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THE APPLICATION RESEARCH OF THE COMPREHENSIVE STRENGTHENING METHOD WITH EXTERNAL PRE-STRESSED FORCE AND PRE-STRESSED CARBON FIBER BOARD

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Abstract—**The method of comprehensive strengthening with external pre-stressed force and pre-stressed carbon fiber board and its superiority have been expounded in this article. By applying the comprehensive strengthening method in Chongqing Gaoliang interchange overpass, comparing the theoretical deformation increment and stress increment of the reinforced control sections with the measured values, the result shows the anticipated target has been achieved. Finally, it gives the flexural bearing capacity calculation formula of comprehensive reinforced beams with rectangular section, T-shaped section and I-shaped section under ultimate state.**

Key words—**external pre-stressed force, pre-stressed carbon fiberboard, comprehensive strengthening, flexural bearing capacity**

I. INTRODUCTION

The bridge structure may have a variety of damages inevitably during the early stage of building up for the limitations of construction condition and technology. In the subsequent operation phase, due to the repeatedly loading of vehicle and overloading and other factors, the damages would keep enlarging and new damages would generate [1]. Hence the reinforcing and strengthening measures should be took to reinforce the bridge structure after a certain service time. The strengthening method of imposing external pre-stressed and applying FRP composites are widely accepted.

II. COMPREHENSIVE STRENGTHENING WITH EXTERNAL PRE-STRESSED FORCE AND PRE-STRESSED CARBON FIBER BOARD

The external pre-stressed reinforcement has numerous merits that cannot be replaced by other strengthening methods. However, it has its limitations. For instance, the stress and steel in anchorage zone and deviator are complex，the layout and installation of large-tonnage pre-stressed tendons are difficult [2]. If the external pre-stressed is imposed excessively and the arrangement of reinforcing bar is unreasonable slightly, the stress performance of bridge structure would be severely compromised for the deviator and anchorage would be cracked and might have relative displacement with the beam [3]. By using the comprehensive strengthening with external pre-stressed force and pre-stressed carbon fiber board, the value of external pre-stressed force and the size of anchor blocks and steering blocks can be reduced. It is benefit for reducing the difficulty of construction and safety construction.

On the other hand, if the externally pre-stressed tendon is exposed to the atmosphere, the traditional technology of external pre-stressed reinforcement would be costly because strict anticorrosion measure should be used to protect its performance from the greatly influence of external factors. The carbon fiber board is one of the best corrosion resistance materials among the building materials. Experiments show that in the weak acid environment, after 10,000 times of freeze - thaw cycles and alternate wetting and drying, certain light application time and soaking in 70℃ hot waters for 30 days, the carbon fiber board 's durability, corrosion resistance and ageing resistance has no significantly decrease[4]. The carbon fiber board’s anti-fatigue performance is very good and it can retain the strength to 80% after more than 10 million stress cycles with the maximum stress 2000MPa. Meanwhile, its relaxation is negligible under the initial stress with 50% tensile strength. The tensile capacity of carbon fiber board is also very strong. Its tensile strength can reach 2950MPa which is much higher than the ordinary steel. Although the advantages are numerous, the carbon fiber board owns some flaws. One obvious weakness is the weak shear strength. When to reinforce structures, the pre-stressed carbon fiberboard cannot be arranged in fold line as the externally pre-stressed tendon. It is unable to reinforce the diagonal cracks working under the action of shearing force and bending moment on the oblique section.

Each strengthening method of external pre-stressed force and pre-stressed carbon fiberboard has its own advantages and disadvantages. Reinforcing structures in either one way is hard to achieve the requirements of improving bearing capacity and constructing conveniently and safety. However, the comprehensive strengthening can combine the advantages of these two methods to achieve the optimal goal by tensioning the carbon fiber board in beam bottom and tensioning the externally pre-stressed tendon in two sides.

III. PROJECT OVERVIEW AND REINFORCEMENT SCHEME

The Chongqing Gaoliang interchange overpass is a pre-stressed concrete continuous girder bridge with the spans of 4×25m+4×25m+(3×25m+30m+25m). The upper-structure is continuous box girder. As shown in Fig. 1. When carrying out the special inspection, it has been found that the bottom slab, web and flange slab of several spans were cracked. Among them, the crack width of the bottom slab, web and flange are 0.12mm, 0.20mm and 0.18mm respectively in spans for

3×25+30+25m. According to these diseases, the design institute has conducted the calculation and analysis to the bridge and made the conclusion of the ultimate bearing capacity and anti-crack performance of the 30m-span were not enough, and propound comprehensive strengthening scheme with external pre-stressed force and pre-stressed carbon fiberboard.

Figure.1： General layout of the bridge

The concrete reinforcement schemes is setting one externally pre-stressed tendon on each left and right side of the box girder in the 30m-span. As shown in fig 2. Each pre-stressed tendon is steel strand for 12φ15.24，the stretching control force is $0.6 f_{pk} = 1116 MPa$. f_{pk} is the normal strength with the value of 1860MPa. External pre-stressed beam is anchored by concrete anchor blocks, which link on web and flange slab by planting bar. On the box girder bottom slab, 24 blocks pre-stressed carbon fiberboard with specification for 12×100mm have been arranged. Tensioning the carbon fiberboard at single-end with the stretching control force for 800MPa. In order to reduce the injury of bottom slab damage, setting half stressing end and anchor end on each side which stagger 1 meter. As illustrated in Fig. 3.

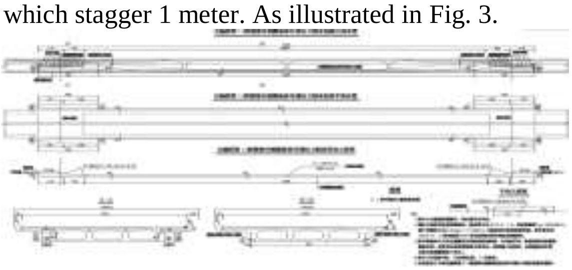


Figure.2: Strengthened with external pre-stressed

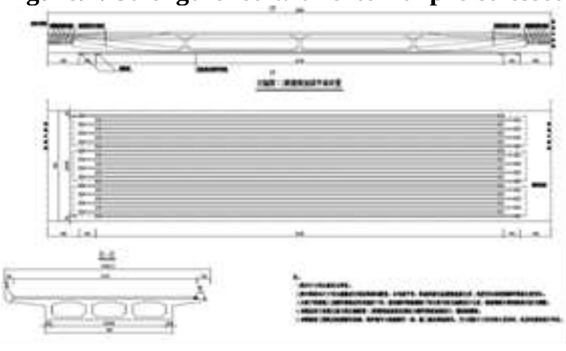


Figure.3: Strengthened with pre-stressed carbon fiberboard

IV. ANALYSIS OF STRENGTHENING EFFECT

A. Establishment of the finite element model

To determine the strengthening effect, using the bridge professional software Midas/Civil to simulation analyze the comprehensive strengthening of the bridge. Referencing the original bridge design drawings and the reinforcement process, the finite element model has been established. The bridge has been divided into 92 units with the superstructure simulated by beam element and the boundary conditions are general support. The finite model is shown in Fig.4.

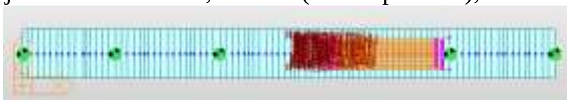


Figure.4: the finite model

B. Analysis of the strengthening effect

During the construction of carbon fiber board，the 24 carbon fiber boards can only be tensioned one by one on the account of the construction unit owning one jack. According to the calculated results, due to the stress increment of the bottom slab in prestressed concrete box girder caused by the tension was small, the external prestressing loss caused by batch tension could be ignored in the analysis of strengthening effect. In order to obtain the practical strengthening effect, the deformations of the 30m-span and its adjacent spans have been tested in the process of comprehensive strengthening with pre-stressed tendon and pre-stressed carbon fiberboard. The theoretical deformation values calculated by finite element and the measured values are illustrated in table1.

Table1: the value comparison of theoretical and measured

	The middle of the side span		The middle of the 30m-span		The middle of the 25m-span	
measuring point	1#	2#	3#	4#	5#	6#
theoretical value(mm)	-1.38	-1.38	3.14	3.14	-1.72	-1.72
measured value(mm)	-1.75	-1.92	3.32	2.71	-1.80	-1.83
measured value/ theoretical value	1.23	1.39	1.06	0.86	1.05	1.06

From the table, the middle of the 30m-span has been respectively elevated 3.14mm in limited element analysis and 3.01mm in practical after comprehensive strengthening. The middle of both adjacent spans has slightly warped down with the measured values of 1.84mm in the side span and 1.82mm in the 25m-span. Thus seen the bridge alignment has been better improved after comprehensive strengthening.

In the practical strengthening process, the strain of mid-span section and fulcrum section in the 30m-span has been monitored synchronously to judge whether the stress fluctuation of bridge control sections was in line with expectations, and speculate whether the stress was overload or not. Monitoring results show that after comprehensive strengthening, the bottom surface of the mid-span section in the 30m-span has won compressive strain with the average of 35 με, which is equivalent to 1.16MPa compressive stress. To extract the theoretical compressive strain (1.42MPa) from finite element simulation model to compare with the measured one, it can be obtained the stress check coefficient of 0.82 is in the reasonably measured range. The results illustrate that the comprehensive strengthening method can effectively resolve and improve the bridge diseases caused by insufficient bearing capacity and crack resistance in pre-stressed continuous concrete beam.

V. CALCULATION OF THE BRIDGE ULTIMATE LIMIT STATE AFTER COMPREHENSIVE STRENGTHENING

A. The ideal failure modes of the comprehensive reinforcement beam

The failure modes of reinforced beam after the comprehensive strengthening mainly have the following several kinds: (1) The carbon fiber board detaches from the concrete before the beam reaches the flexural bearing capacity of normal cross section. Afterwards the externally pre-stressed tendon reaches the limit stress. (2) The compressive region concrete crushed before the tensile region steel yields, the carbon fiberboard snapped break and the externally pre-stressed tendon reaches the limit stress. (3) The carbon fiber board reaches the limit stress and snapped break. Subsequently, the externally pre-stressed tendon reaches the limit stress at the same time the compressive region concrete crushed.

In the first failure mode, the strengthening effect and essence are as well as the external pre-stressed reinforcement. And in practical engineering, it can be avoided by strengthening end anchorage of the carbon fiber board and guaranteeing the adhesive effectiveness. The second mode failed is due to over reinforced damage which the concrete crushed but the steel not yield. And in this situation, other reinforcement methods should be recommended as the comprehensive strengthening method is not suitable. In the third failure mode, the deflection of beam has obvious development after the carbon fiberboard snapped break. And the carbon fiberboard and the externally pre-stressed tendon can fully play its performance as reaching the limit stress. The third failure mode can serve as the strengthening design goal as the bearing capacity of the flexural beam has been improved to the greatest extent.

B. Fundamental assumption

When calculating and analyzing the limit state of the comprehensive strengthening beam after strengthening with external pre-stressed force and pre-stressed carbon fiberboard, several assumptions can be proposed.

1) In the limit state, the failure mode of the strengthening beam is the third mode mentioned above, that is the carbon fiberboard reaches the limit stress and snapped break as soon as the externally pre-stressed tendon reaches the limit stress and the compressive region concrete crushed.

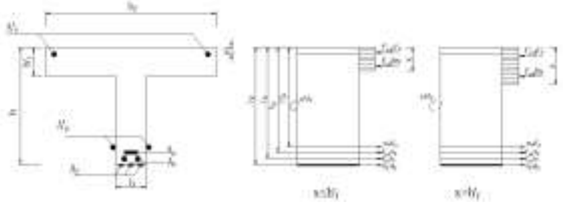
2) The stress distribution of the compressive region concrete is a histogram. The stress value is the design value of concrete compressive strength (f_{cd}).

3) The tension and compression reinforcement, the pre-stressed tendon in the original structures have all reached the strength design value, respectively, f_{sd} , f'_{sd} , f_{pd} . The pre-stressed carbon fiberboard has reached its design value (σ_f) of strength under the limit state.

4) The limit stress of the externally pre-stressed tendon should refer to the "Technical specification for concrete structures pre-stressed with unbounded tendons" (JGJ 92-2004), and ignore the influence of secondary effects.

C. The calculation formula of flexural bearing capacity in limit state

When calculating the flexural bearing capacity of a comprehensive strengthening structure under the limit state, it should be considered in two situations according to the cross-sectional shape and the location of neutral axis.



1) Rectangle section or the neutral axis of T-shaped section and I-shaped section is in the flange slab (x≤ h'f).

$$f_{cd} b_f x + f'_{sd} A'_s = f_{sd} A_s + f_{pd} A_p + \sigma_u A'_p + \sigma_f A_f \quad (1)$$

$$M_u = f_{cd} b_f x (h_0 - \frac{x}{2}) + f'_{sd} A'_s (h_0 - a'_s) \quad (2)$$

2) T-shaped section or I-shaped section and the neutral axis is in the web plate (x＞h'f).

$$f_{cd}(b_f - b) h_f + f_{cd} b x + f'_{sd} A'_s = f_{sd} A_s + f_{pd} A_p + \sigma_u A'_p + \sigma_f A_f \quad (3)$$

$$M_u = f_{cd}(b_f - b) h_f (h_0 - \frac{h_f}{2}) + f_{cd} b x (h_0 - \frac{x}{2}) + f'_{sd} A'_s (h_0 - a'_s) \quad (4)$$

In the above formulas, f_{cd} , f'_{sd} , f_{sd} , f_{pd} are compressive strength value of concrete, compressive strength value of steel, tensile strength value of steel and tensile strength value of externally pre-stressed tendon respectively. A'_s , A_s are steel area of compression zone, steel area of tensile zone respectively. A_p , A'_p are the sectional area of externally pre-stressed tendon. A_f is the sectional area of carbon fiber board. σ_u is the limit stress of externally pre-stressed tendon under limit state. σ_f is tensile strength value of carbon fiberboard. b_f is the effective width of rectangular section, T-shaped section and I-shaped section. b is the web width of T-shaped section and I-shaped section. a'_s is the distance from the steel resultant force action spot of compression zone to the edge of compression zone. The value of h_0 should be determined by the equation(5).

$$h_0 = \frac{f_{sd} A_s h_s + f_{pd} A_p h_p + \sigma_u A'_p h'_p + \sigma_f A_f h_f}{f_{sd} A_s h_s + f_{pd} A_p + \sigma_u A'_p + \sigma_f A_f} \quad (5)$$

h_s is steel area of compression zone. h_p , h'_p are the sectional area of externally pre-stressed tendon. h_f is the sectional area of carbon fiber board.

VI. CONCLUSIONS AND SUGGESTIONS

The method of comprehensive strengthening can fully exploit the advantages of external pre-stressed force and pre-stressed carbon fiberboard, and effectively avoid the deficiency in either method alone. Aiming at the defects of Chongqing Gaoliang interchange overpass, the results of comprehensive strengthening the 30m-span indicate: the bridge alignment has been improved for the middle having been elevated 3.01mm, the adjacent spans warping down 1.82mm and 1.84mm respectively, and the stress reserve has been raised as the bottom surface of the mid-span section has obtained 1.16MPa compressive stress. The expected strengthening effect has been achieved and this method can be a reference extended to reinforce other bridges with the same type.

At the end of this article, the calculation formula of flexural bearing capacity has been proposed. However, when applying this formula to the unbonded pre-stressed concrete, the calculated limit stress would have some errors. Furthermore， whether the carbon fiber plate can reach its design tensile strength remains to discuss. The formula should be conducted in-depth theoretical and experimental verification in order to better apply it in practical engineering.

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