Parametric analysis on mechanical performance of prestressed CFRP reinforced concrete bridge deck

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Abstract. A numerical simulation study of concrete bridge deck unbonded prestressed with CFRP tendons was developed and a verification analysis through ANSYS based on a type of concrete bridge deck with prestressed CFRP tendons was designed. By using the ANSYS model, this paper further studied the parametric sensitivity analysis on static load performance of concrete bridge deck unbonded partially prestressed with CFRP bars. The results show the influence on component strength and mechanical properties caused by factors in concrete bridge deck with prestressed CFRP tendons.

1. Introduction

Background of Research
Fiber Reinforced Polymer/Plastic (referred to as FRP) is non-metallic composite material, it has advantages like low elastic modulus, good stress relaxation, high strength, light weight and strong corrosion resistance[1]. CFRP tendon, which called carbon fiber reinforced plastics, is one kind of FRP tendon. Jiang Tianyong[2] conducted an experimental study on the fatigue properties between CFRP and reactive powder concrete. Jiang Shenghua[3] deduced a calculation formula of the deflection and crack width under the condition of considering the loss of prestress. Chen Wanxiang[4] researched the antiknock performance of CFRP reinforced concrete beam.

1.1. Design of CFRP Reinforced Concrete Bridge Deck
The cross-section of the bridge deck is a solid rectangular section. The concrete strength grade is C40. Prestressed CFRP tendons are made of straight placement of reinforcement and reserve holes are by the pre-buried inner diameter 20mm PVC pipe. The ordinary steel bars use HRB335.

In the preliminary work[5,6], the research has been carried out in the condition of specific reinforcement, C40 strength grade concrete, 0.6 times CFRP tendons under the ultimate tensile strength of prestressed, and specific concrete specimen (specimen section shown in Figure 1) in test. In this paper, the influence of the ordinary steel reinforcement ratio, the reinforcement ratio of CFRP reinforcement and its prestressing force and concrete strength on the mechanical properties of the members are discussed.

Figure 1. Cross-section(unit: mm) Figure 2. Concrete grid diagram and reinforcement model
1.2. Establishment of Finite Element Model of Bridge Deck
The finite element simulation of bridge deck is carried out by using separate models in separate, integral and modular ANSYS models.

1.3. Unit type of Materials
The unit type of concrete materials is selected to use SOLID65 unit in ANSYS. Prestressed CFRP tendons and ordinary reinforcement are selected to use LINK 8 unit of three-dimensional unit.

1.4. Constitutive Model
The material parameters of concrete units, CFRP tendons and ordinary steel units are shown in Table 1-3.

| Table 1. Concrete unit material parameter |
|------------------------------------------|
| Elastic Modulus(MPa) | Poisson's Ratio | Uniaxial compressive Strength(MPa) | Uniaxial Tensile Strength(MPa) | Shear Force Transfer Coefficient Between Cracks |
|-----------------------|----------------|-----------------------------------|-------------------------------|---------------------------------|
| 2350                  | 0.2            | 44.2                              | 3.2                           | Open: 0.5, Closure: 1.0         |

| Table 2. CFRP tendon material parameters |
|------------------------------------------|
| Name | Poisson's Ratio | Elastic Modulus(MPa) | Ultimate tensile strength(f_{cp}) |
| CFRP tendons | 0.3 | 1.5×10^{5} | 1800MPa |

| Table 3. Ordinary steel bar material parameter |
|-----------------------------------------------|
| Name              | Poisson's Ratio | Elastic Modulus(MPa) | Yield Strength(MPa) |
| HRB335 steel bars | 0.2            | 1.5×10^{5}           | 335 |

1.5. Create a Model and Divide the Grid
According to the design of the bridge deck in the preliminary work, the ANSYS model of the unbounded prestressed CFRP reinforced concrete bridge deck is established, as shown in Figure 2.

2. Sensitivity Analysis of Mechanical Behavior of Unbonded Partially Prestressed CFRP Reinforced Concrete Bridge Deck

2.1. Reinforcement Ratio of Ordinary Steel
In order to explore the influence of the reinforcement ratio of ordinary reinforcement on the mechanical behavior of prestressed CFRP bridge deck, four groups of bridge deck model of prestressed CFRP tendons with different reinforcement ratio are shown in Table 4. The results of the finite element analysis are shown in Figure 3-6. Figure 7 shows the comparison of the load-deflection curves of the four groups of bridge decks.

| Table 4. Influence of Reinforcement Ratio of Common Reinforcing Steel Bar on Mechanical Performance of Prestressed CFRP Bridges |
|---------------------------------------------------------------|
| Serial number | Ordinary ratio of reinforcement | Depressive load(kN) | Cracking load(kN) | Cracking deflection (mm) | Ultimate load (kN) | Ultimate deflection (mm) | Residual stiffness (kNmm⁻¹) |
|----------------|---------------------------------|---------------------|------------------|--------------------------|-------------------|--------------------------|-----------------------------|
| P-0            | 0                               | 12.76               | 34               | 0.247                    | 50                | 8.396                    | 5.96                        |
| P-1            | 3Φ6                             | 12.78               | 36               | 0.242                    | 48                | 5.418                    | 8.86                        |
| P-2            | 3Φ8                             | 12.91               | 39               | 0.430                    | 64                | 6.861                    | 9.33                        |
| P-3            | 3Φ10                            | 13.11               | 40               | 0.366                    | 80                | 4.184                    | 19.12                       |
Compared with P-0 bridge deck, the ultimate load of P-2, P-3 bridge decks are increased by 14kN/mm and 30kN/mm. Load-deflection curve appears in triple line mode, which shows that with the improvement of reinforcement ratio of ordinary steel bars, the overall force performance would improve, and the strength and the deformation performance would also increase. In general, compared with pure prestressed CFRP reinforced bridge deck, the ultimate load and residual stiffness of the ordinary reinforcement installed appropriate prestressed bridge deck with CFRP tendons can increase by 28% and 33%. But along with further increase of ordinary reinforcement ratio, the component presents a kind of super-gluten mode damage, which would damage the improvement of ductility. As for the section and the concrete strength in this test, the most appropriate reinforcement ratio of ordinary steel bars should be around 0.2%.

2.2. Tension Control Stress and Reinforcement Ratio of CFRP Tendons
Nine kinds of bridge deck with different tension control stress and reinforcement ratio are shown in Table 5. The results of the finite element analysis deflection image are shown in Figure 8-16.

Table 5. Tension control stress and CFRP tendons reinforcement ratio’s influences on the deck of the mechanical properties

| Serial number | Reinforcement of CFRP | Tension control stress (kN) | Depressive load (kN) | Cracking load (kN) | Ultimate load (kN) |
|---------------|-----------------------|-----------------------------|---------------------|--------------------|--------------------|
| S-1           |                       | 0.4f<sub>cp</sub>           | 8.89                | 28                 | 40                 |
| S-2           | 2Φ6                   | 0.6f<sub>cp</sub>           | 10.32               | 32                 | 56                 |
| S-3           |                       | 0.7f<sub>cp</sub>           | 12.03               | 36                 | 72                 |
| Z-1           |                       | 0.4f<sub>cp</sub>           | 8.89                | 36                 | 56                 |
| Z-2           | 2Φ7                   | 0.6f<sub>cp</sub>           | 12.91               | 39                 | 64                 |
| Z-3           |                       | 0.7f<sub>cp</sub>           | 17.84               | 43                 | 72                 |
| D-1           |                       | 0.4f<sub>cp</sub>           | 21.07               | 48                 | 88                 |
| D-2           | 2Φ10                  | 0.6f<sub>cp</sub>           | 30.45               | 60                 | 86                 |
| D-3           |                       | 0.7f<sub>cp</sub>           | 36.78               | 72                 | 88                 |
Figure 17 is the contrast load-deflection curve of each component under the situation of same CFRP reinforcement ratio and different tension control stress. The depressive load and cracking load increase along with the tension control stress. That indicates that the cracking behavior of the bridge deck is related with tension control stress. When the reinforcement ratio of CFRP tendon is in low and medium level (figure 17a and 17b), the ultimate load of the bridge deck increases with the increase of tension control stress. When the reinforcement ratio of CFRP tendons is in high level (figure 17c), three groups of components appear the characteristics of the “super-gluten damage”. It can be seen in figure 18 that with the increase of reinforcement ratio, the depressive load and cracking load are greatly increased. After cracking, these three groups of components show completely different force process. D-2 is in obvious “super-gluten stress” mode.

In general, increasing the tension control stress and reinforcement ratio of CFRP tendons can improve the depressive load and cracking load of the bridge decks. Tension control stress and reinforcement ratio of CFRP tendons would affect the force performance.

2.3. Concrete Strength

Three kinds of bridge deck with different concrete strength are shown in Table 6. The results of the finite element analysis deflection image are shown in Figure 20-22.

Table 6. Effect of concrete strength on mechanical properties of prestressed CFRP tendon reinforcement deck

| Serial number | Concrete Strength | Depressive Load(kN) | Cracking Load(kN) | Ultimate Load(kN) |
|---------------|------------------|---------------------|-------------------|-------------------|
| C-1           | C30              | 12.82               | 38                | 56                |
| C-2           | C40              | 12.91               | 39                | 64                |
| C-3           | C50              | 12.98               | 37.6              | 72                |
It can be seen in Table 6 and Figure 19 that the compressive load and cracking load with different level concrete strength are almost the same. As concrete strength level rise from C30 to C50, the ultimate load of bridge decks improve from 56kN to 72kN. In general, the increase of concrete strength can improve the ultimate load of the bridge deck, but it has a little effect on the cracking performance and the mechanical properties of the bridge deck.

3. Conclusion
Configuring suitable ratio of ordinary reinforcement, of which of the section in this test is around 0.2%, in the prestressed concrete with CFRP is favorable for the improvement of the bearing capacity, deformation and ductility performance. Improving the tension control stress and reinforcement ratio of CFRP tendons can increase the depressive load and cracking load of the bridge decks which would also affect the force performance of the unbonded partially prestressed concrete with CFRP by affecting the stress increment when the CFRP tendon is eventually destroyed. The increase of concrete strength can improve the ultimate load of bridge deck, but it has a little effect to improve the cracking performance and its mechanical performance.

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