Article no. 15

THE CIVIL ENGINEERING JOURNAL 2-2023

EXPERIMENTAL STUDY ON REAL BRIDGE BEFORE AND AFTER SIMPLY SUPPORTED-CONTINUOUS REINFORCED CONCRETE HOLLOW SLAB

Bowen Hu, Jianxi Yang，Quansheng Sun and Chao Zhang

Department of Civil Engineering, Northeast Forestry University, Harbin，150040, China; sunquansheng@nefu.edu.cn

ABSTRACT

This article studies a concrete hollow slab simply supported-continuous actual engineering project in a certain city. Before the reinforcement of the bridge, there were cracks and exposed rebars, etc. In order to ensure the safe operation of the bridge, a reinforcement method of simply supported-continuous was adopted, prestressed steel strands are used to convert the simple-supported structure into a continuous structure, thereby improving the structural load-bearing capacity and overall integrity. Through conducting comparative analysis of load tests on a bridge before and after reinforcement, this article studies the improvement effect of the simply-supported-to-continuous reinforcement method on the bearing capacity of the bridge. A finite element model of the bridge was established, and comparative analysis was carried out before and after the reinforcement of the bridge. The bearing capacity and work performance of the bridge structure were evaluated. The research shows that the simply supported-continuous reinforcement method has a good improvement effect on the load-bearing capacity of the concrete hollow slab and can be used to improve the insufficient load-bearing capacity of the concrete hollow slab bridge in the city.

KEYWORDS

Concrete hollow slab, Simply supported-continuous, Old bridge strengthening, Finite element analysis, Static load test

INTRODUCTION

Current status of research

With the rapid development of economic construction, bridges have taken on increasingly heavy transportation tasks. The cost of bridge reinforcement and maintenance is 20% to 30% [1] of the cost of building a new bridge. Adopting a reasonable reinforcement method can not only effectively improve the bearing capacity of the bridge, but also has good economic and time benefits [2].

The prestressed concrete hollow slab beam bridge is widely used in China. Many of the bridges built in the early stage have cracks, damages, corrosion of steel reinforcement or strand, hinge joint failure and other bridge faults, resulting in bridge bearing capacity decreased. It cannot meet the needs of transportation development [3]. Therefore, adopting reasonable reinforcement measures to improve the bearing capacity and durability of the bridges and utilizing existing resources to ensure that the existing bridges with defects can still play their role is an important issue that engineers need to solve urgently.

Most of the time, the reinforcement measures are focused on the upper structure of the old bridges. The common reinforcement methods mainly include the steel plate bonding reinforcement method [4], the prestressed rod reinforcement method [5], changing structural system reinforcement method, etc. The "first simple support then continuous structure system" was proposed by the

Portland Concrete Association through research on the arrangement of continuous steel bars in the bridge deck panel above the bridge pier and the concrete transverse partition between the two prestressed beams at the end of the precast beams [6]. The method is to transform the old bridge by setting up temporary supports, pouring continuous segments, and then removing the temporary supports to achieve the transformation of the structure system. In order to improve the problem of insufficient bearing capacity of the bridge, this paper combines practical engineering to reinforce the hollow slab beam bridge by changing the structure system, converting its original simple support system into a continuous system, improving the stress status of the structure system, and enhancing the overall integrity of the structure. In order to study the performance of the reinforcement technology, a finite element analysis model of the whole bridge was established to compare the experimental results with the calculation values, analyze and evaluate the effect of the simply supported-continuous reinforcement technology on the improvement of the bridge bearing capacity.

Overview of the test bridge

The lower structure of a prestressed concrete hollow slab bridge in a certain city adopts a four-pillar concrete bridge pier and column bridge abutment, with pile foundations. The bridge has 21 plates per hole, and the span combination is 4x16m. The total width of the bridge is 20.5m, and the design load level adopts the China Bridge General Design Specification for highway-I Level Load. The bridge elevation view is shown in Figure 1.

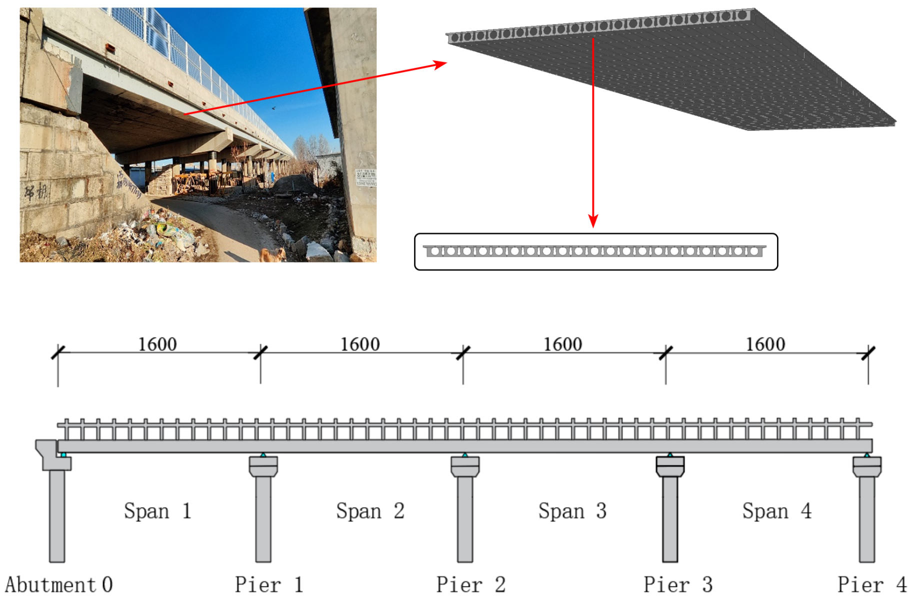


Fig.1 - Bridge type layout (unit: cm)

After many years of operation, the bridge has developed many diseases, such as multiple tensile cracks at the bottom of the beam, seepage and alkali, bearing disengagement, longitudinal cracks have appeared at the location of the negative bending moment at the top of the pier and at the mid-span position, scaling of concrete, water erosion at the corresponding drain hole of some edge plates, etc. Among them, the longitudinal cracks at the bottom of the hollow slab beam are shown in Figure 2.

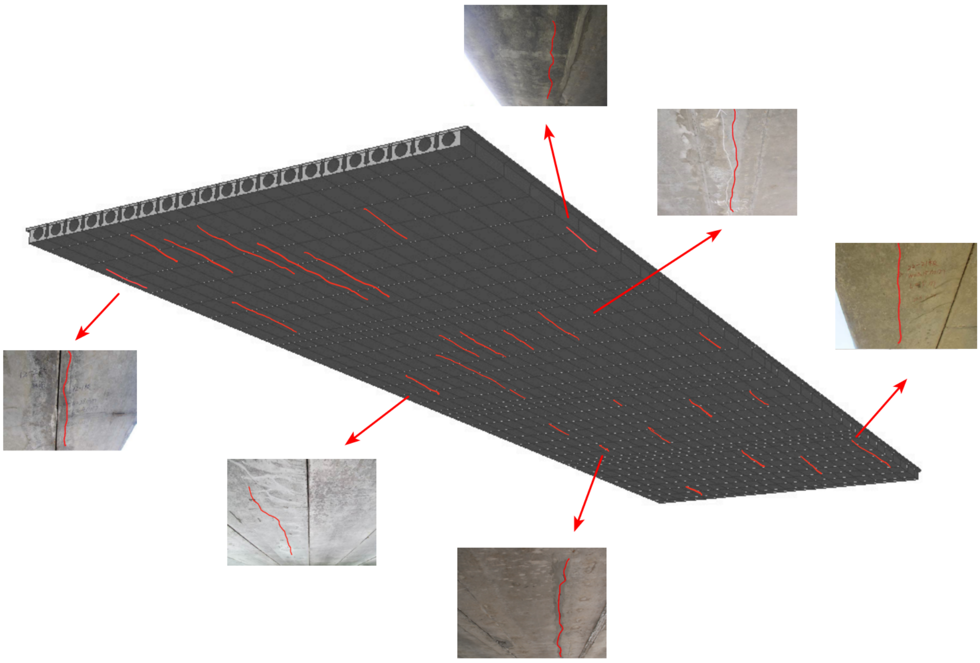


Fig.2 - Diagram of main crack diseases

There are 84 hollow slab beams in the bridge, of which 15.5% have longitudinal cracks at the bottom, with a length of 0.9m to 10m and a width of 0.06 to 0.15mm. The width does not exceed the limit value of the specification. Due to the long-term action of bending moments, concrete cracks of varying degrees may occur at the joints, but the resisting moment will also increase accordingly. Therefore, reinforcing or not reinforcing at the continuity joint may both lead to cracking [7]~[8]. 18% of the hinge joints have seepage and alkali diseases; 12 abutments have partial dislocation, there are 12 support abutments partial void in the whole bridge, 5% of the pier covers have vertical cracks at the top of the bending moment and mid-span position, with a length of 0.2 to 1m and a width of 0.06 to 0.20mm. The width does not exceed the limit value of the specification. The end position of the bent cap is subjected to water erosion, 10% of the bent cap end is concrete scaling, and the steel bars are corroded. Some piers have water erosion and steel bar corrosion expansion at the lower part, and vertical cracks in the concrete.

METHODS

Reinforcement measure

The reinforcement measures mainly aim to enhance the bridge's stability and strength by converting the hollow plates on both sides of the original bridge into solid plates, transforming the simple support system into a continuous structural system. Increasing the shear resistance of the cross-section and adding shear stirrups improve the shear capacity of the plate ends.

The main reinforcement method is to first remove the bridge pavement, chip away the concrete from the top slab and ends of the hollow slab, then insert reinforcement bars and thread prestressed steel strands into the hollow slab cavity, pour in concrete, and tension the prestressed steel strands after the concrete reaches the design strength. The prestressing steel used is high-strength low-relaxation galvanized steel strand with a tensile strength of 1860 MPa, nominal diameter of 15.2 mm, and nominal cross-sectional area of 140 mm. The prestressed steel strand N1 has a control stress of 1395MPa when anchored and pulled, and the prestressed steel strand N2 has a

DOI 10.14311/CEJ.2023.02.0015

control stress of 1209MPa when anchored and pulled. The hollow slab cavity on both sides of the original bridge deck is filled to become a solid slab, increasing the shear section and adding shear stirrups to improve the shear bearing capacity at the slab ends. The bridge deck is removed and relaid, and the concrete paving layer is thickened to improve the overall integrity of the structure and reinforce the transverse force of the bridge. The main reinforcement process is shown in Figure 3.

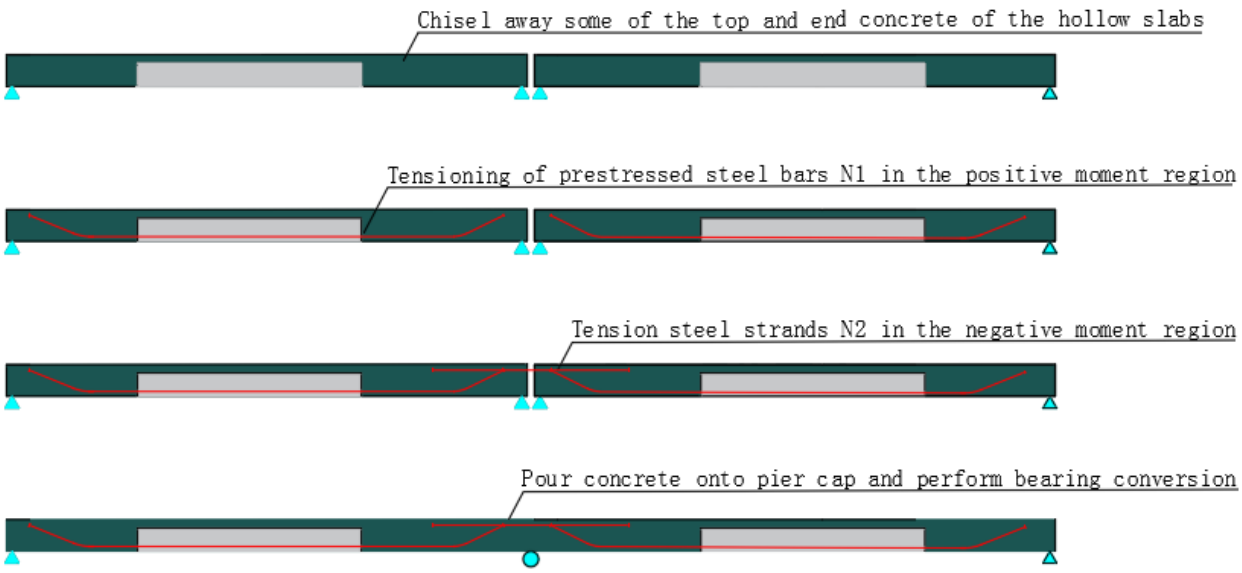


Fig.3 - Reinforcement process flowchart

The hollow slab at the top of the pier is connected with prestressed steel strands, converting the simple support system into a continuous structural system to improve the structural stress condition and increase the overall integrity of the structure. External pre-stressing is set inside the hollow slab cavity to increase the bearing capacity of the hollow slab. The cavity at the continuous end within a range of 5.5m on one side and at the simple support end within a range of 4m is filled with solid slab, converting the simple support system into a continuous system, reducing the bridge bending moment and improving the structure's shear resistance.

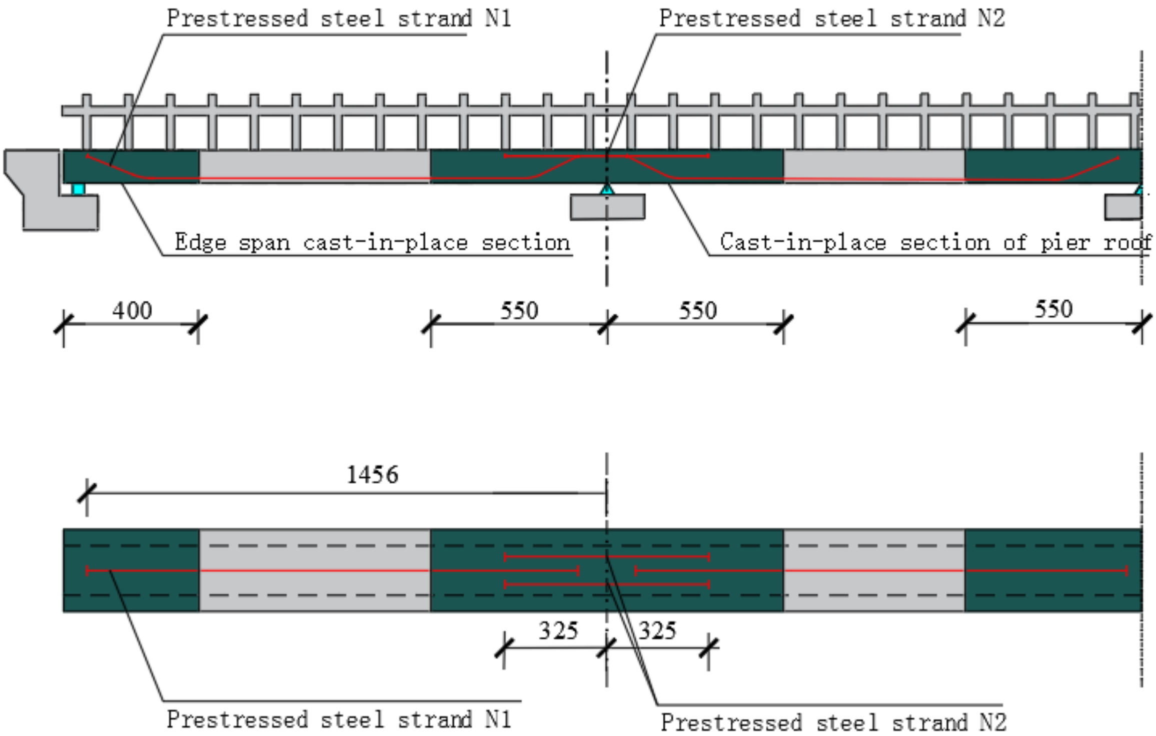


Fig.4 - Prestressed steel strand layout diagram (unit: cm)

Establishment of finite element model

Based on the original bridge design drawings, a three-dimensional finite element calculation model of the original bridge state was established through the finite element analysis software Midas/Civil, and a comparison was made between the new and old structures to perform simulation and analysis of the structure [9]. Before reinforcement, the 1x16m prestressed concrete simple-supported hollow slab was modelled with 597 nodes and 588 elements, as shown in Figure 5. After reinforcement, the 4x16m prestressed concrete continuous hollow slab was modelled with 1901 nodes and 2100 elements, as shown in Figure 6.

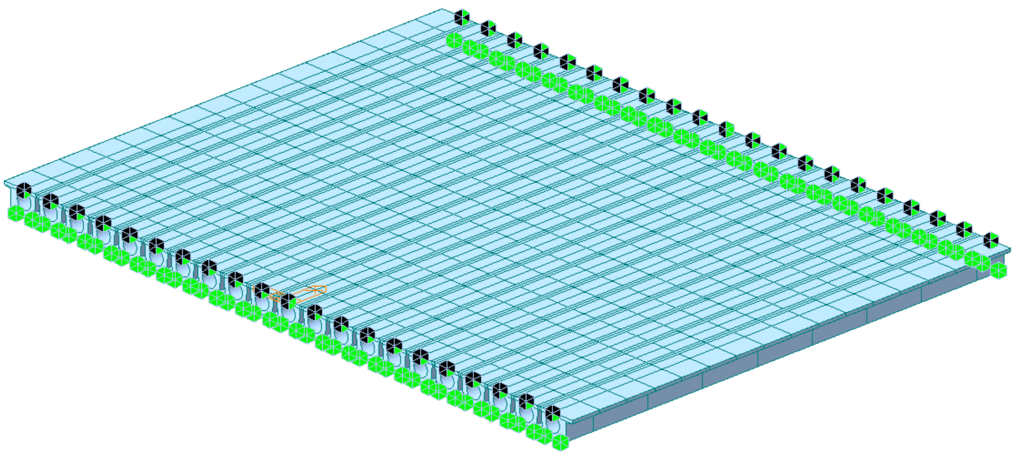


Fig.5 - Diagram of finite element model (before reinforcement)

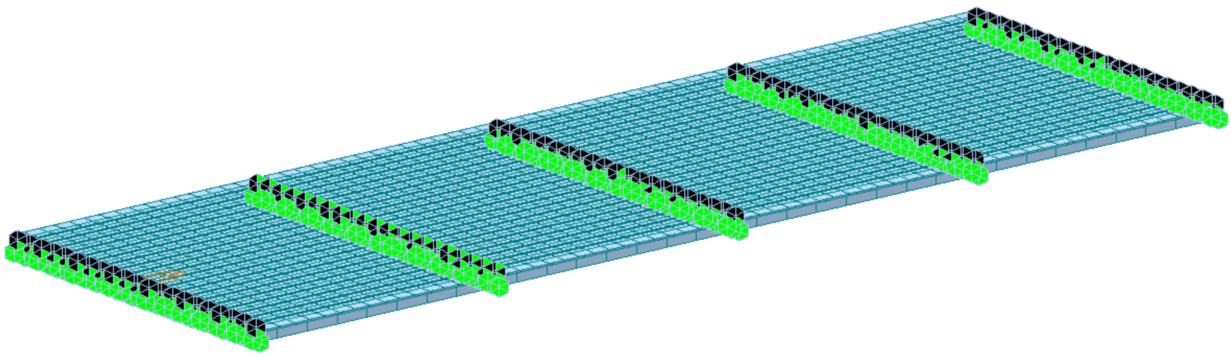


Fig.6 – Diagram of finite element model (after reinforcement)

The finite element software simulates the original bridge using material parameters and structural parameters provided by the completed bridge. The influence of highway- I level load design loads, total weight of the structure, second-phase dead loads, prestressed steel bars, shrinkage creep, non-uniform settlement, and temperature loads on the theoretical model is also taken into consideration. The material parameters can be found in Table 1.

Tab.1 - Main material parameter table

Material	Volumetric weight（kN/m^3）	Elastic modulus（MPa）	Ratio
C40 concrete	25.0	$3.5×10^4$	0.15
prestressed steel strand	78.5	$1.95×10^5$	0.3

Comparative analysis of the model before and after reinforcement

Before reinforcement, the model is simulated using a damage calculation model. The damage calculation model simulates the actual damage state of the bridge by adjusting the rigidity of the bridge model and the prestress [10]. To accurately simulate the degree of damage to the bridge, the most representative bridge damage model of the actual state is determined by comparing different working conditions and the actual state of the bridge.

1. Selection of damage condition of model before reinforcement

According to the analysis of parameters, reliable impact parameters are selected and the following working conditions with different damage states are proposed. The experimental condition of span cracking can be seen in Table 2.

Tab. 2 - Cracking damage condition

Condition	Damage state description
1	no damage, no stress reduction
2	stiffness reduction 10% + prestress reduction 10%
3	stiffness reduction 10% + prestress reduction 20%
4	stiffness reduction 10% + prestress reduction 30%
5	stiffness reduction 20% + prestress reduction 10%

All working conditions are in the same combination: dead load + secondary steel strand + secondary creep + secondary shrinkage + temperature load deflection values are compared with the actual measured deflection values to obtain a more realistic bridge damage model.

2. Determination of damage model

(1) Under the requirement of engineering survey level 2 conduct a composite level measurement and obtain the deflection value of each section by comparing the elevation difference between the measured elevation and the design elevation of each section. It can be seen from the data that the deflection at the mid-span of the bridge edge span is severe, and the maximum deflection value at the mid-span of the slight crack model reaches 12.7mm.

(2) Deflection analysis: Based on the damage calculation model, analyze the deflection under the same unfavourable loads. The deflection values of each calculated working condition are shown in Figure 7.

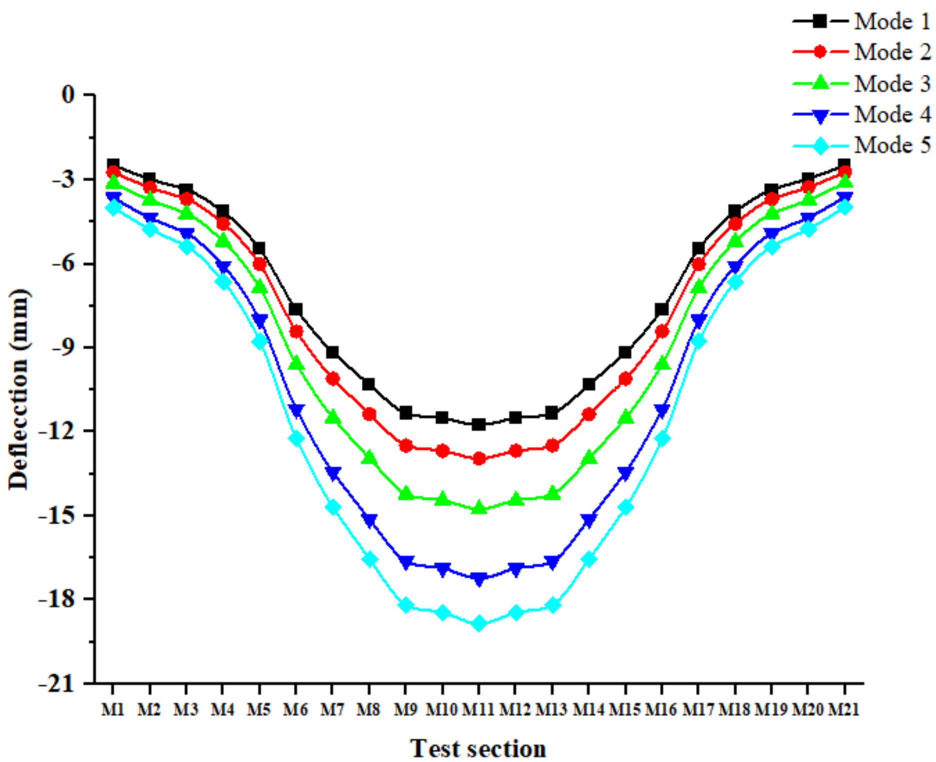


Fig.7 - Deflection value of cracking

As shown in Figure 7, under cracking conditions, the deflection value of the model in working condition two (10% reduction in stiffness + 10% reduction in prestress) is 14.09mm, which is more in line with the actual bridge situation. Therefore, working condition two (10% reduction in stiffness + 10% reduction in prestress) is adopted as the damage model of the bridge before strengthening in the cracking state.

3. Comparative analysis of theoretical values before and after reinforcement

In this section, a comparison analysis is made between the theoretical strain values and deflection values of the damaged model before reinforcement and the model after reinforcement. The result shows the improvement in the load-bearing capacity of the bridge after simple-support continuous reinforcement. The theoretical deflection values of the models before and after reinforcement can be seen in Table 3 and shown in Figure 8.

Tab.3 - Comparison of results before and after reinforcement

/	Before (simple support beam)	After (continuous beam)	Ratio
Max bending moment/（kN· m)	387.0	315.1	22.8%
Max shear /kN	5503.4	4566.9	20.5%
Max deflection/mm	12.94	8.72	32.6%

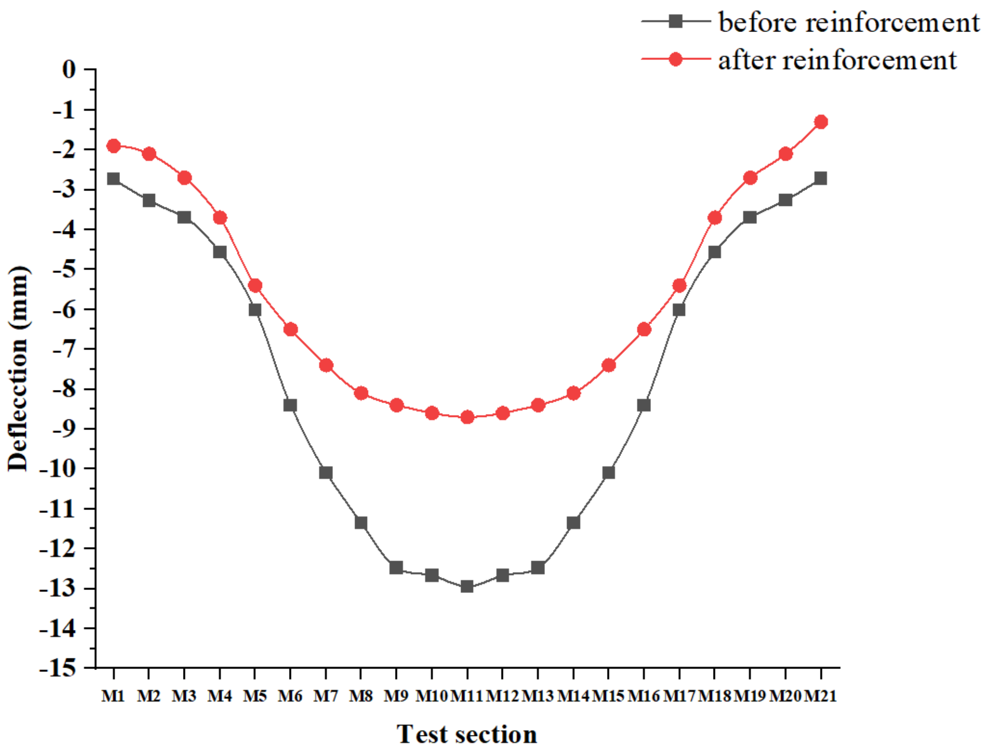


Fig.8 - Comparison chart before and after reinforcement

According to the comparison of the results in Table 3, it can be seen that the simple-supported to continuous reinforcement can effectively enhance the bearing capacity of the bridge, reduce the maximum deflection, and at the same time, the maximum shear force of the continuous beam is significantly increased compared to the simple support beam [11].

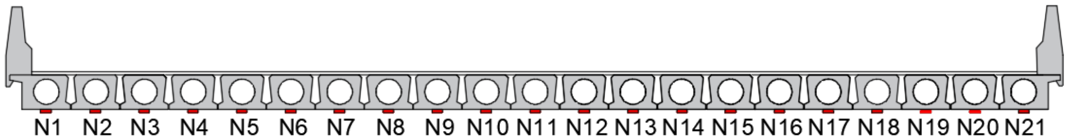
Static load test

In order to comprehensively evaluate the performance of the bridge under simple-supported to continuous reinforcement, static load tests are conducted on the bridge before and after reinforcement, respectively. This test measures the structural response of the bridge under static load and verifies the actual performance of the bridge structure [12]. By comparing the theoretical data before and after reinforcement with the experimental data, the actual stress state of the bridge is analyzed, and the improvement of the structural stress and the degree of improvement in structural performance after reinforcement are observed [13].

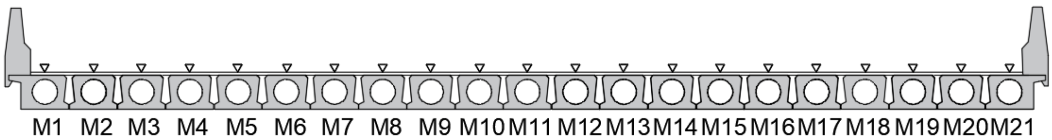
The static load tests are performed on the most unfavourable cross-section of the main beam under test load, using the JM3812 wireless static strain testing and analysis system and the

SDL1X21S-C1 precision level instrument. The arrangement of test points is shown in Figure 9.9a and Figure 9.9b.

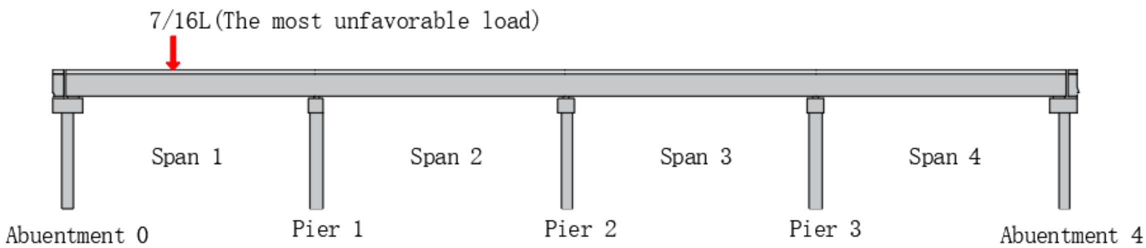
Static load test before and after reinforcement to measure the deflection and strain of main girder under test load. Dial indicator and digital strain gauge are used for testing. The arrangement of measuring points is shown in Figure 9.9c.



(a) The layout diagram of strain measuring points （▬ is strain measuring points）



(b) The layout diagram of deflection measuring point （▽ is deflection measuring point)



(c) Layout diagram of elevation measuring points

Fig.9 - Deflection and stress test sections

Two static load tests were conducted using the same model and tonnage of test vehicles. The most unfavourable effect of vehicle live load under controlled load should be simulated when selecting test vehicle tonnage. Since the design load of the bridge is highway- I level, highway- I level load is used as the control load in the test. Through the finite element software simulation calculation, it is proposed that four 45 tons vehicles be placed in parallel to simulate the effect of highway-I live load. The test load efficiency is calculated to be 1.01, which is in line with the loading efficiency range of 0.95~1.05 in the (Load Test Code for Highway Bridges) JTG/T J21-01-2015 [14]. Test is divided into medium load condition and partial load condition. Due to the similar conclusions, this paper only describes the medium load conditions [15]~[17], and the test conditions are shown in Table 5. The specific information of the loading vehicles is shown in Table 6, and the bridge load test schematic diagram is shown in Figure 10.

Tab.5 - Test conditions

Condition	test conditions	loading position	load efficiency
1	the span 1 7/16L	Span 1 7m	1.01

Tab.6 - Loading vehicle specification table (unit: kN)

Vehicle	Front axle	Middle axle	Rear axle	Total
1	90.1	180.2	180.2	450.5
2	90.0	180.2	180.1	450.3
3	89.8	179.6	179.5	448.9
4	90.1	180.3	180.1	450.5

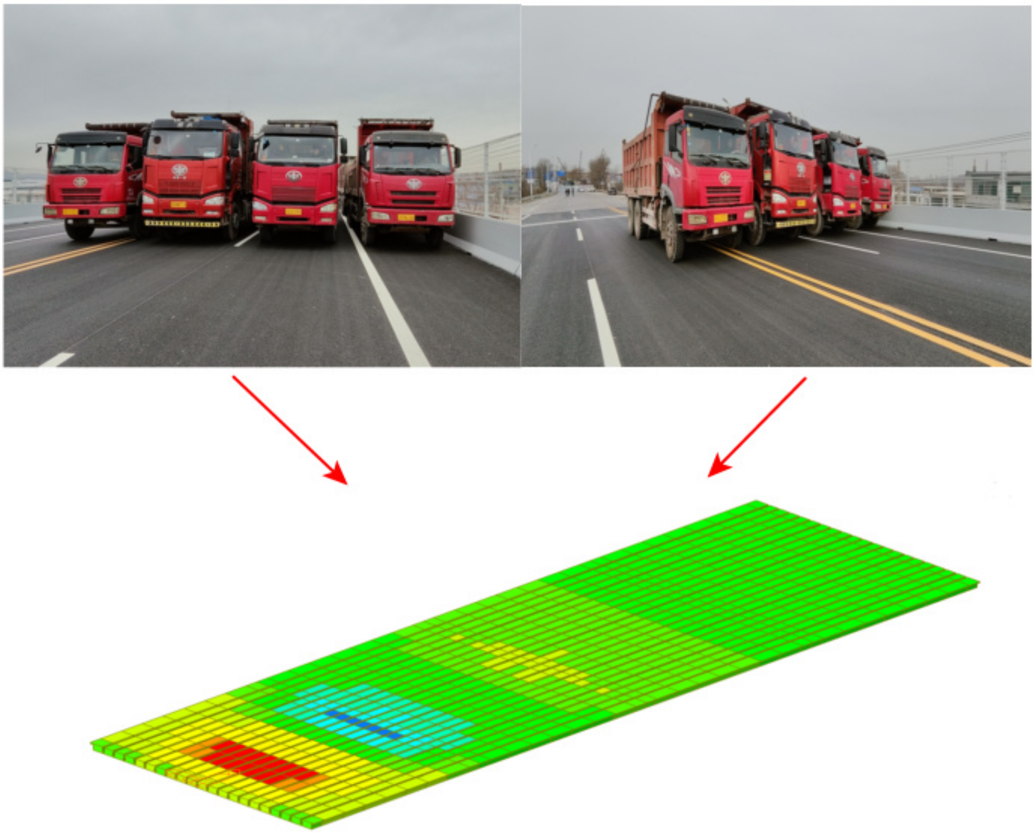
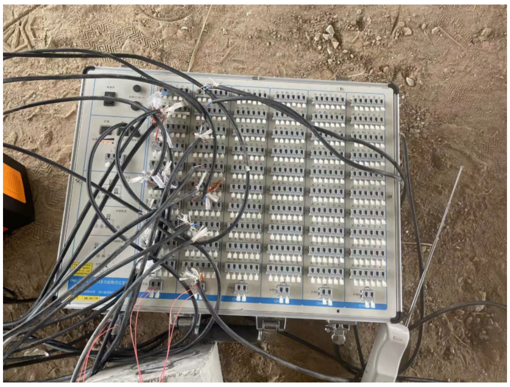


Fig.10 - Schematic diagram of bridge load test

The data acquisition device for bridge load test deflection is shown in Figure 11a). When the bridge is loaded and deflected, a corresponding displacement sensor placed on the deflection detector will measure the deformation displacement and transmit it to the terminal controller. The terminal controller will display the maximum and minimum deflection of the bridge bottom by processing the data with software. The data acquisition device for bridge strain is also shown in Figure 11b). By installing strain gauges at the force-bearing parts of the structure, the small deformation of the force-bearing parts can be measured, and the static strain under load of the structure can be obtained.

DOI 10.14311/CEJ.2023.02.0015

a) deflection measurement



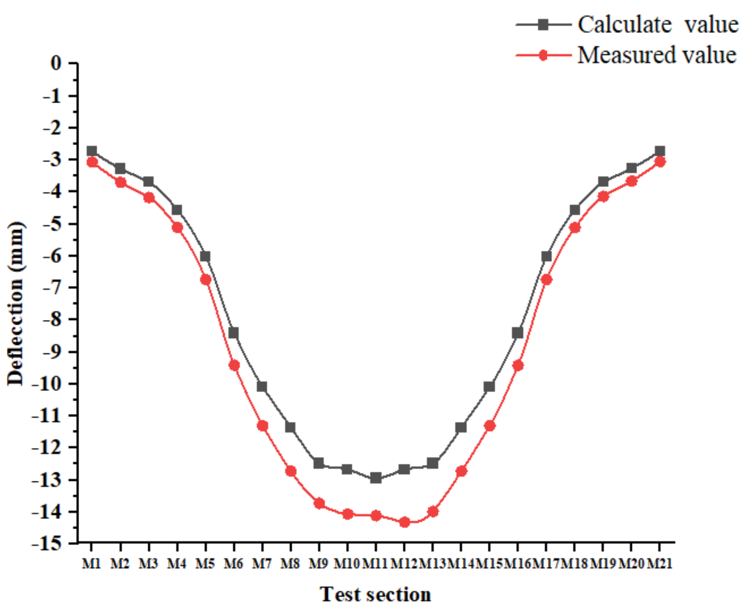
b) strain measurement

Fig.11 - Test measuring instruments

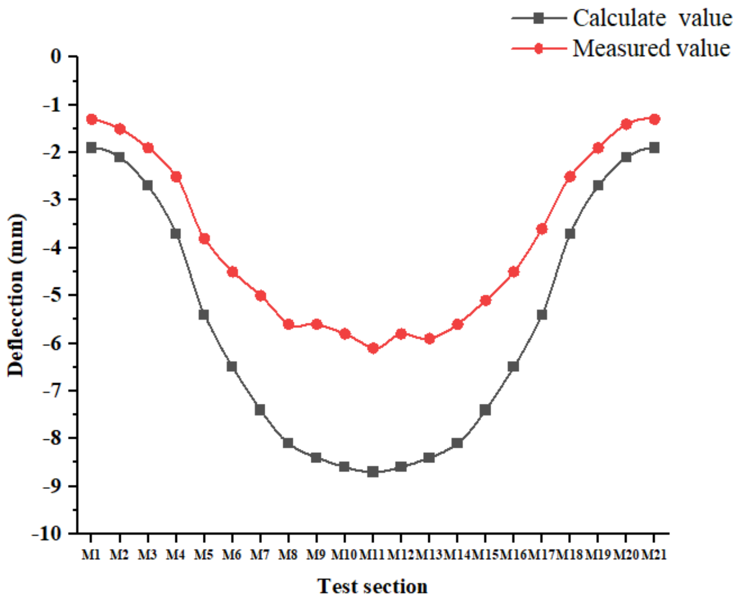
RESULTS

Analysis of deflection test results

Loading in the theoretical model and actual bridge, and analyze the change in the stiffness of the bridge before and after reinforcement through the analysis of the theoretical deflection values and actual measured deflection values at various test points. The comparison between the theoretical values obtained through finite element analysis and the actual measured values of the load test before and after reinforcement is shown in Figure 12.



(a) Measured and theoretical deflection value at before reinforcement (Units: mm)



(b) Measured and theoretical deflection value at after reinforcement (Units: mm)

Fig.12 - Measured and theoretical deflection value (unit: mm)

As shown in Figure 12, before reinforcement, the check coefficient of the deflection of the 1# cross-section was 1.09 to 1.13, exceeding the theoretical calculation value, indicating that the stiffness of the structure could no longer meet the requirements for use. After reinforcement, the check coefficient of the deflection of the 1# cross-section was in the range of 0.67 to 0.70, and the deflection of each cross-section was smaller than the theoretical calculation value.

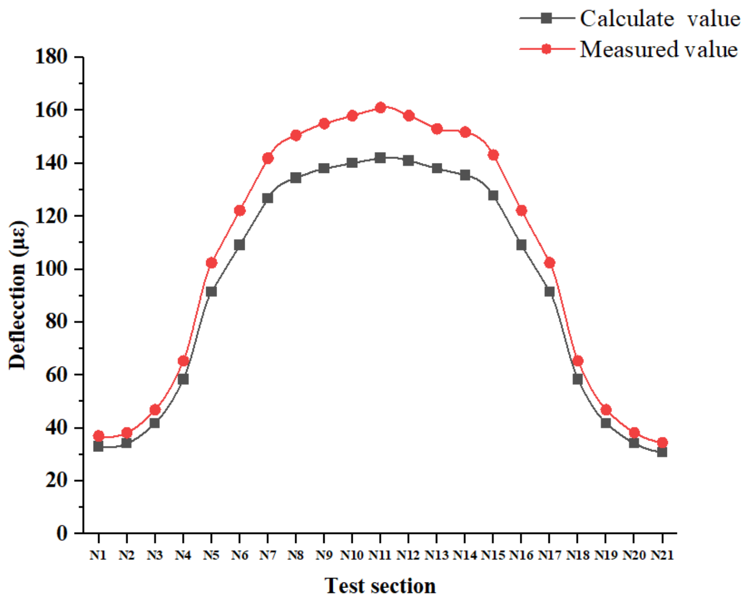
Tab. 7 - Comparison of deflection test results

Measuring point		M7	M8	M9	M10	M11	M12	M13	M14	M15
Before	Theoretical value(mm)	-10.1	-11.4	-12.4	-12.7	-12.9	-12.6	-12.4	-11.4	-10.1
	Measured value(mm)	-11.1	-12.6	-13.7	-14.1	-14.1	-14.3	-13.9	-12.6	-11.0
	Coefficient	1.10	1.11	1.10	1.11	1.09	1.13	1.12	1.11	1.09
After	Theoretical value(mm)	-7.4	-8.1	-8.4	-8.6	-8.7	-8.6	-8.4	-8.1	-7.4
	Measured value(mm)	-5.0	-5.6	-5.6	-5.8	-6.1	-5.8	-5.9	-5.6	-5.1
	Coefficient	0.68	0.69	0.67	0.67	0.70	0.67	0.70	0.69	0.69

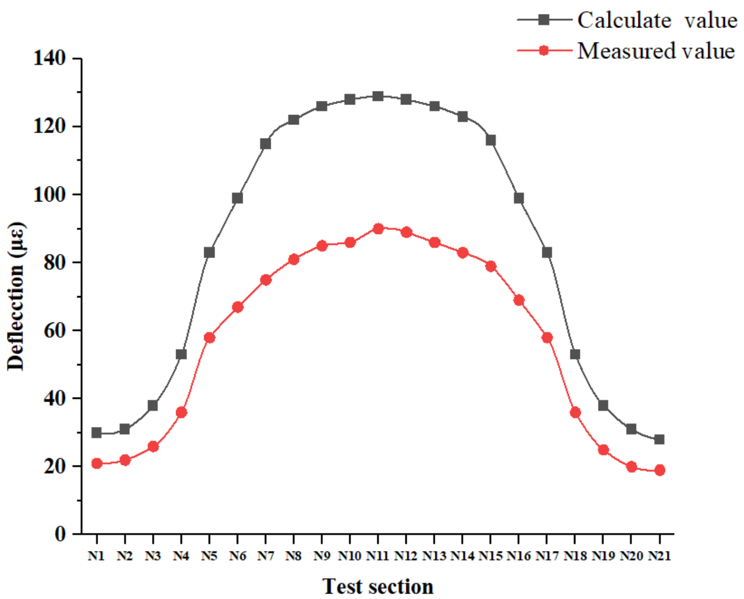
We can learn from Table 7 that the calculated values of bridge deflection obtained through finite element analysis after reinforcement have decreased compared to those before reinforcement., indicating that the structural stiffness has improved after reinforcement. The maximum improvement of the calibration coefficient after reinforcement is 0.46. This means that the structure's stiffness after reinforcement meets the required use and has some safety reserves, indicating that the reinforcement effect is obvious and the reinforcement method is reliable.

Analysis of strain test results

Stress and strain are key data that reflect the stress situation of the structure. By analyzing the stress response of the bridge structure, the stress situation of the structure can be clearly displayed [18]. The comparison between the theoretical values obtained through finite element analysis and the actual measured values of the load test before and after reinforcement for the test cross-section is shown in Figure 13.



(a) Measured and theoretical strain value at before reinforcement



(b) Measured and theoretical strain value at after reinforcement

Fig.13 - Measured and theoretical strain value

The data in Figure 13 shows that the maximum calibration coefficient of deflection at section of span before reinforcement was 1.13, and section were greater than the theoretical calculation value, indicating poor overall integrity of the structure. After reinforcement, the maximum verification coefficient of deflection at each section was 0.70, and the deflection at each section was less than the theoretical calculation value.

Tab. 8 - Comparison of strain test results

Measuring point		N7	N8	N9	N10	N11	N12	N13	N14	N15
Before	Theoretical value(με)	127	134	138	140	142	141	138	134	127
	Measured value(με)	141	151	155	158	161	158	153	151	143
	Coefficient	1.11	1.12	1.12	1.13	1.13	1.12	1.11	1.12	1.13
After	Theoretical value(με)	115	122	126	128	129	128	126	122	115
	Measured value(με)	77	83	85	86	90	89	81	83	79
	Coefficient	0.67	0.68	0.67	0.67	0.70	0.70	0.64	0.68	0.69

As shown in Table 8, the theoretical strain values obtained through finite element analysis and the actual measured values of the load test after bridge reinforcement have decreased compared to before reinforcement, indicating that the overall integrity of the structure has improved after reinforcement. No new cracks have been found after reinforcement, and the structure is capable of meeting usage requirements and has a certain safety reserve.

CONCLUSION

This paper focuses on a prestressed hollow slab beam bridge in a certain city that has developed diseases such as longitudinal cracks due to long-term disrepair, which requires reinforcement treatment. The bridge was reinforced using the system transformation method, which converted the original simply supported hollow slab system into a continuous beam system, optimizing the structural mechanics of the bridge. The Midas/Civil finite element model was utilized to establish the model before and after reinforcement, and the theoretical values extracted from the finite element model were compared and analyzed with the actual measured values from the load test. The following conclusions were drawn:

(1) The calculated values of strain and deflection are in good agreement with the measured values, with small deviations and a basic similarity in the distribution of the measured and theoretical data for each test item.
(2) The reinforcement was most effective in the 7/16L of the 1st span, where the deflection decreased by 8.00 mm, a decrease of 56.7%, and the strain decreased by 71 μ**ε**, a decrease of 44.0%. This greatly improved the load-bearing capacity of the bridge.
(3) Simply supported-continuous reinforcement technology can effectively improve the cracking performance of the main beam, reduce the deflection, and increase the structural stiffness and load-bearing capacity. This method is suitable for the reinforcement of hollow slab bridges in cities.
(4) The design method proposed in this paper significantly increases the load-bearing capacity and stiffness of the bridge, and the bridge operates well after reinforcement. The simply supported-continuous reinforcement method is not only suitable for the reinforcement of slab beams, but also for T-beams. Through the reinforcement and reconstruction method of the bridge, it provides a reference for similar bridge reinforcement and reconstruction in the future.

REFERENCES

[1] Lufei & Pengcheng. (2013). Analysis, comparison and application of common bridge reinforcement methods. Highway (10), 121-123.
[2] Zheng Zhaodong. (2013). Post-evaluation of bridge reinforcement. Scientific and technological information (15), 378 + 440.
[3] Wang Shichao, Wang Chunsheng, Wang Qian, Tian Xiaofeng & Duan Lan. (2018). Flexural behavior

of full-scale prestressed concrete hollow slab beams strengthened with composite reinforcement. Journal of Transportation Engineering (02), 31-41.doi : 10.19818 / j.cnki.1671-1637.2018.02.004.
[4] Hu Zhaofang, Chen Runshui. (2002). Research and examples of reinforcement and lifting technology of old highway bridges. Highway (02), 14-16.
[5] Yuan Quan, Zhang Song. (2003). Reinforcement design of a concrete cable-stayed bridge[J]. East China Highway ,(5):3-5.
[6] Shen Yuqiang. (2009).Mechanical analysis of structural continuous bridge system transformation after simply supported (master 's degree thesis, Chongqing Jiaotong University).https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD2011&filename=2010160918.nh
[7] Maher K.Tadros, Joseth A.Ficenec. (1993). A new technique to continuity in pre-stressed concrete members [J]. PCI Joural, 38 (5):30-38
[8] Robert J.Peterman, Julio A. Ramirez. (1993). Behavior and strength of bridges with full-span pre-stressed concrete form panels [J]. PCI Joural ,43(3):80-91.
[9] Zhu Hanbing,Yang Yaxun & Fan Weiya.(2015).External Prestressing Bridge Reinforcement Technology Review. MATEC Web of Conferences.
[10] Zhao Guodong,Duan Shixin,Sun Bo & Yuan Xiaohua.(2021).Application on large-span reconstructed structure with external prestressing technology. Journal of Physics: Conference Series(4). doi:10.1088/1742-6596/1885/4/042042.
[11] Xin Lijuan, He Huanan & Chen Xu. (2013). Internal force analysis before and after the continuous reinforcement of the old bridge. Low temperature building technology (08), 67-69.
[12] JTG 3362-2018 Specifications for design of highway reinforced concrete and prestressed concrete br idges and culverts [S]. P.R. China, Ministry of Communications, 2018.
[13] Sun Quansheng & Liang Daoyu. (2019). Analysis of the design effect of external prestressed reinforc ement of urban low box girder. Low Temperature Building Technology (09), 56-59+98. doi:10.13905/j.cnki.d wjz.2019.09.014.
[14] Liu Huichao. (2015). Research on Reinforcement Technology of Continuous Girder Bridge of Prestressed Concrete (Master's Thesis, Chang'an University)
[15] Kim SangHyun,Park JongSup,Jung WooTai,Kim TaeKyun & Park HeeBeom. (2021). Experimental Study on Strengthening Effect Analysis of a Deteriorated Bridge Using External Prestressing Method. Applied Sciences(6). doi:10.3390/APP11062478..
[16] Zhou Yongjun, Zhao Yang, Zhao Yu, Cao Qun & Li Zhen. (2021). Study on the impact coefficient of simple support girder bridge based on dynamic load test load efficiency. Vibration and Shock (20), 207-216. doi:10.13465/j.cnki.jvs.2021.20.026.
[17] Wang Ziqiang., 2019. Load Test of Prestressed Concrete Continuous Box Girder Bridge. The wind of science and technology, vol. 400(32), 119., doi.10.19392/j.cnki.1671-7341.201932099
[18] Kim SangHyun,Park JongSup,Jung WooTai,Kim TaeKyun & Park HeeBeom. (2021). Experimental Study on Strengthening Effect Analysis of a Deteriorated Bridge Using External Prestressing Method. Applied Sciences(6). doi:10.3390/APP11062478.