking end, and monitoring measurements are carried out using a total station based on the second-class engineering level standard.

**(1) Linear monitoring**

Based on the characteristics of continuous beam structures, a linear monitoring plan was developed, and total station points were arranged as shown in Figure 12.

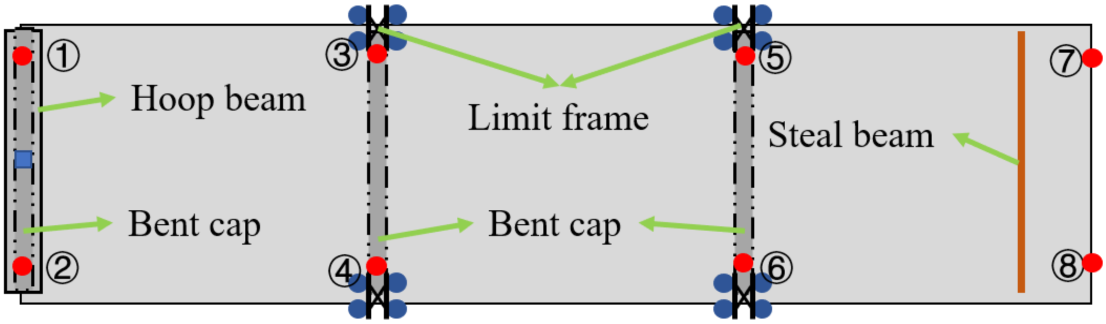



*Fig. 12 - Bridge deck elevation measuring point layout*

By establishing stations, transferring stations, and setting up intermediate stations using a permanent benchmark and total station, the observation points in Figure 12 were monitored regularly to capture the bridge posture during the jacking construction process. The elevation data of the bridge control points collected during the construction process are shown in Table 5.

*Tab 5 - Elevation measurement data (unit: m)*

| Date / point | 9.29 | 10.04 | 10.05 | 10.07 | 10.08 | 10.09 | 10.10 | 10.19 | 10.21 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 126.819 | 128.064 | 128.153 | 128.504 | 128.709 | 129.093 | 129.429 | 130.639 | 126.819 |
| 2 | 127.115 | 128.359 | 128.449 | 128.796 | 129 | 129.385 | 129.694 | 130.888 | 127.115 |
| 3 | 126.737 | 127.996 | 128.088 | 128.398 | 128.603 | 128.913 | 129.271 | 130.435 | 126.737 |
| 4 | 127.011 | 128.269 | 128.36 | 128.719 | 128.911 | 129.283 | 129.527 | 130.737 | 127.011 |
| 5 | 126.541 | 127.792 | 127.883 | 128.139 | 128.436 | 128.813 | 129.043 | 130.216 | 126.541 |
| 6 | 126.863 | 128.117 | 128.204 | 128.424 | 128.756 | 129.135 | 129.344 | 130.533 | 126.863 |
| 7 | 126.491 | 127.721 | 127.81 | 128.074 | 128.385 | 128.78 | 128.954 | 130.21 | 126.491 |
| 8 | 126.813 | 128.056 | 128.138 | 128.394 | 128.695 | 129.089 | 129.269 | 130.498 | 126.813 |

Due to the existence of transverse slope in the bridge, the average of the symmetric monitoring points is used to represent the elevation of the bridge section center. The elevation profile of the bridge during the jacking process is shown in Figure 13.

DOI 10.14311/CEJ.2023.03.0032

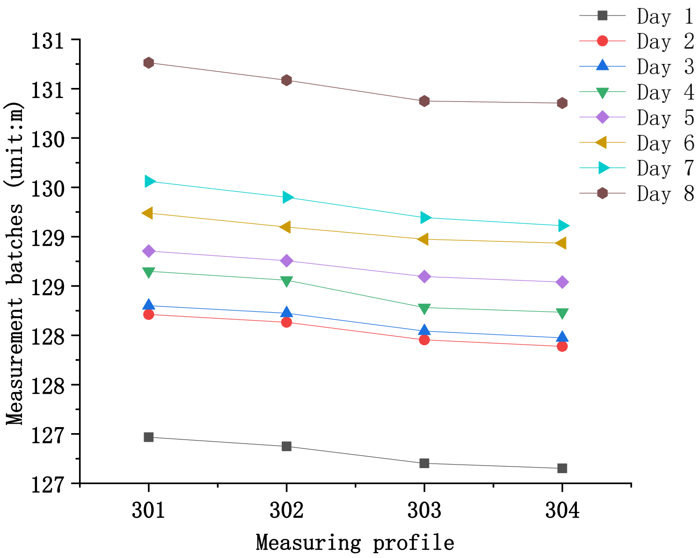
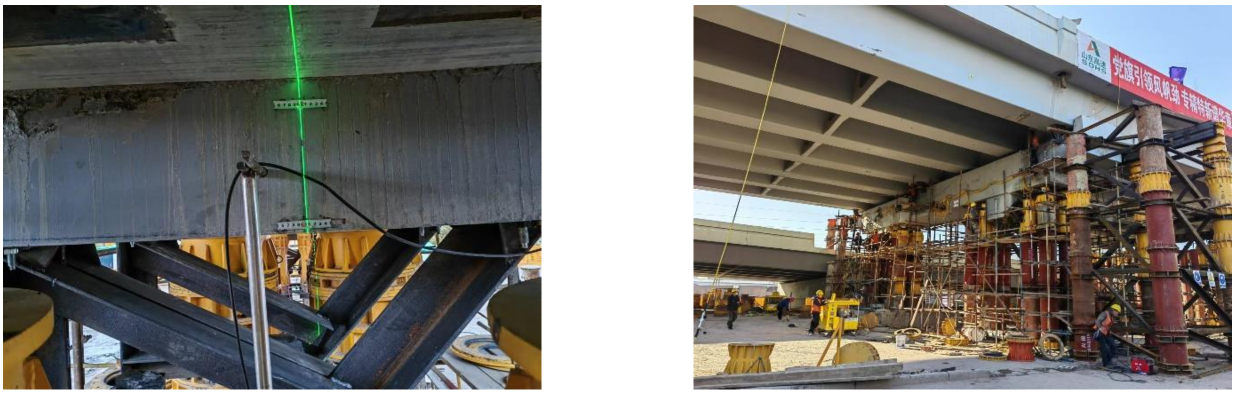



*Fig. 13 - Bridge lifting elevation line chart*

As shown in Figure 13, all control sections were uniformly and synchronously lifted during the jacking process, and no jacking differences occurred. The ramp adjustment and jacking were completed according to the predetermined height, achieving the control elevation. After that, the elevation was fine-tuned through bridge deck paving and other methods to achieve the target alignment.

**(2) Bias monitoring**

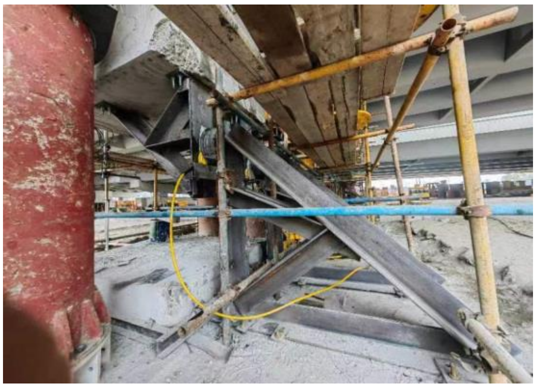
Continuous beam cantilever rotating lifting, the length in the bridge projection direction increases, and there is frictional force between the beam and the cover beam, which causes the support system such as the cover beam to shift, further causing the beam to shift. Due to factors such as construction errors, frictional forces, and construction machinery vibrations, there may be displacement errors during the bridge lifting process. Through laser measurement, total station point measurement, and bridge static measurement equipment, the bridge lifting posture is determined, and the bridge lifting system has cover beam rotation deviation and main beam longitudinal deviation as shown in Figure 14.



(a) Cover beam overturning offset (b) Main girder deflection

*Fig. 14 - Deflection diagram of jacking system*

Based on the characteristics of the project, a correction method was developed. The structural system used column dismantling jacking, and the main components for correction were the cover beam and main beam, with the main deviations being the overturning and offset of the cover beam and the lateral displacement of the main beam as shown in Figure 14. Different correction methods were adopted for different deviations, including pier foundation reaction correction, limit frame reaction correction, and main beam reaction correction as shown in Figure 15.



(a) Pier foundation reaction correction

(b) Counterforce correction of limit frame

(c) Main beam reaction correction

*Fig. 15 - Lifting correction system*

During the top-down lifting process of the structure, the lifting system, monitoring system, and correction system work together to achieve structural system transformation, cyclic lifting, and system correction, and thus achieve the lifting goal. The lifted bridge is shown in Figure 16.

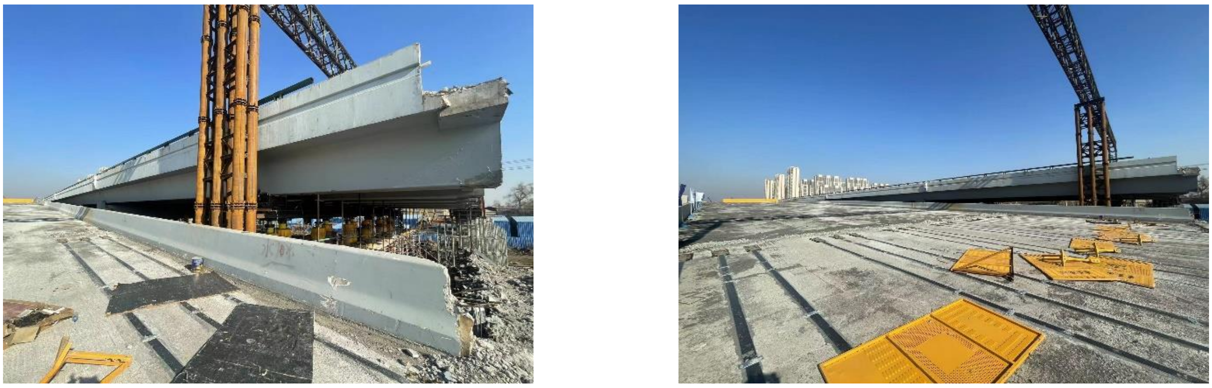
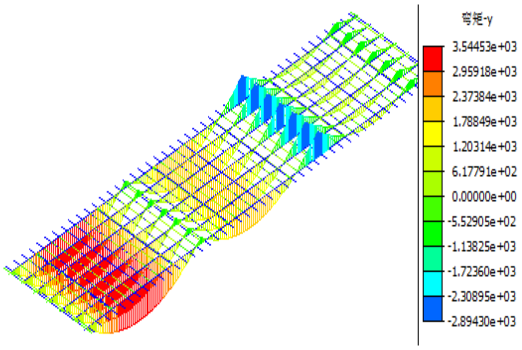


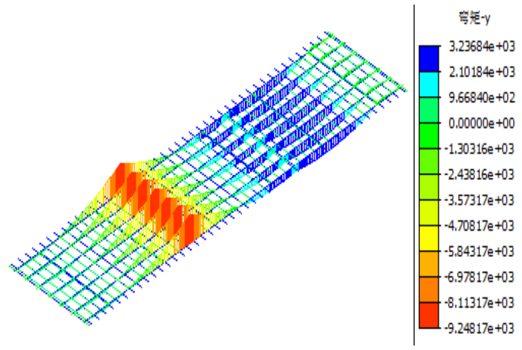
*Fig. 16 - Comparison diagram of left and right bridge jacking construction*

## Analysis of jacking deviation

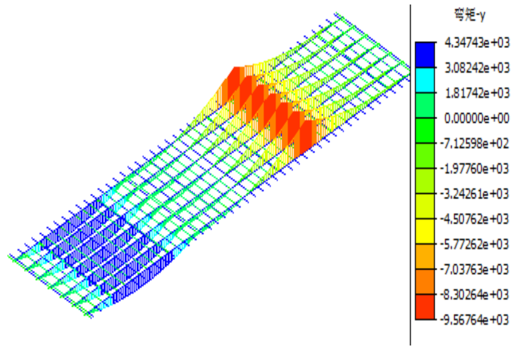
During the synchronous lifting of the multi-span continuous beam, longitudinal deviations may occur due to the unsynchronized hydraulic devices of the bridge pier, distribution beam, and brace beam, as well as the uneven temporary support structure. Midas Civil was used to analyze the possible longitudinal deviations during the lifting process, including scenario 1: lifting of pier No. 301 alone; scenario 2: lifting of pier No. 302 alone; scenario 3: lifting of pier No. 303 alone; and scenario 4: lifting of the cantilever end of pier No. 304 alone. The internal force diagrams of the main beam under various longitudinal deviation scenarios are shown in Figure 17.



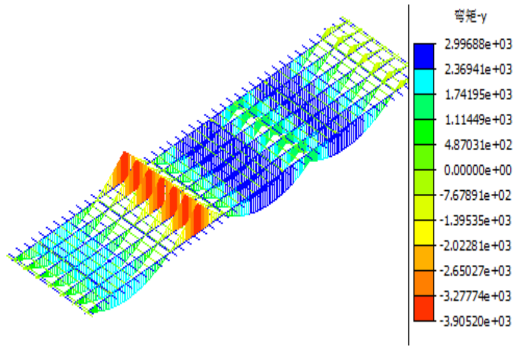

*a) condition 1 internal force diagram*




*b) condition 2 internal force diagram*




*c) condition 3 internal force diagram*




*d) condition 4 internal force diagram*

*Fig. 17 - Internal force diagram of each deviation condition*

Based on the comparative analysis of Figures 8 and 17, it can be concluded that when uneven lifting occurs at the edge support, the positive bending moment of the adjacent span increases, and the negative bending moment of the non-edge support on the symmetrical side increases. When uneven lifting occurs at the non-edge support, the negative bending moment at the top of the pier at that support point increases, and the positive bending moment of the adjacent span on the symmetrical side increases. Stress analyses were conducted on the maximum changing cross-sections of each working condition, and the stress changes for each working condition are shown in Figure 18.

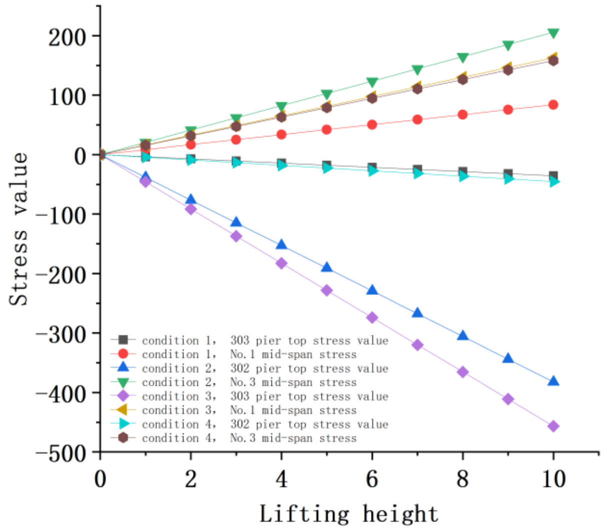



*Fig. 18 - Longitudinal deviation stress variation diagram ( unit : cm )*

Comparing Figure 6 and Figure 15, it can be seen that when there is uneven lifting at the edge support, the positive bending moment of the adjacent span increases, and the negative bending moment of the non-edge support side increases; when there is uneven lifting at the non-edge support, the negative bending moment of the pier top at this support increases, and the positive bending moment of the edge span on the symmetrical side increases. Stress analysis was carried out for the sections with the greatest changes in each working condition, and the stress changes for each working condition are shown in Figure 16.

From Figure 16, it can be seen that when there is uneven lifting at the edge support, the stresses at the section of the pier support and adjacent span on the symmetrical side increase, but the changes are small; when there is uneven lifting at the non-edge support, the stresses at the pier top section and the section of the edge span on the symmetrical side increase significantly, and the stress changes caused by uneven lifting increase linearly with the lifting height. The changes in the internal forces of the main beam caused by uneven lifting at non-edge supports have a greater impact than those caused by uneven lifting at edge supports. Therefore, in the lifting construction process, it is necessary to strictly control the synchronization and uniformity of lifting at each pier to prevent the occurrence of uneven lifting, which may lead to excessively large negative bending moment at the main beam support and positive bending moment at the midspan.

## RESULTS

This article takes the lifting project of the East Third Ring Expressway in Harbin as the research object, using cantilever rotation lifting and synchronous displacement lifting to lift the old bridge to the design elevation and connect it to the newly built elevated bridge. The construction monitoring of cantilever rotation lifting is carried out, and the structural internal force during the lifting process is analyzed through lifting tests and Midas Civil finite element analysis software, and the possible deviations are studied and analyzed. The following conclusions are drawn:

(1) The main beam internal force changes significantly more during the synchronous rotation lifting process than during the synchronous displacement lifting stage. The synchronous rotation lifting and synchronous displacement lifting processes have a relatively small impact on the structure's positive bending moment, but a significant impact on the negative bending moment at the top of the pier. Carbon fiber reinforced plates can be used to strengthen the main beam to prevent cracking due to negative bending moment at the steel distribution beam.

(2) The bridge alignment and deviation during the lifting construction are monitored to verify the correctness of the lifting method. Correction methods for deviations such as foundation reaction

DOI 10.14311/CEJ.2023.03.0032

correction, limit frame reaction correction, and main beam reaction correction after replacement of the bearing are proposed.

(3) Using the finite element extension method, this study investigates the distribution of internal forces in the main beam of a bridge during vertical lifting when longitudinal uneven lifting deviation occurs. When there is uneven lifting at the edge support points, the stress in the section of the symmetrical abutment support points and adjacent spans increases but changes only slightly. However, when there is uneven lifting at non-edge support points, the stress at the top section of the pier and the symmetrical adjacent spans increases significantly, and the sectional stress caused by uneven lifting increases linearly with the lifting height. The effect of uneven lifting at non-edge support points on the change of internal forces in the main beam is greater than that of uneven lifting at edge support points. Therefore, during the lifting construction process, it is necessary to strictly control the synchronized and uniform lifting of each pier to prevent the occurrence of uneven lifting conditions, which can lead to excessive negative bending moments at the main beam support points and excessive positive bending moments at the midspan.

(4) The lifting method used in this project is well-suited for urban bridge renovation to meet the needs of modern transportation development. This method has a high lifting speed, high safety, and high accuracy, and the proposed correction method has been proven to be efficient and accurate through simulation and construction verification.

## ACKNOWLEDGEMENTS

The authors gratefully appreciate the support from the Key R & D Plan Guidance Projects of Heilongjiang Province (GZ20220133).

## REFERENCES

[1] Qian Jihong & Chen Cheng. (2022). Application of bridge jacking technology in urban viaduct reconstruction. Engineering quality (06), 48-51 + 60.

[2] Jiang Yanfeng & Lan Wuyi. (2007) Research on key technology of integral lifting of bridge. Editorial Department of Building Structures. (eds.) The First National Symposium on Reinforcement Design and Construction Technology of Existing Structures (pp.577-579).

[3] Ge Yaojun & Xiang Haifan (2010). The concept and mission of sustainable development of bridge engineering. China Civil Engineering Society Bridge and Structural Engineering Branch. (eds.) The 19 th National Bridge Academic Conference Proceedings (Volume I) (pp.23-39). People 's Transportation Publishing House.

[4] LIU Gao,GAO Yuan,WU HongBo,MA JunHai,ZHANG XiGang & FU BaiYong.(2016).Status and prospect of technical development for bridges in China. Chinese Science Bulletin (4-5). doi:10.1360/n972015-00912.

[5] Min Liu & Dan M. Frangopol.(2004).Optimal bridge maintenance planning based on probabilistic performance prediction. Engineering Structures (7). doi: 10.1016/j.engstruct.2004.03.003.

[6] Itunumi Savage,John C. Eddy & Gregory I. Orsolini.(1999).Seismic analysis and base isolation retrofit design of a steel truss vertical lift bridge. Computers and Structures (1). doi:10.1016/S0045-7949(99)00027-9.

[7] Yuan Zhen, Zhu Wenxia & Xiao Han. (2013). Application of PLC synchronous lifting system in highway bridge reconstruction. Chinese and foreign highway (05), 170-173. doi : 10.14048 / j.issn.1671-2579.2013.05.076.

[8] Wu Yibin & Xu Lihua. (2017). Construction and control technology of large-tonnage synchronous jacking of urban interchange overpass. Construction Technology (20), 31-33 + 60.

[9] James C Thomson (2018).Jacked installation of underbridges. Proceedings of the Institution of Civil Engineers - Bridge Engineering (2). doi:10.1680/jbren.16.00032.

[10] ZHAO Y, WANG J F, PANG M. (2012). Integral lifting project of the Qifeng bridge. Journal of Performance of Constructed Facilities, 26(3):353-361 https://doi.org/10.1061/（ASCE）CF.1943-5509.0000211

[11] Song Chuanwang, Xie Shuaihu, Wang Jing, Sun Fanqing, Xia Xin, Ouyang Ganlin & Wu Zeju. (2018). Design of shift synchronous control system based on PLC.Instrument technology and sensors (08), 47-51.

[12] WANG Yan & CHEN Huai. (2008). Local stress analysis of No.0 beam section of long-span cantilever assembled continuous beam bridge. JOURNAL OF RAILWAY SCIENCE AND ENGINEERING (03), 23-27. DOI : 10.19713 / j.cnki.43-1423 / u.2008.03.005.

[13] Ning Baokuan, Hu Haitao, Xu Yongze & Yang Siting. (2020). Experiment on mechanical properties of reinforced concrete beams strengthened with prestressed carbon fiber sheet. Building Structure (06), 90-94. doi : 10.19701 / j.jzjg.2020.06.017.

[14] Roberto di Giulio,Zivko Bozinovski,Leo G.W. Verhoef... & Dionys Van Gemert.(2007).Externally Bonded Steel or Carbon Fiber Reinforcement. Research in Architectural Engineering Series.

[15] Beth Khan. (2015). Test analysis of continuous box girder bridge loading. Road and Automobile Transport (03), 196-201.