EXPERIMENTAL STUDY OF PERFORMANCE OF STEEL-FRP (FIBER REINFORCED POLYMER) COMPOSITE BAR

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ABSTRACT

Uniaxial and repeated tensile tests of the factory produced Steel-FRP (fiber reinforced polymer) composite bar (SFCB) were conducted, the process of destruction and damage characteristics were observed, the initial modulus of elasticity, post-yielded stiffness, yield strength, ultimate strength, unloading stiffness, and residual strain of the specimens were measured. The stress-strain test curve of SFCB exhibited a stable post-yielding stiffness after its core steel bar yielded, showed small residual strain and good recoverability under cyclic tensile load. Since the theoretical model for stress-strain curve of SFCB under uniaxial load derived according to the mixing rule has large error with repeated tensile test data, the unloading stiffness of SFCB under cyclic load is constructed by statistic analysis of the characteristics of repeat tensile stress-strain relationship test curve. The statistical unloading stiffness can display soundly the law of SFCB degrades with the repeated loading, and the predicted results are in good agreement with experimental results.

KEYWORDS

Steel-FRP composite bar (SFCB); post-yield stiffness; mechanical properties; cyclic load; unloading stiffness.

INTRODUCTION

Current advances in earthquake engineering favor performance-based approaches for seismic design, and many existing structures do not satisfy the new seismic design philosophy. It is realized (Kawashima 1998, Christopoulos 2003, 2004) that certain post-yield stiffness (stiffness after yielding) of concrete structures can reduce residual deformation after earthquakes effectively, thus ensuring good recoverability. Iemura et al. (2002) developed a new concrete pier with small residual deformation and good recoverability under earthquakes by mixing ingeniously bonding and non-bonding steel bars in conventional concrete pier to ensure post-yield stiffness of the structure after yielding. Ikeda et al. (2002) proposed a new design concept for concrete piers in which vertical prestressing was introduced only in the critical sections; pseudo-dynamic test results verified that piers exhibit excellent seismic performance with advanced restoration capabilities against near field earthquakes.

A new reinforcing bar is proposed in this paper, named Steel-FRP composite bar (SFCB) (Wu 2006, 2009) which is a compound of elasto-plastic steel and linear elastic fiber with stable post-yield stiffness (Figure 1). Moreover, steel and fiber reinforced polymer (FRP) can be complementation for each other in the composite:

![Stress-strain relationship and configuration of SFCB](image1.png)

(a) Stress-strain relationship of SFCB

Figure 1. Stress-strain relationship and configuration of SFCB

(b) Longitudinal components

An new reinforcing bar is proposed in this paper, named Steel-FRP composite bar (SFCB) (Wu 2006, 2009) which is a compound of elasto-plastic steel and linear elastic fiber with stable post-yield stiffness (Figure 1). Moreover, steel and fiber reinforced polymer (FRP) can be complementation for each other in the composite:
FRP has traits of high strength, low elastic modulus, poor ductility, good durability and light weight; while steel is just the opposite. Combining the advantages of the two, the new composite material is supposed to have outstanding comprehensive properties like high strength, high elastic modulus, and good ductility, anti-erosion and low cost. Axial tensile and repeated tensile test are conducted in this paper, the mechanical properties of SFCB is investigated.

**SFCB FACTORY PRODUCS**

The ultrusion devices of FRP tendon was renovated as the machine to achieve industrialized production of SFCB (Wu 2009), Figure 1b and Figure 1c shows the configuration of the factory products of pultruded SFCB, with constant spacing between their spiral ribs, which contain both resin and bended longitudinal fiber formed by plastic tape, and the batch of SFCB produced in this way was used as the studying object in this test.

<table>
<thead>
<tr>
<th>Type</th>
<th>Elastic modulus (GPa)</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Density (g/cm³)</th>
<th>Diameter (μm)</th>
<th>Elongation rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon fiber</td>
<td>230</td>
<td>-</td>
<td>3680</td>
<td>1.80</td>
<td>8</td>
<td>1.6</td>
</tr>
<tr>
<td>Basalt fiber</td>
<td>90</td>
<td>-</td>
<td>2250</td>
<td>2.63</td>
<td>13</td>
<td>2.5</td>
</tr>
<tr>
<td>Steel bar</td>
<td>200</td>
<td>420</td>
<td>-</td>
<td>7.80</td>
<td>10³</td>
<td>15.0</td>
</tr>
<tr>
<td>Resin</td>
<td>3.6</td>
<td>-</td>
<td>95</td>
<td>1.06</td>
<td>-</td>
<td>6.1</td>
</tr>
</tbody>
</table>

This test applied two kinds of fiber to produce SFCB, T700-12K carbon fiber and 2400Tex basalt fiber. Crescent-rib steel bar with a diameter of 10 mm was used as the inner core steel bar and Atlac430 bisphenol A epoxy vinyl ester resin was applied (Table 1). There are four types of SFCB, as shown in Table 2, where tex represents the weight of single bundle fiber per kilometer and 12 k means each bundle of carbon fiber has 12,000 fibers.

<table>
<thead>
<tr>
<th>Types</th>
<th>Diameter of inner steel bar (mm)</th>
<th>Type of fiber</th>
<th>Fiber amount (bundle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C40S10</td>
<td>10</td>
<td>Carbon fiber (12k)</td>
<td>40</td>
</tr>
<tr>
<td>C24S10</td>
<td>10</td>
<td>Carbon fiber (12k)</td>
<td>24</td>
</tr>
<tr>
<td>B30S10</td>
<td>10</td>
<td>Basalt fiber (2400Tex)</td>
<td>30</td>
</tr>
<tr>
<td>B20S10</td>
<td>10</td>
<td>Basalt fiber (2400Tex)</td>
<td>20</td>
</tr>
</tbody>
</table>

**TEST SET UP**

**Anchorage for SFCB**

The ratio of transverse compressive strength to axial-tensile strength of FRP is only about 1/20. Therefore, conventional clamping anchorage does not fit SFCB for too weak transverse compressive strength would result in premature invalidation of the outside fiber. Sleeve bonding anchorage (Figure 2a) is adopted to ensure the anchoring performance. The high strength of the bonding material ensured good bonding effects that met the requirements of this test. To avoid premature failure of this region, additional fiber cloth was applied locally as protective and reinforcing cover. SFCB specimens finally finished are shown in Figure 2b.
Loading Program

The test was carried out on MTS (material testing system) electro-hydraulic servo fatigue testing machine. Monotonic loading controlled by displacement was applied in this test. The speed of tension loading was 0.2 mm/min at the beginning; and later after all wrapped fiber of SFCB fractured, the speed increased to 2 mm/min till the failure of the inner core steel bar.

During repeated loading, single-cyclic load was applied with level difference of equal displacement. Plastic strain would happen to SFCB after the yielding of the inner steel bar. As a result, to avoid compressive fracture during unloading, one end of SFCB specimen was fixed while leaving the other free. As shown in Figure 3, the lower end of anchorage was put through a steel plate with a hole and fixed soundly with nuts on the upper and lower opening respectively; for the steel plate on the top, nut was only used on the upper opening of the sensor and anchorage at the lower opening was unfixed. Hence, the top of the specimen was a compression-free end and undertook tension merely during repeated loading. When the tensile load of the specimen decreased to 0, the nut on its top would separate from the sensor.

Specimen design

There were 10 specimens in uniaxial tensile test and 8 specimens in repeated loading test. The number and dimensions of each specimen can be seen in Table 3, where “M” means monotonic tensile loading, “C” means cyclic tensile loading.

<table>
<thead>
<tr>
<th>Number</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
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</thead>
<tbody>
<tr>
<td>SFCB</td>
<td>C24S10</td>
<td>C24S10</td>
<td>C40S10</td>
<td>C40S10</td>
<td>B20S10</td>
<td>B20S10</td>
<td>B20S10</td>
<td>B20S10</td>
<td>B30S10</td>
</tr>
<tr>
<td>Number</td>
<td>M10</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
<td>C5</td>
<td>C6</td>
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<td>C8</td>
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<tr>
<td>SFCB</td>
<td>B30S10</td>
<td>C24S10</td>
<td>C40S10</td>
<td>B20S10</td>
<td>B20S10</td>
<td>B30S10</td>
<td>S10</td>
<td>S10</td>
<td></td>
</tr>
</tbody>
</table>

TEST RESULTS

Axial tensile test results

Figure 4a shows the typical load-strain curves of SFCB specimens under axial tensile loading. The tensile loading test had following characteristics: 1. the failure could be divided into distinctive stages including steel yielding, fiber fracture and steel tensile failure, exhibiting obvious and stable post-yield stiffness. 2. Spots of fiber fracture, yielding and tensile failure of steel were comparatively concentrated to a specific region, leaving other sections unaffected by fiber failure or debonding of fiber from the inner core steel bar, etc. 3. Adhesive at anchorage entrance showed good anchoring effects without any obvious deformation or crack, while fiber cover at anchorage end most had longitudinal cracks in the later period and its poor protective strength should be enhanced.

Repeated tensile test results

From load-strain curves of SFCB and steel bar specimens under repeated loading in Figure 4, it is found that when strain was comparatively small, the unloading curve of SFCB could be regarded as a straight line after yielding. The reloading curve, largely overlapping the unloading curve, could pass through the last peak point. Repeated load had no obvious weakening effects on the tensile bearing capacity of SFCB. As the development of plastic strain, the unloading curve of SFCB represented more and more evident non-linear characteristics. In the process of unloading, unloading stiffness of SFCB decreased gradually and the reloading curve stopped overlapping the unloading curve but still could pass through the last peak point, forming with unloading curve a close hysteretic loop. Figure 5 shows the final failure. All of the failure happened in the middle of the specimens, which indicated the anchorage method was effective.

Through comparing the repeated tensile loading curves of SFCB and steel bar specimens (Figure 6), we can find that under the same unloading peak strain, the unloading curve of steel bar specimen maintained the shape of a straight line and a ways overlapped its reloading curve while SFCB specimen has a pinching effect, that is, SFCB had a smaller residual strain than steel bar when unloading from the same strain.
THEORETICAL CALCULATION FOR STRESS-STRAIN RELATIONSHIP OF SFCB

Suppose the wrapped fiber had fine interface bonding and harmonious deformation with the inner core steel bar in the process of loading, namely, they had the same strain in one section, mixing rule could be used to predict the stress-strain relationship of SFCB.

According to the mixing rule, the value of tensile property of SFCB could be got from those of steel and fiber. Equations of tensile stress $\sigma_f$ and elastic modulus $E_f$ are as follows:

$$\sigma_f = \varepsilon (E_s A_s + E_f A_f) / A, \quad 0 \leq \varepsilon \leq \varepsilon_y$$  (1)

$$E_f = (E_s A_s + E_f A_f) / A, \quad 0 \leq \varepsilon \leq \varepsilon_y$$  (2)

Where $E_s$, $A_s$ and $\varepsilon_y$ are the elastic modulus; cross section area and yield strain of steel respectively; $E_f$ and $A_f$ are the elastic modulus and cross section area of outside continuous fiber cover; $A_r$ is the area of resin in the composite bar; and $A$ is the total area of cross section of SFCB, $A = A_f + A_r$. 

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Figure 4. Load-strain cure of specimens under tensile and repeated tensile loading

Figure 5. General view of failed SFCB

Figure 6. Comparison between SFCB and steel bar
Then, equations of tensile stress $\sigma_{II}$ and elastic modulus $E_{II}$ from the yielding of steel to the fracture of outside fiber cover are as follows:

$$\sigma_{II} = \left( f_y A_y + \varepsilon E f A_f \right) / A, \quad \varepsilon_y < \varepsilon \leq \varepsilon_{fu}$$

(3)

$$E_{II} = \left( E f A_f \right) / A, \quad \varepsilon_y < \varepsilon \leq \varepsilon_{fu}$$

(4)

Where $f_y$ is the yield stress of steel and $\varepsilon_{fu}$ is the fracture strain of outside wrapped fiber.

At last, without considering the hardening effect of steel, equations of tensile stress $\sigma_{III}$ and elastic modulus $E_{III}$ from the fracture of outside fiber to the fracture of steel are as follows (to be consistent with previous study, the area of SFCB was counted in calculating its stress, though the outside fiber cover has fractured):

$$\sigma_{III} = f_y A_y / A, \quad \varepsilon_{fu} \leq \varepsilon \leq \varepsilon_{s,max}$$

(5)

$$E_{III} = 0, \quad \varepsilon_{fu} \leq \varepsilon \leq \varepsilon_{s,max}$$

(6)

Where $\varepsilon_{s,max}$ is the fracture strain of steel.

Thus, the stress-strain relationship of SFCB can be concluded in Eq. (7):

$$\sigma_{sf} = \begin{cases} 
E_i \varepsilon_{sf} & , 0 \leq \varepsilon_{sf} < \varepsilon_{sfy} \\
 f_{sfr} + E_{II} (\varepsilon_{sf} - \varepsilon_{sfr}) & , \varepsilon_{sfr} \leq \varepsilon_{sf} \leq \varepsilon_{sfr}
\end{cases}$$

(7)

Where $\sigma_{sf}$ and $\varepsilon_{sf}$ are the stress and strain of SFCB respectively; $E_i$ is the elastic modulus of SFCB before yielding; $E_{II}$ is the post-yield stiffness of SFCB; $f_{sfr}$ and $\varepsilon_{sfr}$ are the yield stress and yield strain of SFCB respectively; $f_{sfu}$ and $\varepsilon_{sfu}$ are the ultimate stress and ultimate strain of SFCB when its wrapped fiber fractured; $f_{sfr}$ is the residual strength of SFCB; $f_{sfr}$, $f_{sfu}$ and $f_{sfr}$ are obtained by substituting $\varepsilon_y$, $\varepsilon_{fu}$ and $\varepsilon_{s,max}$ into Eqs. (1), (3) and (5).

Calculated value compared with test value

Based on test results in Table 4 and the cross section area of SFCB $A_{sd}$ calculated from measured diameter of SFCB specimen, equivalent elastic modulus $E_i$, yield strength $f_{sfy}$, post-yield strength $E_{II}$ and ultimate strength $f_{sfu}$ of each SFCB specimen can be calculated. The comparison of test value with calculated value is shown in Table 4. Results of both of the comparisons show that the theoretical model has fine precision.

<table>
<thead>
<tr>
<th>Number</th>
<th>$A_{sd}$ (mm$^2$)</th>
<th>$E_i$ (GPa)</th>
<th>$f_{sfy}$ (MPa)</th>
<th>$E_{II}$ (GPa)</th>
<th>$f_{sfu}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp</td>
<td>Theo</td>
<td>Exp</td>
<td>Theo</td>
<td>Exp</td>
<td>Theo</td>
</tr>
<tr>
<td>M1</td>
<td>95.0</td>
<td>158.9</td>
<td>142.3</td>
<td>391.4</td>
<td>313</td>
</tr>
<tr>
<td>M2</td>
<td>98.5</td>
<td>168.5</td>
<td>142.3</td>
<td>356.3</td>
<td>313</td>
</tr>
<tr>
<td>M3</td>
<td>109.4</td>
<td>160.9</td>
<td>155.5</td>
<td>335.6</td>
<td>342.2</td>
</tr>
<tr>
<td>M4</td>
<td>113.1</td>
<td>153</td>
<td>155.5</td>
<td>343.1</td>
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</tr>
<tr>
<td>M5</td>
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<td>141.8</td>
<td>137.1</td>
<td>322.6</td>
<td>301.7</td>
</tr>
<tr>
<td>M6</td>
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<td>147</td>
<td>137.1</td>
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<td>301.7</td>
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<td>137.4</td>
<td>137.1</td>
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<td>M10</td>
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<td>123.5</td>
<td>142</td>
<td>271.8</td>
<td>312.3</td>
</tr>
</tbody>
</table>

Stress-strain relationship of SFCB under repeated tensile loading

SFCB is a new reinforcing material for ideal seismic structures in our research. The unloading stiffness of SFCB will have a great influence on the dynamic analysis precision of SFCB reinforced concrete structures. Thus, it is necessary to learn the stress-strain relationship of SFCB under repeated load.
According to load-strain curves of these 6 SFCB specimens under repeated load, the unloading stiffness was basically the same as the stiffness before yielding $E_I$ in hysteretic loop before load reached the yield load; after load exceeded the yield load, the unloading stiffness decreased gradually for the development of plastic strain. The changes of unloading stiffness of SFCB in the repeated loading test $E_u$ as the development of plastic strain.

Based on statistical analysis, equation for the unloading stiffness is as follows:

$$
E_u = \frac{E_I}{1 + \gamma \frac{\varepsilon}{E_y}}
$$

where $\gamma (\gamma \geq 0)$ is the degradation coefficient of stiffness ($\gamma = 0.055$ for SFCB specimens in this paper). This equation, meeting structural maturity in mathematics, takes into account mainly the effects of plastic development after the yielding of SFCB on its unloading stiffness.

CONCLUSIONS

This paper conducted first an explorative research on key issues like the composite technique of SFCB. Uniaxial tensile test devices were designed in this paper to conduct tests to determine the mechanical properties of industrialized SFCB products.

The initial elastic modulus, post-yield stiffness, yield strength, ultimate strength, unloading stiffness and residual deformation were studied. Test results showed that the stress-strain curve of SFCB was linear before fiber fracture and had stable post-yield stiffness after yielding under monotonic load. Under repeated tensile loading, SFCB had small residual deformation and good recoverability; its strength and stiffness could stay unaffected from the repeated load.

Theoretical models for SFCB under monotonic load was derived from the mixing rule: the former was in good agreement with test data, proving the mixing rule can be used to predict and design the mechanical properties of SFCB. The stress-strain relationship of SFCB was constructed and its unloading stiffness is calculated by statistical analysis.

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REFERENCES


