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EXPERIMENTAL ANALYSIS OF COVERING LAYER-PRESTRESSED WIRE ROPE REINFORCED BRIDGES

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ABSTRACT

With the application of prestressed steel wire rope in bridge reinforcement project, mortar or composite mortar as the embedded material of steel wire rope is also gradually exposed to low strength, easy to crack, easy to fall off, and affect the durability of the wire rope and other shortcomings. Polyurethane-cement (PUC) composite, as a polymer concrete material, is characterized by light weight, high strength, high toughness, and good adhesion and corrosion resistance. In this paper, two kinds of reinforcement methods, PUC prestressed steel wire rope and prestressed steel wire rope, were used respectively, and the load test before and after reinforcement was carried out, and the effectiveness of the reinforcement methods was verified through the collection of parameter information, such as strain and deflection, before and after reinforcement. Although the PUC-strengthened bridge is less than the mortar-strengthened bridge each piece of girder arranged 15 pre-stressing steel wire rope, but the two bridges strengthened girder stiffness increase amplitude is comparable, under the action of the symmetrical load, the middle girder are increased by 13%, after the reinforcement of the bridge in the measured deflection to meet the highway load standard requirements of class Ⅱ. The PUC overlay layer has a good adhesion with the original beam body, and no cracks were found. However, the mortar overlay layer has cracks of varying degrees. The crack width is 0.15 mm, and the average spacing is approximately 150 mm.

KEYWORDS

Covering layer -prestressed wire rope, Reinforced bridges, Comparative analysis, Load tests

INTRODUCTION

Bridges are an important part of highway transportation and have a pivotal role in the road transportation business [1]. With the continuous development of social and economic development, transportation is getting busier and busier, and bridges are playing an irreplaceable role as the throat of highway transportation [2,3].

With the development of social and economic development, the transportation industry unprecedented prosperity, vehicles as a carrier of transportation, compared with the previous changes have occurred greatly, to the vehicle load and flow of the increase in the most obvious [4-

8]. Due to rapidly increasing vehicle loads, natural conditions such as acid rain, air and temperature, a series of diseases such as stress cracks, concrete deterioration, and corrosion of steel reinforcement have occurred in the bridge structures [9-12]. These man-made and natural factors affect bridges to varying degrees, mainly in terms of structural safety, suitability and durability, and ultimately reduce the load-bearing capacity of bridges, jeopardizing their long-term operation. The insufficient load carrying capacity of old bridge structures has long been a common problem across the world [13,14].

Polyurethane cement (PUC) composites belong to polymer concrete materials, which are characterized by light weight, high strength, high toughness, and the material itself has good bond strength and resistance to acid and alkali corrosion [15,16]. PUC prestressed wire rope reinforcement method is embedded with prestressed wire rope in polymer concrete, which can solve the problem of pre-cracked cracks that cannot be closed actively in passive reinforcement [17]. The use of PUC to replace composite mortar as the embedding material for prestressing steel wire ropes not only solves the problem of durability of reinforced beams due to cracking and peeling of composite mortar, but also the material itself can be reinforced for the main beams [18,19]. Kexin Zhang [20] and others conducted an indoor experimental study on PUC-prestressed wire rope reinforced beams, considering parameters such as the thickness of PUC, the configuration of prestressed wire rope. The results of the study show that compared with composite mortar-prestressed wire rope reinforced beams, PUC-prestressed wire rope reinforced beams show a significant increase in load carrying capacity and stiffness, especially after the yielding of ordinary steel reinforcement. However, the research on PUC-prestressed wire rope reinforced beams is limited to indoor tests and theoretical studies, and there is a need to study PUC-prestressed wire rope reinforcement of actual bridges. In this paper, two kinds of reinforcement methods, PUC-prestressed steel wire rope and composite mortar-prestressed steel wire rope, were used for actual bridges, and load tests were carried out before and after reinforcement, and the validity of the reinforcement methods was verified by collecting information on the parameters such as strain and deflection before and after reinforcement.

ENGINEERING BACKGROUND

In this paper, two T-structured bridges with similar construction age and structure were selected as the dependent projects, and the design of two bridge reinforcement was completed by using PUC prestressing steel wire rope reinforcement and composite mortar prestressing steel wire rope reinforcement respectively, and the verification test of the reinforcement effect was carried out.

The bridge one is located in Heilongjiang Province, , the bridge was built in the 1980s. The upper structure of the bridge is 5×20.0 m prefabricated reinforced concrete T beams, each transverse span 5 T beams, T beam flange plate width of 1.6 m, T beams are arranged between the cross beams, the bridge floor net width of 7 m + 2×1.0 m.

The bridge two is located in Heilongjiang Province, which was also built in the 1980s and has been in service for more than 30 years. The upper structure of the bridge is a typical concrete T-beam structure, with a total length of 40 m and a single-hole span of 20 m. The cross section of the bridge is composed of 5 T beams, the width of the flange plate of the T beam is 1.8 m, the total width of the bridge is 10.0 m, and the cross section arrangement is 2×1 m (collision barrier) +8 m (carriageway).

After the actual inspection of the two bridges, it was found that the surface of the main girder had more stress cracks and the load carrying capacity did not meet the requirements, and the main girder disease diagram is shown in Figure 1. In order to improve the bearing capacity of the main girder and extend the operation time, the two bridges were strengthened.

(a) - Main beam cracks *(b) - Concrete deterioration*

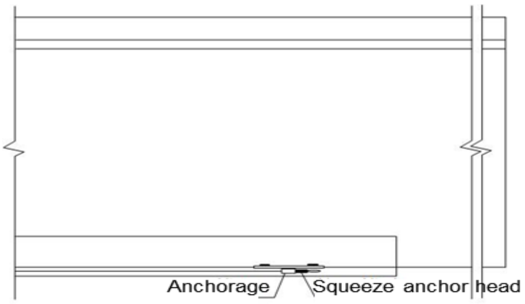
Fig. 1 - Main girder disease diagram

The overlay layer - prestressed steel wire rope reinforced beam has the advantages of simple construction and no impact on the clear height under the bridge. First, make a groove at the end of the beam and weld the anchor. Secondly, tension and anchor the prestressed steel wire rope. Secondly, pour PUC material or mortar material. Finally, remove the formwork. Polyurethane cement - Reinforcement method for prestressed steel wire ropes: Active force reinforcement of prestressed steel wire ropes, passive force participation of polyurethane cement. The polyurethane cement covering layer can reduce the usage of prestressed steel wire ropes and enhance their durability.

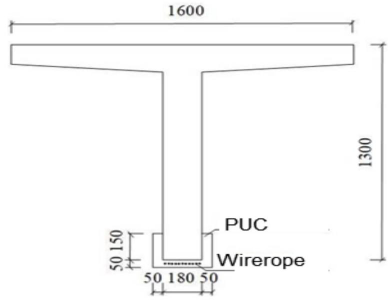
REINFORCEMENT SCHEME

Reinforcement Scheme for Bridge Number One

The structural design of the bridge is based on the traffic conditions in the 1980s, and the design load is the old standard automobile -20, trailer -100. The bridge is located on the main highway of the heilongjiang Province, and from the time it was built to the present, the traffic flow on the route has been so great that the bridge has been overloaded for a long time. The main girder after a long period of operation and caused the stiffness and bearing capacity of different degrees of reduction in the main girder girder body appeared a number of cracks, after the identification of the bridge has not been able to meet the current demand for traffic, can not meet the highway Ⅱ load standards, the traffic management department has decided to strengthen the bridge to ensure highway operation safety, so that after reinforcement the bridge to meet the highway Ⅱ pass load standards. Lateral view, cross-section view and steel wire rope arrangement view of bridge one are shown in Figure 2.



(a) - Lateral view



(b) - Cross-section view

(c) Steel wire rope arrangement of beam bottom

Fig .2 - Lateral view, cross-section view and steel wire rope arrangement view of bridge one (Unit:mm)

As shown in Figure 2, the main girder is reinforced with PUC prestressing steel ropes in the longitudinal direction of 16 m. 11 prestressing steel ropes are arranged at the bottom of the T-beam, and the thickness of the PUC is 50 mm, and the height of the side is 150 mm, so as to ensure that the structural load carrying capacity and stiffness can meet the specification requirements. The bridge one reinforcement diagram is shown in Figure 3, which shows the construction of prestressing wire ropes, the erection of pouring formwork, and the mixing and pouring of PUC material, respectively. The density of PUC material used in the actual construction process is 1500 kg/m^3, according to the mass ratio of material preparation, polyol: isocyanate: cement = 1:1:2, with an electric mixer in an iron bucket for 3 min (Figure 3c), and then manually poured (Figure 3d), pouring is completed, and then in a dry environment maintenance 7 d.

Fig .3 - Reinforcement figures of bridge one

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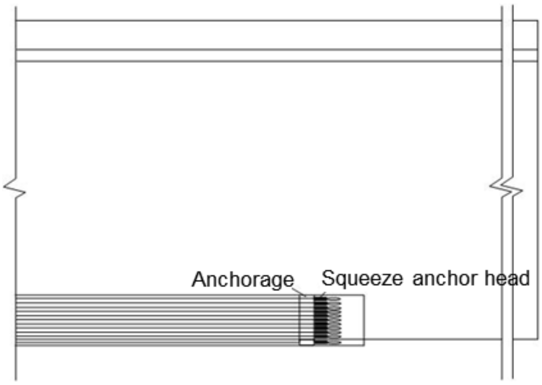
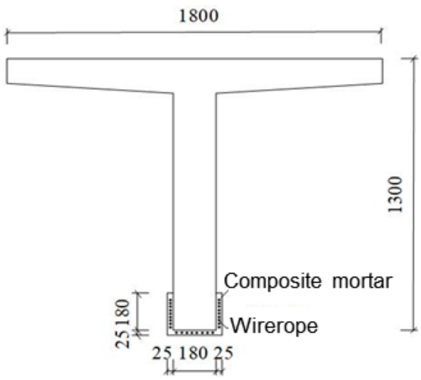
Reinforcement Scheme for Bridge Number Two

The bridge two is located in Jixi City, Jidong County, also built in the 1980s, the design load for the old standard automobile -20, trailer -100. From its completion to the present, the route has seen a tremendous amount of traffic and the bridges have been overloaded for a long time. The main girder has been operated for a long time and the stiffness and bearing capacity have been reduced to different degrees, according to the bearing capacity calculation and the results of the bridge load test, the bridge has not been able to meet the demand of the traffic volume, and can not meet the highway Ⅱ load standard, the traffic management department has decided to strengthen the bridge to ensure the safety of highway operation, so that the strengthened bridge reaches the highway Ⅱ pass load standard.

The bridge adopts the composite mortar prestressing wire rope reinforcement method, each piece of T-beam arrangement of 26 prestressing steel wire ropes, respectively, along a bottom surface and two sides of the arrangement, as shown in Figure 4, the bottom surface of the arrangement of 8, the two sides of the arrangement of 9 steel wire ropes, prestressing steel wire rope arrangement range of the main beam within the longitudinal range of 14 m, steel wire rope embedded in the 25 mm thickness of the composite mortar. Compared with the bridge one, this bridge has 15 more prestressing wires per girder than bridge one. The reinforcement diagram of the bridge two is shown in Figure 4, which are the prestressed steel wire rope tension diagram and the bottom diagram of the reinforced beam respectively. The reinforcement diagram of the bridge two is shown in Figure 5.



(a) - Lateral view



(b) - Cross-section view

(c) - Steel wire rope arrangement of beam bottom

Fig .4 - Lateral view, cross-section view and steel wire rope arrangement view of bridge two (Unit:mm)

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Fig .5 - Reinforcement figures of bridge two

STATIC LOAD TEST OF BRIDGE BEFORE AND AFTER REINFORCEMENT

In order to comprehensively evaluate the stress performance of the two solid bridges after reinforcement, field load tests before and after reinforcement were carried out on bridge one and bridge two, respectively, to verify the actual reinforcement effect of the bridge. The reinforcement effect was evaluated by the measured results before and after reinforcement, and a comparative analysis was made between the PUC prestressing wire rope reinforcement method of the bridge one and the composite mortar prestressing wire rope reinforcement method of the bridge two.

Test Load Determination

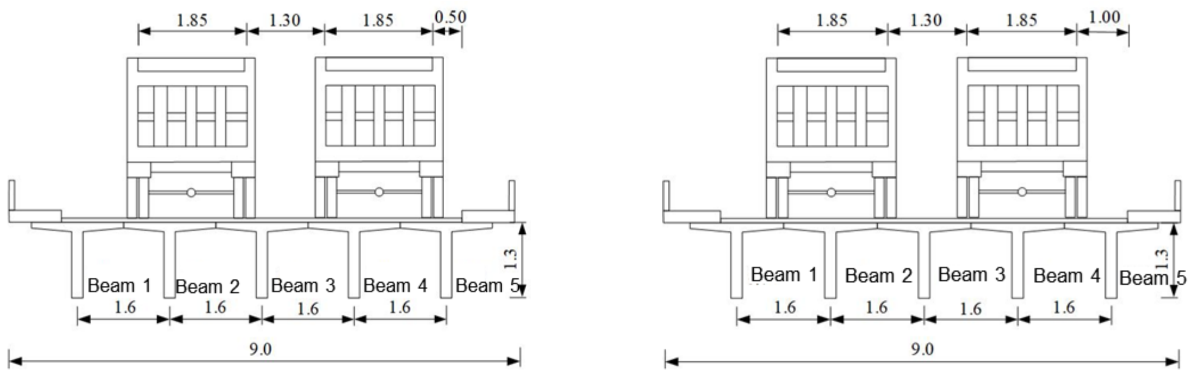
The load is distributed according to the most unfavorable position to ensure that the load test efficiency η is between 0.95 and 1.05. The load is distributed according to the most unfavorable position, and in order to accurately simulate the highway-class-II loads of the two bridges, two 42 t loaded cars and two 40 t loaded three-axle trucks are used as the test loads, respectively. Unbalanced load and medium-load tests were carried out by simulating the highway class II load standard after accurate weighing. The vehicle loads used for the load tests on the bridge one and two are shown in Tables 1 and 2, respectively. Each time the load is stabilized for a period of time, the data of each measurement point is collected. The solid bridge reinforcement diagrams are shown in Figures 6 to 9.

Tab. 1 - Loading vehicle parameters before and after reinforcement (Bridge one)

Vehicle		Front axle weight(kN)	Central axis weight(kN)	Rear axle weight(kN)	Front to middle wheelbase(m)	Mid rear wheelbase(m)
Before reinforcement	A	81.4	162.8	162.8	3.5	1.35
	B	84.2.	168.4	168.4	3.5	1.35
After reinforcement	A	83.4	166.8	166.8	3.5	1.35
	B	84.6	169.2	169.2	3.5	1.35

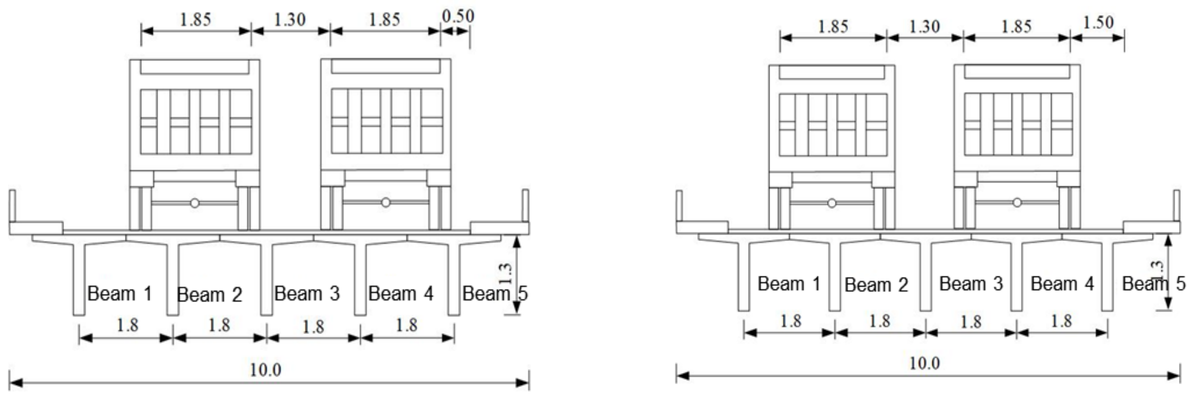
Tab. 2 - Loading vehicle parameters before and after reinforcement (Bridge two)

Vehicle		Front axle weight(kN)	Central axis weight(kN)	Rear axle weight(kN)	Front to middle wheelbase(m)	Mid rear wheelbase(m)
Before reinforcement	A	79.3	158.6	158.6	3.5	1.35
	B	78.6	157.2	157.2	3.5	1.35
After reinforcement	A	79.0	158.0	158.0	3.5	1.35
	B	80.6	161.2	161.2	3.5	1.35



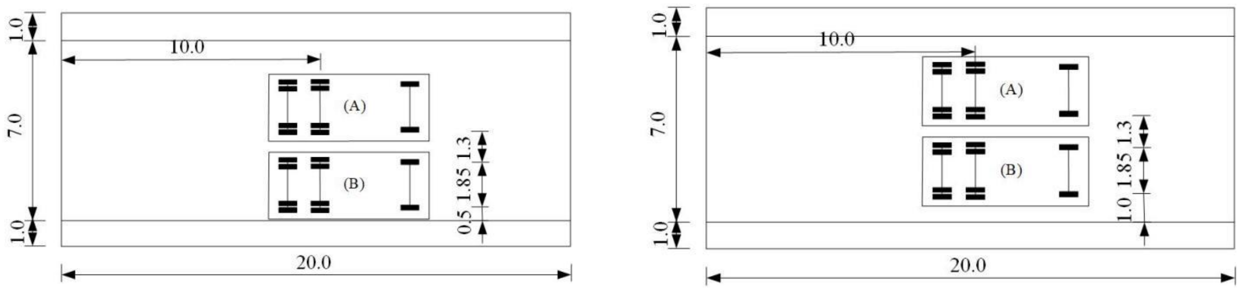
(a) - Cross section under the eccentric load *(b) - Cross section under the symmetrical load*

Fig .6 - Load cross-sectional view of bridge one (Unit:m)



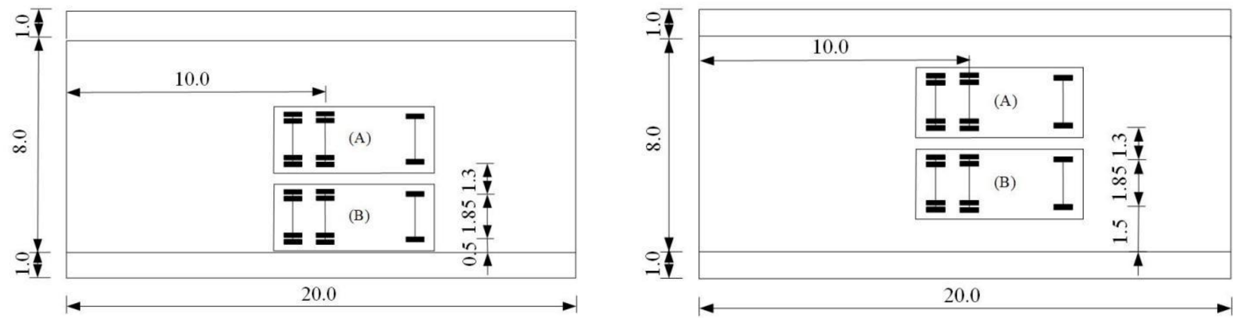
(a) - Cross section under the eccentric load *(b) - Cross section under the symmetrical load*

Fig .7 - Load cross-sectional view of bridge two (Unit:m)



（a）- Cross section under the eccentric load　（b）- Cross section under the symmetrical load

Fig .8 - Load cross-sectional view of bridge one (Unit:m)

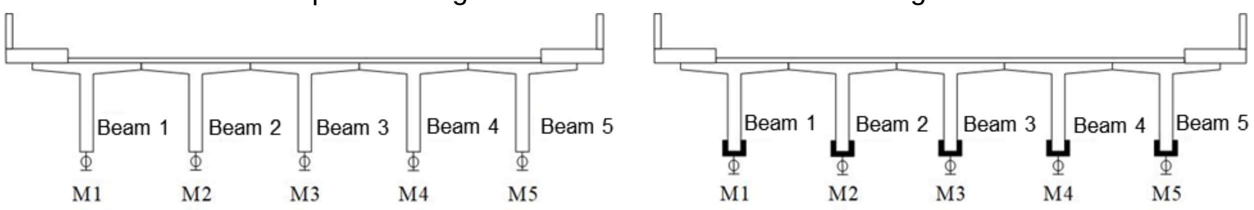


（a）- Cross section under the eccentric load　（b）- Cross section under the symmetrical load

Fig .9 - Load cross-sectional view of bridge two (Unit:m)

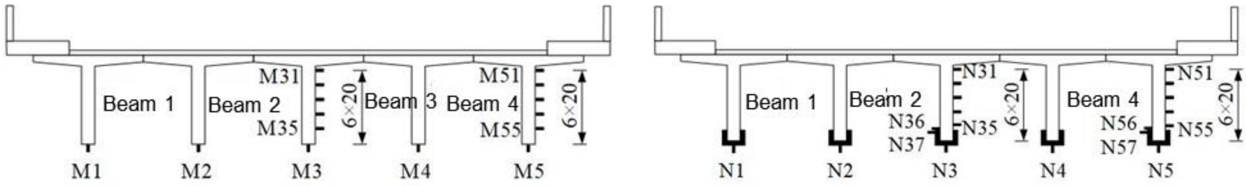
Test Point Arrangement

In order to test the deflection of the girder, a deflectometer is installed at the bottom of the girder in the span of each T-beam to test the deflection value of each piece of the main girder under the test condition, the deflection of the bridge one is shown in Figure 10, and the deflection arrangement of the bridge two is the same as that of the bridge one. Before and after the strengthened girder strain measurement point arrangement is shown in Figure 11, the real bridge two strain measurement point arrangement is the same as the real bridge one.



（a）- Before reinforcement　（b）- After reinforcement

Fig .10 - Deflection test point layout of bridge one



(a) - Before reinforcement *(b) - After reinforcement*

Fig .11 - Strain gauge layout of bridge one

LOAD TEST RESULT

Deflection Test Results

The deflection values of the load test before and after the reinforcement of the real bridge one and two are shown in Table 3 and Table 4, and the deflection graphs are plotted according to the deflection data as shown in Figure 12 and Figure 13.

Tab. 3 - Deflection under the eccentric load before and after reinforcement

Measurement point number	Before the bridge one reinforcement deflection (mm)	After the bridge one reinforcement deflection (mm)	Decrease rate	Before the bridge two reinforcement deflection (mm)	After the bridge two reinforcement deflection (mm)	Decrease rate
M1	9.0	7.4	17.8%	8.3	7.3	12.0%
M2	9.2	7.9	14.1%	8.6	7.8	9.3%
M3	10.1	8.5	15.8%	9.4	8.1	13.8%
M4	10.4	8.9	14.4%	10.1	8.6	14.8%
M5	10.5	8.9	15.2%	10.2	8.7	14.7%

Tab. 4 Deflection under the symmetrical load before and after reinforcement

Measurement point number	Before the bridge one reinforcement deflection (mm)	After the bridge one reinforcement deflection (mm)	Decrease rate	Before the bridge two reinforcement deflection (mm)	After the bridge two reinforcement deflection (mm)	Decrease rate
M1	9.0	7.7	14.4%	8.6	7.6	11.6%
M2	9.7	8.3	14.4%	9.4	7.8	17.0%
M3	9.9	8.6	13.1%	9.6	8.3	13.5%
M4	9.5	8.5	10.5%	9.3	8.1	12.9%
M5	8.9	7.8	12.4%	8.8	7.5	14.8%

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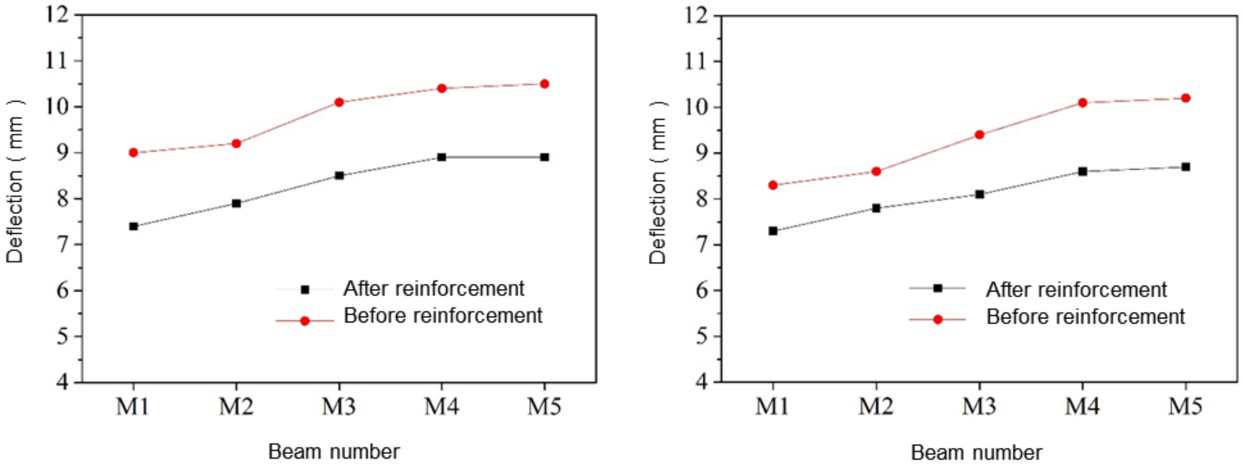

（a）- Bridge one *(b）- Bridge two*

Fig .12 - The deflection results under the eccentric load before and after reinforcement

As can be seen in Figure 12, the deflections under bias load of bridges strengthened with PUC prestressed wire rope reinforcement and composite mortar prestressed wire rope reinforcement are reduced to different degrees. The deflection of the beam on the side of the eccentric load is maximum under the eccentric loads used. Before reinforcement, under the test load, the deflections of 4# and 5# girders of the bridge two were 10.1 mm and 10.2 mm respectively, and after reinforcement by composite mortar pre-stressing steel wire rope method, under the test load, the deflections of 4# and 5# girders were 8.6 mm and 8.7 mm, which were reduced by 14.8% and 14.7% respectively. Under the test load before reinforcement, the deflections of 4# and 5# girders of the bridge one were 10.4 mm and 10.5 mm respectively, and after reinforcement by the method of PUC prestressing steel wire rope, the deflections of 4# and 5# girders were 8.9 mm and 8.9 mm, which were reduced by 14.4% and 15.2% respectively. Although the bridge one is less than the bridge two each piece of girder arranged 15 pre-stressing steel wire rope, but the two bridges after reinforcement the stiffness of the girder body to improve the magnitude of the same, 4# girder and 5# girder are increased by 14%, after reinforcement the bridge deflection measured deflection to meet the requirements of the highway class Ⅱ loading standards.

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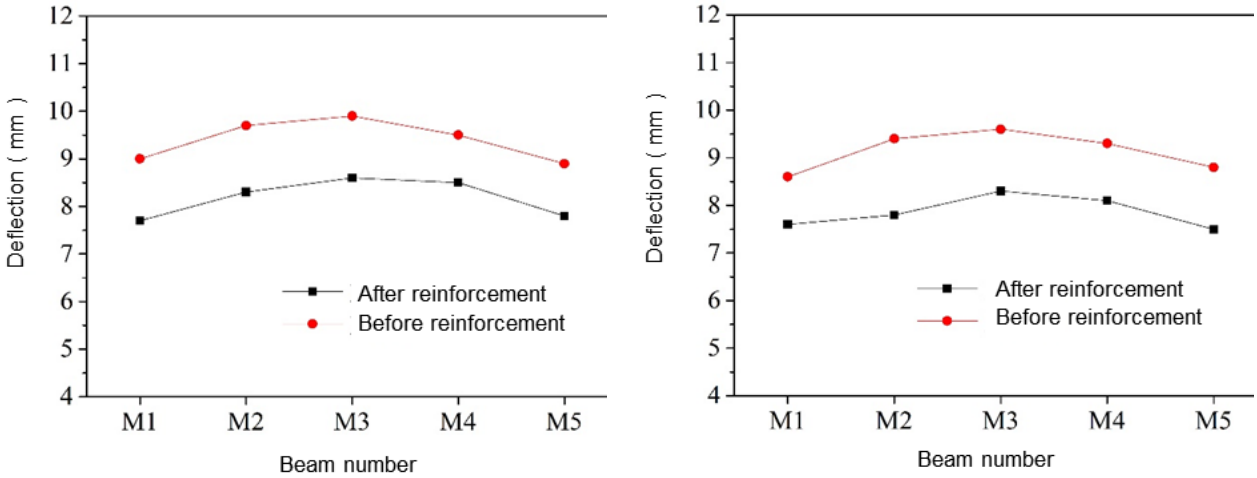


(a) - Bridge one *(b) - Bridge two*

Fig .13 - The deflection results under the symmetrical load before and after reinforcement

As can be seen in Figure 13, the deflections under medium load of bridges strengthened with PUC prestressed wire rope reinforcement and composite mortar prestressed wire rope reinforcement are all reduced to different degrees. The deflection of girder 3# is the largest under medium load. The deflection of 3# girder of the bridge two was 9.6 mm under test load before reinforcement, and the deflection of 3# girder was 8.3 mm under test load after using composite mortar prestressing steel wire rope reinforcement, the deflection was reduced by 13.5%. Under the test load before reinforcement, the deflection of #3 girder of the bridge one was 9.9 mm, and the deflection of #3 girder after reinforcement with PUC prestressing steel wire rope was 8.6 mm, the deflection was reduced by 13.1%. Although the bridge one is less than the bridge two each piece of girder arranged 15 pre-stressing steel wire rope, but the two bridges strengthened girder stiffness increase amplitude is comparable, under the action of the medium load, 3# girder are increased by 13%, after the reinforcement of the bridge in the measured deflection to meet the highway load standard requirements of class Ⅱ.

Strain Test Results

The strains at the bottom of the girders before and after reinforcement under the deflected load conditions of the bridge one and two are shown in Table 5, and the graphs are plotted as shown in Figure 14. The strains at the bottom of the girders before and after reinforcement under the medium load conditions of the bridge one and two are shown in Table 6, and the graphs are plotted as shown in Figure 15.

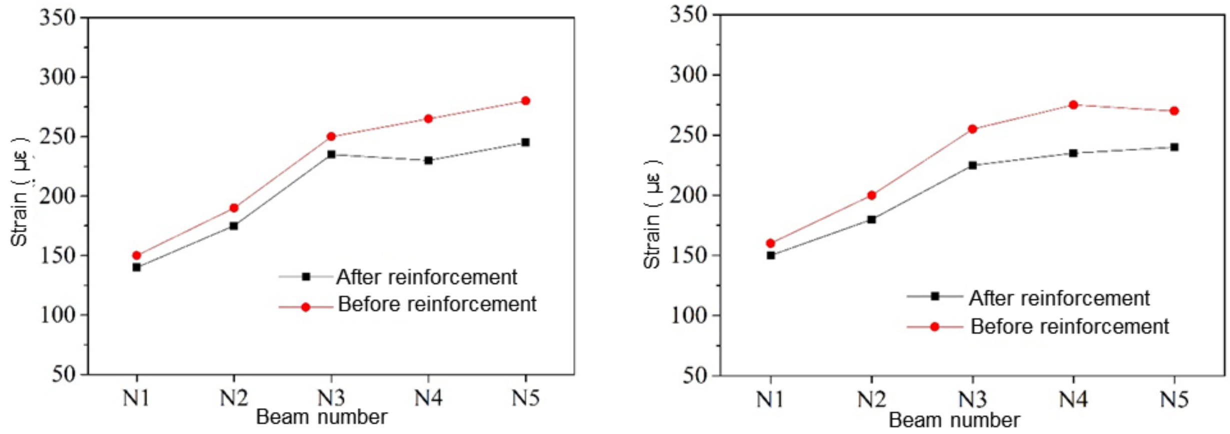
Tab. 5 - Beam bottom strain under the eccentric load before and after reinforcement

Measurement point number	Before the bridge one reinforcement strain (με)	After the bridge one reinforcement strain (με)	Decrease rate	Before the bridge two reinforcement strain (με)	After the bridge two reinforcement strain (με)	Decrease rate
N1	150	140	7.1%	160	150	6.7%
N2	190	175	7.8%	200	180	11.1%
N3	250	235	6.4%	255	225	13.3%
N4	265	230	15.5%	275	235	14.5%
N5	280	245	12.5%	270	240	11.1%

Tab. 6 - Beam bottom strain under the symmetrical load before and after reinforcement

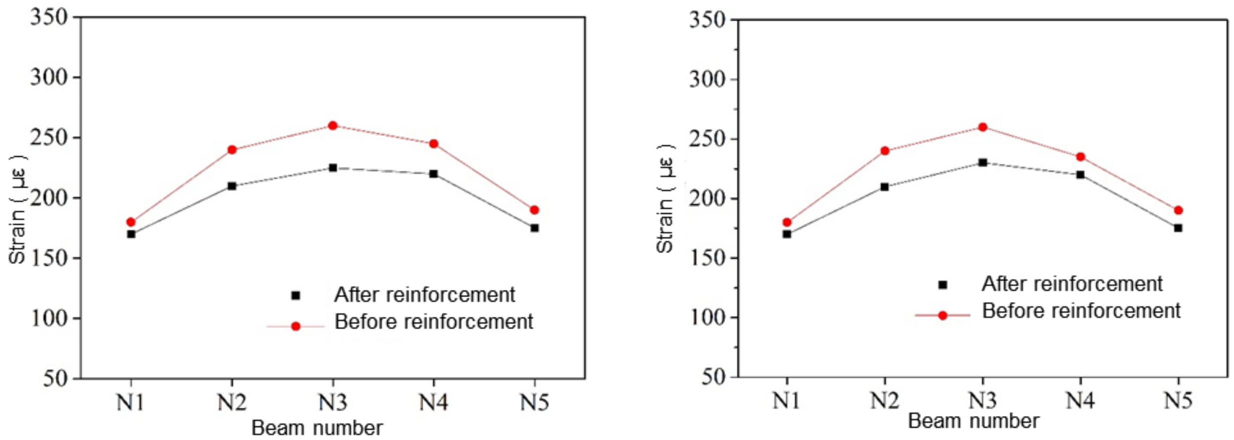
Measurement point number	Before the bridge one reinforcement strain (με)	After the bridge one reinforcement strain (με)	Decrease rate	Before the bridge two reinforcement strain (με)	After the bridge two reinforcement strain (με)	Decrease rate
N1	180	170	5.6%	205	180	12.2%
N2	240	210	12.5%	230	205	10.9%
N3	260	225	13.5%	265	225	15.1%
N4	245	220	10.2%	250	215	14.0%
N5	190	175	7.9%	200	180	10.0%

As can be seen in Figure 14, the bottom strain of each main girder of the bridge strengthened with PUC prestressed wire rope reinforcement method and composite mortar reinforcement method is reduced to a different degree under the eccentricity test load of the bridge. The bridge one, the strains at the bottom of girders 4# and 5# under bias load before reinforcement are 265 με and 280 με, and the strains at the bottom of girders 4# and 5# after reinforcement are 230 με and 245 με, which are 15.5% and 12.5% lower than those before reinforcement, respectively. The bridge two, under the bias load, the strains of girders 4# and 5# are 275 με and 270 με before reinforcement, and 235 με and 240 με after reinforcement, which are reduced by 14.5% and 11.1%, respectively. The strain reduction rates after reinforcement are similar for both bridges, and the strains under the measured bias loads of the strengthened bridges meet the requirements of highway class II loading standards.



（a）- Bridge one （b）- Bridge two

Fig .14 - The strain results under the eccentric load before and after reinforcement



（a）- Bridge one （b）- Bridge two

Fig .15 - The strain results under the symmetrical load before and after reinforcement

As can be seen in Figure 15, the bridges strengthened by the PUC prestressing wire rope method and the composite mortar prestressing wire rope reinforcement method show different degrees of reduction in the bottom strains of the main girders of each piece under symmetrical loading. The strain at the bottom of girder 3# girder under symmetrical loading in bridge one before reinforcement is 260 με, and the strain at the bottom of girder 3# girder after reinforcement is 225 με, which is 13.5% lower than that before reinforcement. The strain of girder 3# of the bridge two was 265 με before reinforcement, and it became 225 με after reinforcement, which was reduced by 15.1%. After reinforcement the two bridges, the measured strains under medium loads meet the requirements of highway class II loading standards.

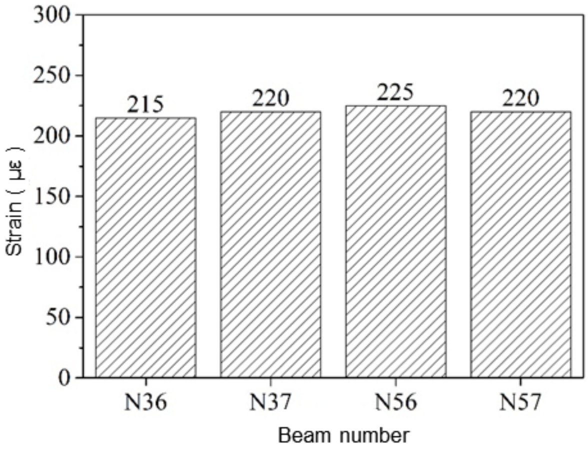


Fig .16 - Lateral strain under the eccentric load after reinforcement

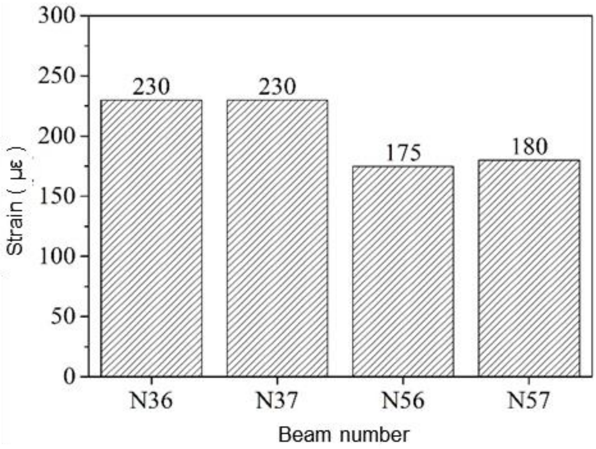


Fig .17 - Lateral strain under the eccentric load after reinforcement

N36 and N37 are strain measurement points adjacent to the side of girder 3#, N36 is used to measure concrete strain and N37 is used to measure PUC strain. N56 and N57 are strain measurement points adjacent to the side of girder 5#, N56 is used to measure concrete strain and N57 is used to measure PUC strain. As can be seen in Figure 16, the strains at the two measurement points N36 and N37 are 215 με and 220 με, respectively, and the strains at the two measurement points N56 and N57 are 225 με and 220 με, respectively, under eccentric loading, and the strains of the urethane cement material at the same locations are similar to the concrete strains. As can be seen from Figure 17, under symmetrical loading, the strains at the two measurement points N36 and N37 are 230 με and 230 με, respectively, and the strains at the two measurement points N56 and N57 are 175 με and 180 με, respectively, which are the same as in the case of partial loading, the strains of the PUC material at the same position are similar to those of the concrete, which indicates that the PUC coordinates the deformation of the main beams well with that of the PUC after casting.

Surface Observation

One month after the completion of the reinforcement, on-site observation of the use of the bridge one and the bridge two were carried out respectively, and no cracking was found on the surface of the PUC of the bridge one, and the reinforcement layer was well bonded with the original girder. On-site observation of the bridge two found that each beam reinforcement layer mortar have different degrees of cracking phenomenon, crack width of 0.15 mm, the average spacing of about 150 mm, cracks vertical longitudinal bridge direction, the two sides of the through the U-shaped cracks, as shown in Figure 18, most of them are force cracks.

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(a) - Composite mortar crack diagram *(b) - Composite mortar crack diagram*

Fig .18 - Composite mortar crack diagram of bridge two

CALCULATION METHOD OF BEARING CAPACITY

The ultimate bearing capacity calculation of RC damaged beams reinforced by PUC and prestressed steel wire ropes is based on the test failure mode. The calculation adopts the constitutive model of concrete and steel bars in the specification. When the PUC material reaches the ultimate tensile strain, the steel bars have already reached their yield strength before that. Therefore, when the reinforced beam reaches its ultimate bearing capacity, the stress of the reinforcing bars is calculated based on its yield strength f_y. The calculation diagram is shown in Figure 19, and the ultimate bearing capacity can be calculated as follows.

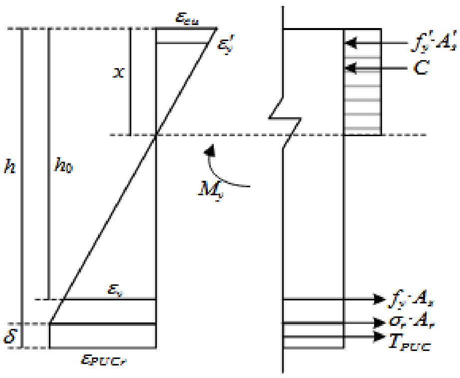

Fig. 19 - Simplified calculation diagram of the ultimate flexural bearing capacity of reinforced beams

From the assumption of the flat section, it can be known that the strain of the steel wire rope caused by the deformation of the beam body at this time is:

$$\varepsilon_{r1} = \varepsilon_{PUCr} \tag{1}$$

Considering the strain lag and the pre-tension stress of the wire rope, the true strain of the wire rope is:

$$\varepsilon_r = \varepsilon_{r1} + \varepsilon_{pr} - \varepsilon_{r0} \tag{2}$$

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Then the stress of the steel wire rope when the reinforced beam reaches the ultimate bearing capacity is:

$$\sigma_r = \varepsilon_r . E_r \tag{3}$$

If it is a single-reinforcement cross-section beam, from the equilibrium relationship, it can be obtained that:

$$f_{cd} bx = f_y . A_s + \sigma_r . A_r + f_{PUCr} . A_{PUC} \tag{4}$$

$$M_y = f_y . A_s (h_0 + \frac{x}{2}) + \sigma_r . A_r (h - \frac{x}{2}) + f_{PUCr} . A_{PUC} (h - \frac{x}{2} + \frac{\delta}{2}) \tag{5}$$

If it is a double-rib cross-section beam, from the equilibrium relationship, it can be obtained that:

$$f_{cd} bx + f_y^{'} . A_s^{'} = f_y . A_s + \sigma_r . A_r + f_{PUCr} . A_{PUC} \tag{6}$$

$$M_y = f_y . A_s (h_0 - \frac{x}{2}) + \sigma_r . A_r (h - \frac{x}{2}) + f_y^{'} . A_s^{'} (\frac{x}{2} - a_s^{'}) + f_{PUCr} . A_{PUC} (h - \frac{x}{2} + \frac{\delta}{2}) \tag{7}$$

In the formula:

ε_{pr} — The strain of the steel wire rope under the action of prestress.

ε_{r0} — The hysteresis strain of the steel wire rope caused by the initial bending moment.

x — When the bending ultimate bearing capacity state is reached, the equivalent rectangular height of the concrete in the compression zone is obtained by solving the force equilibrium equation.

CONCLUSION

1. After reinforcing the structure with PUC prestressed steel wire rope, the stiffness and strength of the structure have been significantly improved to meet the requirements of the highway-II loading standards. The measured values of deflection and strain of each beam were significantly reduced after reinforcement, and the structural safety reserve was improved.

2. The PUC prestressed wire rope-reinforced bridges had a large number of fewer prestressed wire ropes than the composite mortar-reinforced bridges, but the deflections and strains measured for the two reinforced bridges were reduced to a comparable degree compared to the pre-strengthened bridges.

3. The strain of the PUC material at the same position is similar to that of the concrete, indicating that the PUC coordinates well with the main beam after casting and the surface of the reinforcement layer is not cracked.

4. On the one hand, PUC, as the covering layer of prestressed steel wire ropes, can effectively reduce the pre-applied force of the steel wire ropes, lower the stress at the beam ends, and prevent stress concentration at the anchoring ends. On the other hand, the excellent toughness and corrosion resistance of PUC prevent the internal steel wire rope from rusting due to the cracking of the covering layer.

REFERENCES

[1] Siwowski T, Piątek B, Siwowska P,. 2020. Development and Implementation of CFRP Post-tensioning System for Bridge Reinforcement. Engineering Structures, vol. 207, p. 110266. ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2020.110266

[2] Miller T C, Chajes M J, Mertz D R,. 2001. Reinforcement of a Steel Bridge Girder Using CFRP Plates. Journal of Bridge Engineering, vol. 6, n. 6, p. 514-522. ISSN 1943-5592, https://doi.org/10.1061/(ASCE)1084-0702(2001)6:6(514)
[3] Crawford B, Soto R, Lemus-Romani J,. 2021. Investigating the Efficiency of Swarm Algorithms for Bridge Reinforcement by Conversion to Tied-arch: A Numerical Case Study on San Luis bridge. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 2021, 45: 2345-2357. ISSN 2228-6160, https://doi.org/10.1007/s40996-020-00531-5
[4] Williams G, Al-Mahaidi R, Kalfat R,. 2011. The West Gate Bridge: Reinforcement of a 20th century bridge for 21st century loading. Special Publication, vol. 275, p. 1-18.
[5] Schnerch D, Dawood M, Rizkalla S,. 2007. Proposed Design Guidelines for Reinforcement of Steel Bridges with FRP Materials. Construction and Building Materials, vol. 21, n. 5, p. 1001-1010. ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2006.03.003
[6] Birajdar H S, Maiti P R, Singh P K,. 2016. Reinforcement of Garudchatti Bridge after Failure of Chauras Bridge. Engineering Failure Analysis, vol. 62, p. 49-57. ISSN 1350-6307. https://doi.org/10.1016/j.engfailanal.
2015.12.002
[7] Sen R, Liby L, Mullins G,. 2001. Reinforcement Steel Bridge Sections using CFRP Laminates. Composites Part B: Engineering, vol. 32, n. 4, p. 309-322. ISSN 1359-8368. https://doi.org/10.1016/S1359-8368(01)00006-3
[8] Pang B, Yang P, Wang Y,. 2015. Life Cycle Environmental Impact assessment of a Bridge with Different Reinforcement Schemes. The International Journal of Life Cycle Assessment, vol. 20, p. 1300-1311. ISSN 0948-3349. https://doi.org/10.1007/s11367-015-0936-1.
[9] Herbrand M, Adam V, Classen M,. 2017. Reinforcement of Existing Bridge Structures for Shear and Bending with Carbon Textile-reinforced Mortar. Materials, vol. 10, n.9, p. 1099. ISSN 1996-1944. https://doi.org/10.3390/ma10091099
[10] Kazem H, Zhang Y, Rizkalla S,. 2018. CFRP Shear Reinforcement System for Steel Bridge Girders. Engineering Structures, vol. 175, p. 415-424. ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.
2018.08.038
[11] Kang J, Wang X, Yang J,. 2013. Reinforcement Double Curved Arch Bridges by Using Extrados Section Augmentation Method. Construction and Building Materials, vol. 41, p. 165-174. ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2012.11.115
[12] Wang Z, Yang J, Zhou J,. 2022. Reinforcement of Existing Stone Arch Bridges Using UHPC: Theoretical Analysis and Case Study.Structures. vol. 43, p. 805-821. ISSN 2352-0124. https://doi.org/10.1016/j.istruc.
2022.06.055
[13] Nanni A, Ludovico M D, Parretti R,. 2004. Shear Reinforcement of a PC Bridge Girder with NSM CFRP Rectangular Bars. Advances in Structural Engineering, vol. 7, n.4, p. 297-309. ISSN 1369-4332. https://doi.org/10.1260/13694330416535
[14] Trentin C, Casas J R,. 2015. Safety Factors for CFRP Reinforcement in Bending of Reinforced Concrete Bridges. Composite Structures, vol. 128, p. 188-198. ISSN 0263-8223. https://doi.org/10.1016/j.compstruct.
2015.03.048
[15] Puurula A M, Enochsson O, Sas G,. 2015. Assessment of the Reinforcement of an RC Railway Bridge with CFRP Utilizing a Full-scale Failure Test and Finite-element Analysis. Journal of Structural Engineering, vol. 141, n. 1, p. D4014008. ISSN 1943-541X. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001116
[16] Moy S S J, Bloodworth A G,. 2007. Reinforcement a Steel Bridge with CFRP Composites. Proceedings of the Institution of Civil Engineers-Structures and Buildings, vol. 160, n. 2, p. 81-93. ISSN 0965-0911. https://doi.org/10.1680/stbu.2007.160.2.81
[17] Lee H, Jung W T, Chung W,. 2018. Field Test of an Old RC Bridge Before and After NSM Reinforcement. Composite Structures, vol. 202, p. 793-801. ISSN 0263-8223. https://doi.org/10.1016/j.compstruct.
2018.04.024

[18] Kim S H, Park J S, Jung W T,. 2021. Experimental Study on Reinforcement Effect Analysis of a Deteriorated Bridge Using External Prestressing Method. Applied Sciences, vol. 11, n. 6, p. 2478. ISSN 1454-5101. https://doi.org/10.3390/app11062478

[19] Lonetti P, Pascuzzo A,. 2014. Vulnerability and Failure Analysis of Hybrid Cable-stayed Suspension Bridges Subjected to Damage Mechanisms . Engineering Failure Analysis, vol. 45, p. 470-495. ISSN 1350-6307. https://doi.org/10.1016/j.engfailanal.2014.07.002

[20] Zhang K, Sun Q,. 2018. Experimental Study of Reinforced Concrete T-beams Strengthened with a Composite of Prestressed Steel Wire Ropes Embedded in Polyurethane Cement (PSWR–PUC). International Journal of Civil Engineering, vol. 16, p. 1109-1123. ISSN 2383-3874. https://doi.org/10.1007/s40999-017-0264-x