MECHANICAL AND BONDING PERFORMANCES OF STEEL CABLE-GFRP COMPOSITE REBAR

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ABSTRACT

Glass fibre reinforced Polymer (GFRP) rebar is the most applicable civil engineering structural FRP material for its good mechanical properties and low price. However, the low tensile elastic modulus of GFRP limits its application. According to the hybrid principle of FRP material, steel cable-GFRP composite rebar is made of high modulus steel cable as the core and GFRP as the outer protection layer. The composite rebar has higher tensile modulus, while GFRP protection layer improves the durability of the steel cable. In this paper, we have done the tension and bonding experiments on the different diameters composite rebars manufactured by pull-winding process. The experimental results indicate that SGFRP composite rebars have larger modulus than GFRP rebar, which obey the rule of larger cable fraction, the larger tensile modulus. But to the tensile strength and bonding strength, the principles of the two strength with diameter (the larger diameter, the smaller strength), are not fully satisfied, which is caused by the different steel cable fraction.

KEYWORDS

Steel cable-GFRP composite rebar, hybrid principle, bonding performance, tensile elastic modulus

INTRODUCTION

With the social and economic development, steel as a traditional civil engineering structure material can’t satisfy the application requires, because of the severe corrosion and high density of steel. FRP (Fibre Reinforced Polymer) material, for its light weight, high strength and good durability, is first used in space and defence industry. In recently years, there are more and more research and applications of FRP material in civil engineering structure, which substitute for steel in existing structures for strengthening and new structures as reinforcement. FRP material can be applied in the field of corrosion environment structures, such as bridge, tunnel, dam, marine structures and large span space structure, as super large bridge, stadium. There are some troubles for the FRP practical application in civil engineering, such as relative high price, low tensile modulus (S. Kocaoz 2005), and weak shear property. The most applicable FRP material is GFRP (Glass Fibre Reinforced Polymer), because of low price comparing to CFRP (Carbon Fibre Reinforced Polymer). The tensile modulus of GFRP material is about 1/4 of steel. So as reinforcing elements to new constructing civil structure, GFRP rebar can’t exhibit its strength property, because of large deformation. And the deformation is the crucial designing parameter in FRP rebars reinforced concrete, while the bearing capacity is reference parameter, which is different from steel rebar reinforced concrete (Zhang 2006).

To cater the deformation requirement, the GFRP rebar reinforcing ratio must be increased, but its strength can’t be exploited. And the large ratio of reinforcement may lead the construction difficulties in its application. So using high modulus FRP rebar can optimize the design and construction of FRP rebar reinforced concrete. To GFRP rebar there are some methods to improve the elastic modulus: 1) Fibre material hybrid, by adding another kind of high modulus fibre (Carbon fibre). According to the modulus hybrid principle of FRP material, and the different ultimate strain of the different kind of fibre, FRP rebar made of fibre hybrid doesn’t only has higher modulus than GFRP, but also display bi-linearity of stress and strain curve, which will ensure the application reliability (He 2007, Nanni, bakis 1996, Ning Pan 1998). But by the expensive fibre, the price of this kind of rebar is relative high. 2) Steel material as core, spiral winding FRP material as out layer. This kind of rebar also has large ductility, but the modulus improvement is limited, and the ultimate tensile strength decrease (Zheng 2004, Nanni 2001). The reason for limitation of modulus and strength is the relative low modulus of FRP outer layer and low strength of core steel. Moreover D. Serdjus (2003) using carbon and glass FRP as core, and steel...
wire strand as out-lay, made the composite cable, which has good ductility and good impact resistance and high modulus, but for out-lay of steel wire, there is potential durability problem.

In this study, according to hybrid principle of composite, SGFRP (steel cable GFRP composite) rebar was firstly made, which high-strength steel cable as the core, and unidirectional GFRP package around the cable. The steel cable is as high modulus reinforcing element, and the GFRP as the protecting layer of cable. The significance of steel cable GFRP rebar is to produce a relative cheaper, higher modulus and good durability FRP rebar. The physical, tensile, and bonding properties of 4 kind diameters steel cable GFRP composite rib rebar was made, the results indicates that composite rebar has higher modulus and bonding performance than pure GFRP rebar.

STEEL CABLE GFRP REBAR FABRICATION AND EXPERIMENTAL PREPARATION

Steel Cable GFRP Ribbing Composite Rebar Fabrication

Steel cable GFRP ribbing composite rebar is manufacture by pull-winding process including the following 5 steps: (1) fibre yarn resin impregnating, (2) rebar performing, (3) rib winding, (4) oven curing, and (5) pulling. Figure 1 shows the experimental setup. The rib is made of glass fibre yarns with the style of double helix, and the pitch is the same as the length of diameter.

According to the hybrid principle, the more steel cable content, the higher tensile modulus of the composite rebar, but to guarantee the durability performance of the rebar, there should be a definitive thickness of FRP layer. At the same time, to confirm the co-deformation of the composite elements, and almost the same thickness FRP protecting layer, the steel cable should be specially arranged in the section in the form of regular or unfilled corner hexagon. To cater the cable arrangement in the section, two kinds of steel cables with the diameters of 1.5 and 2mm were selected for different diameter composite rebar. Basing on the above considerations, we give the composite rebar material composition and cable arrangement in table.1. The fibre and resin used in this study are E glass fibre and epoxy resin, respectively.

<table>
<thead>
<tr>
<th>Number of rebar</th>
<th>Designing diameter(mm)</th>
<th>Fibre volume fraction(%)</th>
<th>Cable volume fraction(%)</th>
<th>Cable arrangement in the section</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGFRP-8</td>
<td>8mm</td>
<td>44.85</td>
<td>26.75</td>
<td><img src="image1" alt="Diagram" /></td>
</tr>
<tr>
<td>SGFRP-10</td>
<td>10mm</td>
<td>39.78</td>
<td>30.98</td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>SGFRP-12</td>
<td>12mm</td>
<td>42.84</td>
<td>28.88</td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>SGFRP-14</td>
<td>14mm</td>
<td>47.46</td>
<td>23.75</td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

In the section arrangement picture, the red one represents 1.5mm steel cable; the black one is 2mm cable.

**Experimental Preparation**

*Density and cross section measurement*

For the deformed surface of the composite rebar, drainage method is employed to measure the cross section. From Eqs. (1) and (2), we can calculate the density. The measurement setup is shown in figure 2.

\[
S = \frac{(m_1 - m_2)}{L} \quad (1)
\]

\[
\rho = \frac{m_0}{(m_1 - m_2)} \quad (2)
\]

Where \( S, \rho \) are the cross section and density of the composite rebar, respectively. \( m_1, m_2 \) are the mass of the composite rebar in air and water. \( m_0, L \) are the mass and length of the composite rebar. The number of each series of composite rebar is five, and the length is 100mm.
Tensile performance measurement

The loading speed of the experiment is 1.5mm/min. The deformation can be read from the indicator, with 50mm length gauge. To avoid the shear failure of the rebar, the rebar is anchored by resin filling weld type anchor. The tensile experimental setup is shown in figure 3.

Bonding performance measurement

The pull-out bonding performance of 4 series of composite rebar was measured. The bonding length is 5 times of the diameter, and the concrete block has a dimension of $100 \times 100 \times 100$mm. Each series of composite rebar has 3 specimens. During our experiment, the loading rate is set to be 0.5mm/min. The load and deformations in the free and loading end are measured simultaneously. The pull-out bonding experimental setup was shown in figure 4.

RESULT ANALYSIS AND DISCUSSION

Figure 5 shows the composite rebar picture, It can be seen that the steel cable arrangement has the same configuration as designing.

Table 2 lists the basic physical parameters, such as measurement diameter, density, and cross-section of the rebar. It is obvious that the 4 series of rebar have different density, which is ascribed to the different steel cable content. Sample SGFRP-10 has the largest density of 3.6g/cm$^3$, which is about 1/2 of steel density.
Table 2. Basic physical parameters of composite rebars

<table>
<thead>
<tr>
<th>Number of rebar</th>
<th>Measurement diameter(mm)</th>
<th>Density(g/cm³)</th>
<th>Measurement cross-sectional(cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGFRP-8</td>
<td>8.5</td>
<td>3.16</td>
<td>0.56</td>
</tr>
<tr>
<td>SGFRP-10</td>
<td>10.8</td>
<td>3.60</td>
<td>0.91</td>
</tr>
<tr>
<td>SGFRP-12</td>
<td>12.9</td>
<td>3.21</td>
<td>1.31</td>
</tr>
<tr>
<td>SGFRP-14</td>
<td>15.1</td>
<td>2.94</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Tensile performance

To SGRP-8 and SGFRP-14, the composite rebar broke with the GFRP outlayer, the GFRP and steel cable broke at the same time. But to SGFRP-10 and 12, the GFRP out-layer breaking first, and then the inner steel cable core broke. From figure 6, a linear dependence of the tensile stress on the strain can be clearly seen. According to the composite hybrid law, Young modulus \( E \) can be expressed as:

\[
E = V_i E_i
\]

(3)

Where \( V_i \) and \( E_i \) is the volume fraction and Young modulus of \( i \)th component of the composite rebar. From table 3 and figure 7, we find that the experimental result follows the hybrid law. The composite rebar with the larger steel cable fraction has the larger modulus. The tensile modulus of four kinds of composite rebar is all larger than pure GFRP rebar (not more than 50GPa for rib GFRP rebar). To the tensile strength of the composite rebar, the principle between tensile strength and diameter was not completely met, which is the larger diameter, the smaller tensile strength existing in pure FRP rebar.

From table 1, we can see that the SGFRP-10 rebar is wholly made of 1.5mm steel cable (19 filaments with one strand), but the other three are made of 2.0mm diameter steel cable (7 filaments with 6 strands). The steel filaments in the steel cable are not completely unidirectional. To the 2.0mm cable there is larger deformation in steel filaments than 1.5mm cable. And the calculating sectional area of steel cable here is calculated by the linear density and volume density of the steel cable below:

\[
s = \rho_\text{L} / \rho_v
\]

(4)

Where \( S \), is the calculating sectional area of the steel cable (cm²), \( \rho_\text{L}, \rho_v \) are the linear and volume density of the steel cable (g/cm³, g/cm). Because of the deformation of steel filament, the calculating sectional area is larger than real one. And the difference between calculation and true section of 2.0mm cable is larger than 1.5mm cable. The cable fraction of the composite rebars shown in table is not accurate. So there are large differences of modulus for the composite rebar with different diameter rebar.

From figure 7, it’s indicated that the tensile strength of the rebars agree the rule of the larger fraction of steel cable, the higher tensile strength. In this paper our aim is to improving the modulus of FRP rebar, and don’t think about the subsequence of glass fibre and steel cable, which can lead the pseudo yield of the rebar. So the glass fibre and steel cable fraction ratio is not defined, which is mainly kept the large steel cable large fraction. In SGRFRP rebar, the ultimate strain of glass fire is smaller than steel cable, so in the tension process, presuming them bonding well, the glass fibre first breaks, and then the steel cable. To SGRFRP-8 and 14, after the glass fibre broke, the load carried by glass fibre transferring to steel cable, but because of low steel cable fraction, the cable can’t afford the total load, so the composite rebar broke with the breaking of GFRP out-layer. While to SGRFRP-10, 12, because of relative high steel fraction and low glass fibre fraction, the steel cable can bear the load after glass fibre breaking. There should be a pseudo yield happened to the composite rebar. From table 1, we can see that the total reinforcement fractions of four type of rebar are all about 70%. But for the property variance of glass fibre, the tensile strength of steel cable is larger than the glass fibre. So in a word, the large steel cable fraction is, the higher tensile strength the composite rebar will have.

Table 3. Tensile performances of the composite rebars

<table>
<thead>
<tr>
<th>No.</th>
<th>Tensile strength (MPa)</th>
<th>Tensile modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>Variance</td>
</tr>
<tr>
<td>SGFRP-8</td>
<td>779.1</td>
<td>39.0</td>
</tr>
<tr>
<td>SGFRP-10</td>
<td>1027.5</td>
<td>27.5</td>
</tr>
<tr>
<td>SGFRP-12</td>
<td>836.6</td>
<td>14.1</td>
</tr>
<tr>
<td>SGFRP-14</td>
<td>771.8</td>
<td>23.7</td>
</tr>
</tbody>
</table>

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Bonding performance

Figure 8 displays the experimental results of bonding stress and slip of the composite rebar. The damage formats of the four kinds of composite rebar, except of SGFRP-10, are all the slipping of the composite rebars, with the damage of winding glass fibre strand. But to the SGFRP-10 rebar concrete cracking happened to all of three specimens; The bonding strength of four kinds of composite rebar with the loading end slip deformation less than 1mm, is individually 16, 19, 14 and 12 MPa, and the maximum bonding strength is 18, 19, 17 and 13 MPa. From above mentioned maximum bonding strength, SGFRP-10 is an exception, which doesn’t obey the rule of bonding strength with diameter (the larger diameter, the smaller bonding strength), and the reason is for its large tensile elastic modulus (for the large steel cable fraction). The bonding behaviour between FRP rebar and concrete is mainly supplied by the friction, mechanical gear between FRP rebar and concrete. So the rebar surface deformation controls the bonding performance. To the commercial available FRP rebar, the surface deformations are mainly made of curing resin, deformation of axial fibre and helix winding resin impregnated fibre. But sometime the large deformation may cause the mechanical performance decreasing. For example the FRP rebar with large rib made of deformed axial fibre, has relative small tensile elastic modulus and large creep, because of fibre bending. And the bonding performance is also affected by the tensile modulus of FRP rebar. Lu (2005) tested the bonding behaviours of CFRP and GFRP rebar with same diameter and surface deformation, and the CFRP displayed better bonding performance than GFRP rebar. And the difference between two kinds of rebar is the difference of tensile modulus. So SGFRP composite rebar doesn’t only have relatively higher tensile elastic modulus, but also better bonding performance with concrete than pure GFRP rebar (with same surface configuration).
CONCLUSIONS

In this paper, we firstly introduced fabrication progress of the steel cable GFRP (SGFRP) rebar with rib. The tensile property and bonding behaviour of four different diameters SGFRP composite rebar were examined. From this study, we obtained the following conclusions:

1. The composite rebars have a relative high tensile modulus, which is determined by the steel cable fraction. However, the relation of strength and diameter of FRP rebar is not fully obeyed, also because of different steel cable fraction.

2. To keep the co-deformation of reinforced element (steel cable and GFRP) and ensure durability performance, the steel cable must be regularly arranged in the cross-section of the composite rebar. So to specific diameter composite rebar, the steel cable fraction can only be improved by using small diameter steel cable. To the composite rebar made in this paper, SGFRP-10 rebar has the best tensile performance, with 89GPa tensile modulus, about 1000MPa tensile strength.

3. The SGFRP composite rebar does not display common relation of bonding strength with diameter, which is caused by the different tensile modulus of the rebar. The improvement of the tensile modulus of FRP rebar can improve the bonding behaviour under the same surface configuration.

In this paper, to the four kinds of composite rebars with different diameter shown different tensile modulus, which is caused by the different steel cable fraction, and will make trouble in its designing and application. So the future work should be focused on selecting even thinner steel cable or high strength wire to keep the same steel fraction in the section of different diameter composite rebar.

REFERENCES


