# USE OF EXTERNAL CFRP PRESTRESSING IN HEWEI BRIDGE IN CHINA

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**ABSTRACT**

CFRP (Carbon Fibre Reinforced Polymer) is a kind of plastic which has characteristics of high strength, light weight, low relaxation and non-corrosion, and its applications in bridge engineering have been increasing recently. In this paper, the use of CFRP as the external prestressing tendons on Hewei Bridge in Jiangsu Province, China, is described.

## 1. INTRODUCTION

Because of its properties of high strength, light weight, low relaxation and non-corrosion, Carbon Fibre Reinforced Polymer (CFRP) tendons have recently been used on a trial basis in concrete bridges in place of prestressing steel bars.

The applications of CFRP tendons in bridge engineering began in Japan, Canada, the USA and some countries in Europe around 1980. Up to now, dozens of bridges, including pedestrian and traffic bridges have been built with prestressed CFRP tendons (Nabil, et al., 2003). The guidelines for the design of CFRP reinforced and prestressed concrete buildings have been published in those countries since 1993 (JSCE, 1997; ACI 440.4R, 2004). In China, a CFRP cable-stayed pedestrian bridge was designed by Southeast University (Mei, 2005) and erected on the campus of Jiangsu University, Zhenjiang (Jiangsu, China) in 2005. Hewei Bridge in Huai'an, Jiangsu Province, is the first CFRP prestressed highway bridge in China. The bridge layout is shown in Figure 1.

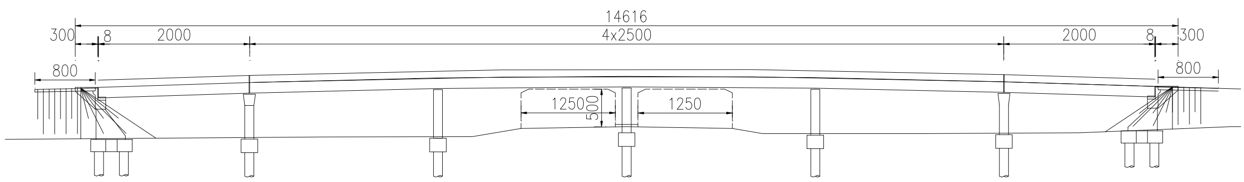


**Figure 1. Layout of Hewei Bridge**

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Hewei Bridge is a highway flyover bridge over the Nanjing-Xuzhou expressway in China. The four middle spans have a continuous concrete box girder structure and are prestressed by internal steel strands, while both side spans are designed as simply supported monolithic concrete girders 20 m in length. External CFRP prestressed concrete girders not only have the same advantages of ordinary external prestressed concrete girders, such as low friction loss and convenient periodic inspection and tendon replacement, but also non-corrosion and high strength. External prestressed double-T beams were therefore designed for the two side spans of Hewei Bridge. One span is prestressed by external CFRP cables and the other by external ordinary steel tendons for comparison. The bridge was erected in April 2007.

## 2. DESIGN PARAMETERS OF CFRP TENDONS

CFRP material is composed of carbon fibre and resin. Two kinds of commercially available tendons can be used for bridge construction. One is CFRP rod which is made by extruding epoxy-impregnated Carbon Fibre Reinforced Polymer, the other is Carbon Fibre Composite Cable (CFCC) which is formed by twisting a number of small-diameter CFRP rods similar to conventional steel strands. The photos shown in Figure 2 are examples of these two kinds of CFRP materials, and their properties and some parameters used for bridge design are listed in Table 1.

a) CFCC Cable b) CFRP Rod

**Figure 2. CFRP tendons**

**Table 1. Parameters of CFCC and CFRP rod used as prestressing tendons**

| | Nominal Diameter (mm) | Effective Cross Section Area | Modulus of Elasticity (Gpa) | Nominal Mass Density □ g/m□ | Elongation □ %□ | Heat Resistance □ □ □ | Guaranteed Tensile Strength □ MPa□ | Fatigue Capacity/ Guranteed Capacity |
|---|---|---|---|---|---|---|---|---|
| CFCC | 40 | 779.4 | 127 | 1508 | 1.6 | 130 | 1410 | 0.55 |
| Rod | 10 | 69.4 | 120 | 115 | 1.5 | 120 | 1600 | 0.60 |

| | Coefficient of Friction | | Relaxation Ratio □ %□ | Thermal Expansion Coefficient (×10-6□ ) | Anchor Deformation and Tendon Contraction (mm) | Stress Limited Value/Guranteed Tensile Strength | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | During Construction | | Service Limit State |
| | *μ* (1/rad□ | *k* □ 1/m□ | | | | During Prestressing | Immediately after Prestressing | |
| CFCC | 0.3 | 0 | 2.3 | 0.6 | 1 | 0.8 | 0.7 | 0.7 |
| Rod | 0.3 | 0 | 3.0 | 0.7 | 8 | 0.8 | 0.7 | 0.6 |

Note: CFCC product is made in Japan, and CFRP rod is made in China.

In the design stage of Hewei Bridge, in order to compare the efficiency of the two types of CFRP tendons, both of these materials were considered for use as the external prestressing tendons, but ultimately CFCC was selected for the bridge.

## 3. DESIGN OF THE CFRP GIRDERS IN HEWEI BRIDGE

### 3.1 External prestressed CFRP girders

For the sake of convenience when applying external prestressing and carrying out periodic inspection, a double-T-shaped cross-section was designed for the external CFRP prestressed girders. The width of the girders is 850 cm, the height is 146 cm and the web thickness is 42 cm. The plan and the elevation of the girders are shown in Figure 3, and the cross-sections are shown in Figure 4. The dimensional unit in these figures is centimetres.

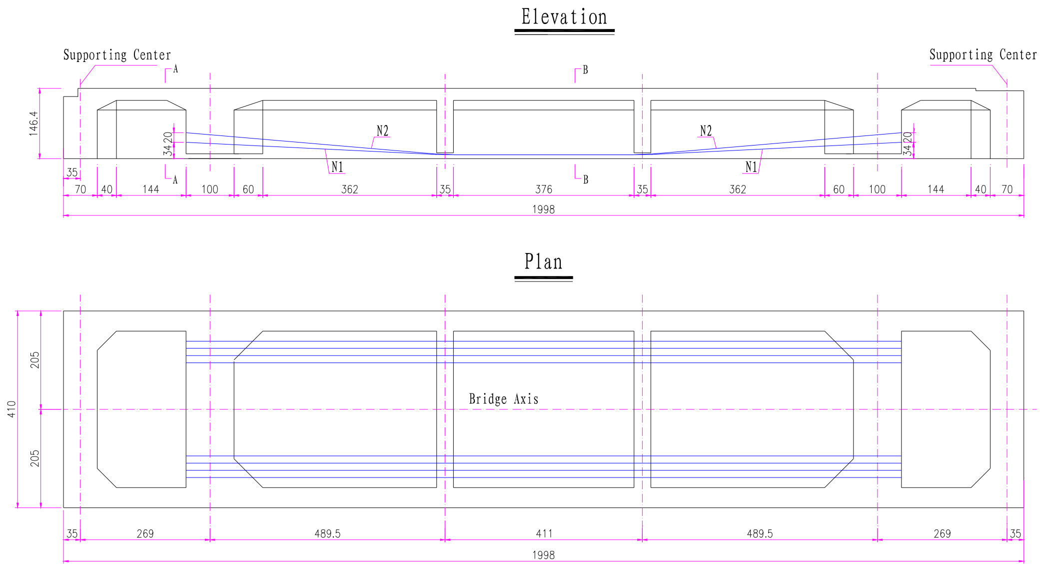


**Figure 3. Simply supported girders with external CFCC prestressing**

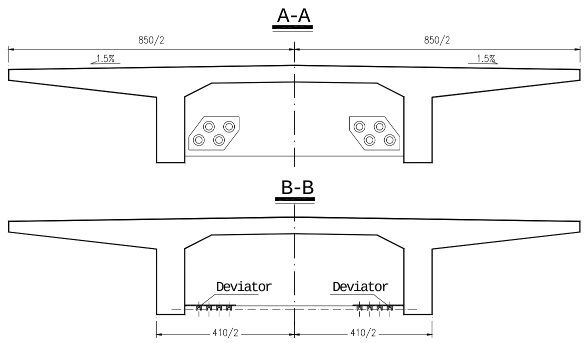


**Figure 4. Cross-section of girders with external CFCC prestressing**

A total of six diaphragms connect the webs of each girder. To allow for post-tension prestressing and replacing of the prestressing tendon, the CFRP tendons are bent gradually through deviators fixed at the bottom of the two intermediate diaphragms, and anchored symmetrically to the 2nd and 5th diaphragms adjacent to the end diaphragms.

According to the product manual from Tokyo Rope Co Ltd, the strength of CFCC decreases gradually with the increase of bending angle under normal conditions. When the angle of curvature is 5 and 10 degrees, the reduction in strength is about 5% and 15% respectively. Therefore in the design stage of Hewei Bridge much attention was paid to the angle of curvature, and finally a curvature of 5 degrees was decided on as the limit of the angle. The actual maximum bending angle used in the CFRP girder of Hewei Bridge is 4.87 degrees, and the anchor location in the anchorage diaphragm is 54 cm above the bottom of the diaphragm.

The anchorage diaphragms are regarded as bending and shear-torsion members. In total, 8 cables are anchored to the anchorage diaphragms, and the anchor force of each cable is 872.4 kN. The anchorage diaphragms were designed as RC members, the thickness of which is equal to 100 cm.

3.2 Design of anchor and deviator

Because of their lower transverse shear strength and lower lateral compression strength, CFRP tendons cannot be anchored in the same way as prestressing steel tendons. Damage may occur to the anchors as well as the deviators, and therefore much attention should be paid to this problem. Design of a safe, practicable and economical type of anchorage device is one of the most important aspects in the use of CFRP tendons in prestressed concrete structures.

Three main types of anchors have been developed in Japan, Canada, the USA and other countries, one type being the grouted anchor, which is the most reliable. However, it has practical drawbacks such as the tendons having to be pre-cut to the designed length and the need for curing time for the grouting material. The wedge-type anchor is more suitable for post-tensioning construction because of its convenience for assembling and prestressing. The research work on anchors for CFRP tendons has also been progressing in China in recent years (Zhu, 2004).

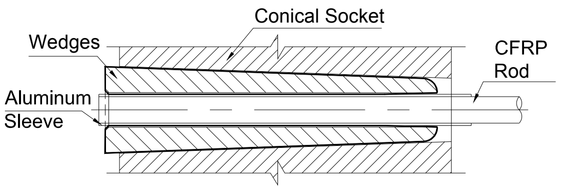


**Figure 5. Wedge-type anchor for CFRP rod**

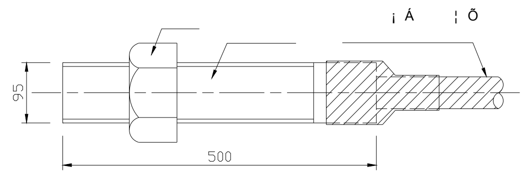


**Figure 6. RS anchor for CFCC**

Figure 5 shows a multi-rod wedge anchor developed by the authors, which is designed for CFRP rods. It consists of three components: a stainless steel conical socket, a set of two-piece stainless steel wedges and a thin aluminium sleeve for each socket which is placed between wedges and the CFRP rod. In order to reduce the lateral pressure on the CFRP rod, the wedge anchor is longer than an anchor for steel strands. The taper angle of the wedge is slightly larger than that of the inner surface of the barrel. The difference in angle helps to produce a more desirable radial stress distribution in the tendon. The inner surface of the wedge is threaded. When the CFRP rod is under tension, the wedges clamp it through the aluminium sleeve. The sleeve protects the rod's surface from damage so as to ensure its tensile strength.

Figure 6 shows the RS (resin single) anchor for CFCC cables made by Tokyo Rope Co Ltd, which is a type of grouted anchorage used for the CFCC cables in Hewei Bridge.

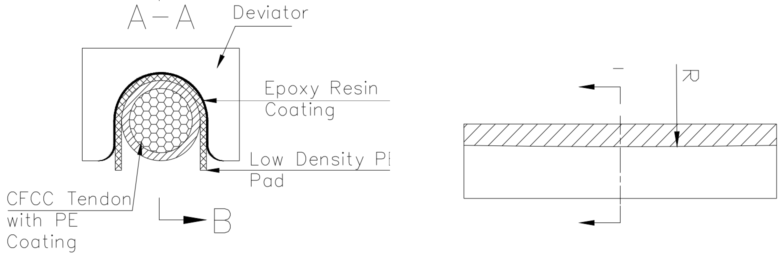


**Figure 7. Deviator for CFCC tendon**

Figure 7 shows the deviators, which are fixed at the bottom of the two intermediate diaphragms to locate the CFCC cables. The fixed tendons, angle of curvature, installation error, friction and movement of the tendons under vehicle and temperature loads should be all considered in the design of the deviator. In addition, according to the product manual of Tokyo Rope Co Ltd, the diameter of the curved surface of the deviator should not be less than 100 times that of the steel tendon. In Hewei Bridge, the length of the deviator is 35 cm, and the two curvature radii are equal to 4 000 mm and 6 000 mm.

### 3.3 Prestress loss

The prestress loss of CFRP cables is different from that of steel strands, and is still a problem that needs to be studied in greater depth. The immediate prestress loss due to anchorage set and friction can be expressed in the same way as the losses for steel strands, and only some parameters for CFRP, such as the coefficient of friction and the modulus of elasticity, etc., need to be corrected. In the process of designing Hewei Bridge, the prestress loss due to relaxation of CFRP tendons was calculated in the same way as for as steel strands, but some parameter values were changed. Table 1 lists some parameters for CFRP prestress loss, such as the coefficient of friction and the modulus of elasticity, etc.

#### *3.3.1 Loss due to shrinkage and creeping of concrete*

As the modulus of elasticity of CFRP tendons is lower than that of steel strand, the loss due to shrinkage and creeping of concrete in CFRP prestressed girders is also less than that in steel strand prestressed girders. In the design stage of Hewei Bridge, the prestress loss in CFRP due to shrinkage and creeping of concrete was simplified and calculated using the equation for steel prestressing strand and corrected by multiplying it by the modulus ratio of CFRP tendon to steel strand. This equation is shown below:

$$\sigma_l = \sigma_l{}'\left(E_{fp} / E_{sp}\right) \qquad (1)$$

where

$\sigma_l'$ is the loss in steel strand due to shrinkage and creeping of concrete; $E_{fp}$ and $E_{sp}$ are the moduli of CFRP tendon and steel strand respectively.

#### 3.3.2 Loss due to friction

Because the CFRP tendons are externally anchored to the girder, the loss due to friction occurs only in the case of draped tendons between the surfaces of the deviator and the tendon, and it can easily be calculated by structural mechanics. If the friction coefficient between the prestressing cable and the deviator is μ, and the pressure on the deviator from the prestressing cable is N, then the loss due to friction can be expressed as follows:

$$\sigma = \mu \cdot N / A \qquad (2)$$

Here A represents the cross-sectional area of the prestressing cable.

#### *3.3.3 Loss due to temperature changes*

Compared with conventional prestressed concrete, there is an additional loss or increase due to temperature changes in CFRP prestressed concrete girders due to the smaller thermal expansion coefficient of CFRP material, which is only about 1/20 that of concrete. When the environmental temperature increases, the expansion of the concrete is greater than the expansion of the CFRP tendons, therefore the prestress increases. When the environmental temperature decreases, the contraction of the concrete is greater than the contraction of the CFRP tendons, and prestress loss occurs. This can be expressed as follows:

$$\sigma_{lT} = \Delta T \left| \alpha_f - \alpha_c \right| E_{fp} \tag{3}$$

where

$\alpha_f$, and $\alpha_c$ are the thermal expansion coefficients of CFRP tendon and concrete respectively.

For CFCC, the margin between the environmental temperature during construction and the average annual lowest temperature is assumed to be 35 $^{o}$C. According to the above formula, the loss is 51.6 MPa, which is about 5% of the initial prestressing, and should obviously not be neglected.

*3.3.4 Total prestress losses*

According to the above analysis, the total prestress losses of CFRP tendons are summed up and listed in Table 2, in which two kinds of CFRP materials are listed. The total prestress losses of CFRP rod are relatively greater than that of CFCC cable, and this is mainly because the anchorage styles for these two kinds of materials are different.

**Table 2. Comparison of the prestress losses of CFCC and CFRP rod**

| Type of Prestress loss | Loss Due to Anchorage Draw-in | Loss due to Friction | Loss Due to Elastic Shortening of the Concrete | Loss Due to Tendon Relaxation | Loss Due to Thermal Variation | Loss Due to Shrinkage and Creep of the Concrete | Total Amount |
|---|---|---|---|---|---|---|---|
| CFCC (MPa) | 12.8 | 22.9 | 19.2 | 22.0 | 51.6 | 38.1 | 166.6 |
| Loss/Ini.prestress | 0.013 | 0.024 | 0.020 | 0.023 | 0.054 | 0.040 | 0.174 |
| CFRP Rod(MPa) | 99 | 0 | 14.6 | 28.3 | 47.5 | 36.1 | 225.5 |
| Loss/Ini.prestress | 0.105 | 0 | 0.015 | 0.030 | 0.050 | 0.038 | 0.239 |

Considering the stability of materials and anchors, the specified initial prestress of CFCC cable is 957 MPa, which is 68% of its guaranteed tensile strength, and that of CFRP rod is 967 MPa, which is 60% of its guaranteed tensile strength. The stress limitations for these two kinds of CFRP are listed in Table 1.

## 4. LOAD CAPACITY OF THE STRUCTURE

4.1 Simplified theoretical analysis method

The simplest way to analyse an external CFRP prestressed girder is to directly apply the theoretical analysis methods for unbonded post-tensioned concrete structures. The following equation (Naaman et al. 2002) was used to calculate the stress of CFRP tendon at the ultimate limit state:

$$f_{p\,frp} = f_{pe} + \Omega_u E_{frp} \varepsilon_{cu} (R_d d_p / c_u - 1) L_1 / L_2 \tag{4}$$

Where

$\Omega_u = 3.0/(L1/d_p)$ is the strain reduction coefficient at the ultimate limit state; $\varepsilon_{cu}$ = 0.003 is the extreme compression strain of concrete. The depth reduction factor $R_d$ is determined by equation (5) as follows:

$$R_d = 1.14 - 0.005\left(L_1 / d_p\right) - 0.19\left(S_d / L_1\right) \tag{5}$$

If $R_d$ is greater than 1.0, then it is assumed to be 1.0. Other parameters in the equation are shown in Table 3. The result of the equation should not be greater than the guaranteed tensile strength of the tendon.

**Table 3. Effect of external tendons at the ultimate state**

| Depth of Tendon dp (m) | Strain Reduction Factor Ωu | Depth Reduction Factor Rd | Height of Compressive Area *Cu* (cm) | Ultimate Tensile Stress of Tendon Mpa | Stress/ Guaranteed Tensile Strength | Total Capacity of External Tendons (KN·m) |
|---|---|---|---|---|---|---|
| 1.25 | 0.155 | 1.010 | 9.9 | 1 410 | 1.000 | 10 642 |
| 1.08 | 0.134 | 0.871 | 11.1 | 1 178 | 0.650 | 7 620 |

To prevent the worst case of the bridge collapsing due to failure of the CFRP tendons, some ordinary reinforced steel bars were designed into the external CFRP prestressed girders in Hewei Bridge. If all the CFRP tendons were to lose the effect, the ordinary reinforced steel bars would bear the whole dead load of the bridge.

4.2 Analysis of the structure at the construction and service stages

The cast-in-place construction method was used for the side span girders of Hewei Bridge. There was nothing especially complicated about erecting the formwork and pouring of the concrete. The construction sequence of the Hewei Bridge was: pouring the girder concrete on fully supported formworks; dismantling the supports and the formworks; post-tensioning the external tendons; and pouring the concrete for the guard rails and deck pavement. There was a slight difference from the usual P.C. girder construction in that post-tensioning followed the dismantling of the formwork for purposes of the test study.

The analysis included calculation of the deflection, stress of the structure under static load, prestresssing at the construction stage, live load at the service stage, and load capacity at the ultimate limit state (China HPDI, 2004).

Apart from the simplified theoretical method, FEM was also used for the analysis of the external CFRP prestressed girders. In the process of establishing the FEM model, solid elements were used to simulate concrete and linking elements were used to simulate tendons. Coupled nodes were used to simulate the effect of deviators on the CFCC girders. The bottom fibre stresses of each girder at mid-span calculated by these two analysis methods are illustrated in Figure 8. The results of the two methods are very close.

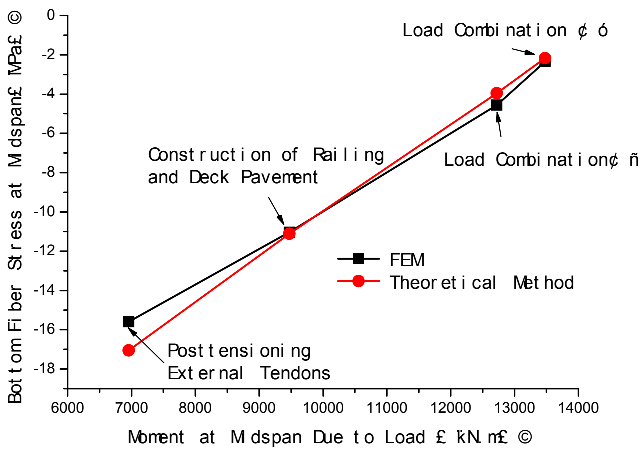


**Figure 8. Relationship between bottom fibre stress and moment at mid-span**

The relationship of external tendon stress to mid-span moment due to loads obtained by the FEM method is illustrated in Figure 9.

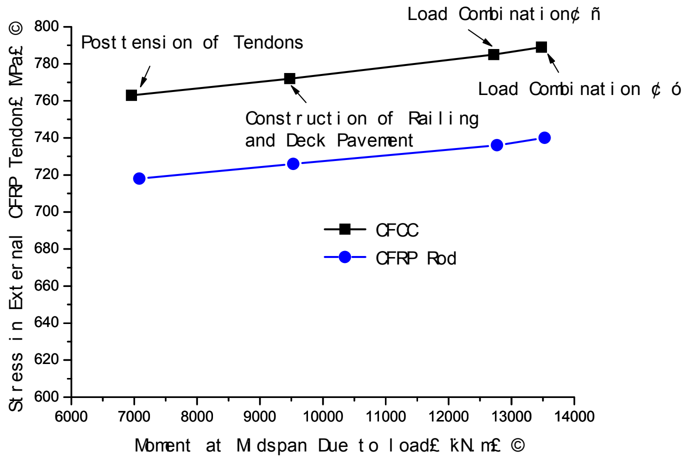


**Figure 9. Relationship between tendon stress and the mid-span moment**

It can be seen that the increase in the stress in external tendon is small while the load increases greatly. Both CFCC and CFRP rod schemes indicate the same conclusion consistent with the observed results of Bridge Street Bridge, the first CFRP tendon prestressed concrete highway bridge in the USA (Nabil, et al., 2002). The relationship of deflection to moment at mid-span due to loads is illustrated in Figure 10.

The post-tensioning of external tendons causes the girder to deflect upwards, which counterbalances deformation due to load on the railings and deck pavement. The results of the two schemes are basically consistent.

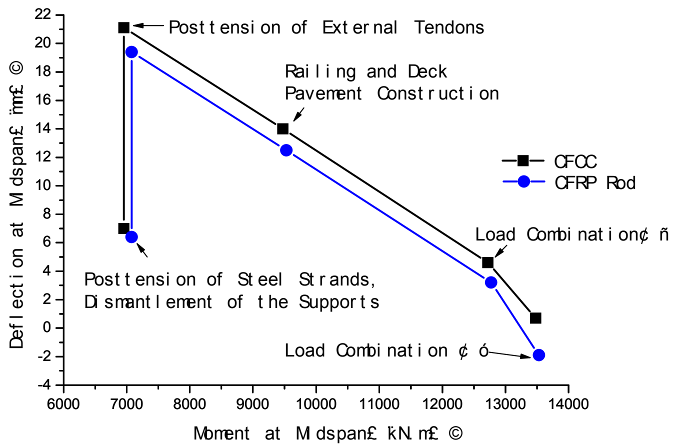


**Figure 10. Relationship between deflection and mid-span moment**

The amount and cost of the main materials are listed in Table 4. Compared with ordinary prestressed concrete box girders with the same span and the same height, CFRP external prestressed girders contain less concrete (10%) and fewer steel bars (42%). However, owing to the high price of a CFRP tendon and its anchor, especially the high price of imported CFCC and its grouted anchor, the cost of CFRP external prestressed girders is much higher than that of ordinary prestressed girders.

**Table 4. Comparison of material quantities for the side span superstructures**

| Design Propsal | Cross-Section | Concrete □m3□ | Steel Bars□kg□ | Steel Strand□ kg□ | CFCC Φ40mm □m□ | CFRP Rod Φ10mm □m□ | Cost(□) |
|---|---|---|---|---|---|---|---|
| Ordinary Prestressed | Box-shaped | 106.4 | 24714 | 2904 | | | 350705 |
| CFCC | Double-T | 78.9 | 25800 | | 160.6 | | 1004653 |
| CFRP Rod | | 78.9 | 26813 | | | 2275.5 | 581337 |

## 5. CONCLUSION

CFRP material has properties of high strength, non-corrosion, light-weight and low relaxation amongst others. Because of its brittleness, lack of ductility and high cost, up to now it has been used in only very few bridges instead of in the world. Owing to the development of CFRP material, the researchers are confident that CFRP tendons will be used in P.C. bridges in China. Hewei Bridge is the first example of a highway bridge using CFRP prestressing tendons. Having reviewed the design and analysis process of this bridge, the following conclusions were drawn:

CFRP rods or CFRP strands (CFCC) are available today as a viable alternative to conventional steel tendons, but the problems, which include layout of tendons, loss of prestressing, design of anchors and structural analysis should be studied carefully when designing a bridge. These problems should definitely be future research areas in the application of CFRP tendons.

Comparing the two types of CFRP tendons, the work efficiency of CFCC tendons is higher than that of CFRP rods in external prestressed bridge girders. CFCC cables can be easily laid out in a draped tendon profile according to the variation of bending moment along the length of girder. But for CFRP rods, only multi-rod anchors and straight tendon profiles can be used in order to obtain a smaller eccentricity of the tendon. In practice, the cost of CFCC girders is higher than that of CFRP rod girders in China as CFCC has to be imported. Both the CFCC strands and CFRP rods are more expensive than ordinary steel tendons for prestressed girders.

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