Experimental Study on Concrete Beams Strengthened with Embedded Smart Carbon Fiber Reinforced Plates

Langni Deng, Risheng Luo, Xiangguo Qian, Jinchao Ma and Xiaoxia Huang

ABSTRACT

Carbon Fiber Reinforced Polymer (CFRP) has been widely used in the field of structural reinforcement and rehabilitation. It would be incorporated with the Optical Fiber Bragg Grating (OFBG) sensing feature, developing the smart carbon fiber reinforced plates (CFRP-OFBG). And then, embedded experiment on five rectangular section beams strengthened with the smart carbon fiber plates were carried out and detected wavelength variation by OFBG to calculate the strain value of carbon fiber plates. Measured center wavelength variation of CFRP-OFBGs and measured strain of CFRPs from strain gauges at the same location were analyzed and plotted by computer. The results demonstrated that: on the one hand, both wavelength and strain showed a better linear relationship, and the slope was about $1.2 \text{ pm/ } \mu \varepsilon$. It was in good agreement with the CFRP-OFBG strain sensing degrees, which was $1.281\text{ pm/ } \mu \varepsilon$. On the other hand, using CFRPs to strengthen concrete beams could improve the yield load and ultimate load and reduce deformability of concrete beams. In summary, there are the widely application prospect and value on structural health monitoring and structural reliability analysis in the future.

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INTRODUCTION

In recent years, owing to increase of service period and erosion of worse environment in the building structure, experiment and detection on the building structure demonstrated that more and more building structures had shown the phenomenon of decrease in the load capacity at not reaching the design working life.

Faced with such serious problems, a great deal of researchers had extensively concentrated on the rehabilitation of building structures by structural strengthening technique. Traditional strengthened techniques still play a great role in the file of structure reinforcement and rehabilitation, such as the method of increase section, prestressed strengthening, changing structure transfer force strengthening and external steel strengthening, and so on [1]. Over past, many structures were destroyed when steel bars were corroded. So a large number of researches were tested to find a new type material to replace the steel bars. Early test on concrete using carbon fiber reinforced polymer in 1990s showed that carbon fiber reinforced polymer was an ideal material [2-3]. Carbon Fiber Reinforced Polymer (CFRP) is a new kind of material, which has a lot of desirable characteristics, for instance light weight, high strength and high resistance to corrosion [4-5]. Because of their better performances, CFRPs have become more and more popular in strengthening and repairing structures [6]. At present, building structure strengthened with CFRPs has obtained fully affirmative from many scholars both domestic and abroad. For example, the works were done by Wight et al. and EI-Hacha et al., who found that CFRP could notably improve serviceability as well as the ultimate strength [7-8]. Deng et al. had achieved the experimental study on the flexural behavior of six reinforced concrete beams strengthened with prestressed CFRPs, and the resulting CFRPs could improve flexural load capacity and resistance to crack of member [9]. Zhang et al. tested on the steel beams strengthened with CFRPs, and demonstrating structural strengthened by CFRPs could improve flexural load capacity, stiffness and ductility of member to a certain extent [10]. Testing on eight reinforced concrete T-beams by Han T. Choi et al., they found that partially bonded beams showed an enhancement of deformability [11].

For reinforced concrete strengthened with CFRPs, stress state and property monitoring during the period of working are an urgent problem to be solved after strengthened with CFRPs. Because of electrical-resistant strain gauges are easily disturbed from surrounding environment, they are not applicable for long-term use on structural health monitoring. Optical Fiber Bragg Grating (OFBG) is a kind of better property sensing element, which obtains monitoring information by reflected wavelength to perceive external stress-strain. In 1990s, some researchers tested on a large of concrete beams, and they concluded that the Optical Fiber Bragg Grating could be used to monitoring the behavior of the concrete beams. The results showed that using OFBG sensors to measure the strain or stress agreed a quite well with the calculated values [12]. Because of it has better properties of higher resistance to electromagnetism disturbed, higher sensibility, easy to bury and work under harsh
environments that they were used in various fields [13-16]. But Optical Fiber Bragg Grating also has some drawbacks, such as fragile texture and so on. If they are not encapsulated, they are easily to destroy and lead to failure in the structural health monitoring during the period of working. In the work of Ou et al., experimental study showed that embedded fiber reinforced polymer bar with optical fiber bragg grating could develop CFRP-OFBG composite material which had the properties of higher strength and smart detection [17]. Moreover, Deng et al. proposed the combination of carbon fiber reinforced plates and buried optical fiber bragg grating, also developing a new kind of composite material which had the highly desirable characteristics both CFRP and OFBG [18].

Compared with external bonded CFRP on the surface of concrete beams, Embedded bonded method, grooves are slotted into the concrete beams firstly and then CFRPs are bonded in the grooves with epoxy, has been researched by many researchers [19-20]. In this paper, Embedded experiment on five rectangular section beams strengthened with the smart carbon fiber plates were carried out and detected wavelength variation by the OFBG to calculate the strain value of carbon fiber reinforced plates. Measured center wavelength variation of smart carbon fiber plates and measured strain of carbon fiber plates from strain gauges at the same location were analyzed and plotted by computer. Experiment results showed that CFRP-OFBG smart carbon fiber plates have the widely application prospect and value on structural health monitoring and structural reliability analysis in the future.

DEVELOPMENT OF SMART CARBON FIBER PLATES

In order to achieve the demand of structural health monitoring strengthened with CFRP, we needed to develop the CFRP-OFBG smart carbon fiber reinforced plates. Reinforced material of CFRP-OFBG smart carbon fiber plates were two-way and orthogonal CFRP silks, and reinforced matrix of them adopted epoxy adhesive. Because of the desirable characteristics of higher resistance to electromagnetism disturbed and higher sensibility, Optical Fiber Bragg Grating was treated as sensing material of smart monitoring. They paralleled with CFRP silks to prevent forming a region with much epoxy adhesive around the OFBG, when Optical Fiber Bragg Grating sensors were buried in the CFRP plates. In this way, it could further decrease and reduce non uniform stress zone around the sensors and the loss of measurement accuracy of OFBG. The processes of CFRP-OFBG plates fabrication were the same as traditional CFRP plates, and CFRP-OFBG plates are shown in Figure 1. The differences of OFBG plates were layout position, comparing with ordinary CFRP plates. For the sake of better coordinated deformation with CFRP-OFBG plates, operators should control the OFBG position in the middle of CFRP silks, respectively.
BASIC MATERIAL PROPERTIES OF SMART CARBON FIBER PLATES

In this experiment, two-way and orthogonal CFRP silks, epoxy adhesive, Optical Fiber Bragg Grating were used as reinforced materials, reinforced matrix and smart monitoring materials, respectively. Table 1 presents the measured performance parameters of carbon fiber plates by tensile test and Table 2 presents the parameters of OFBG by GM8037 high-resolution OFBG sensor measuring.

Figure 1. Making device of CFRP-OFBG plates.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Tensile strength (Mpa)</th>
<th>Tensile modulus (Mpa)</th>
<th>The rate of cracked elongation (%)</th>
<th>width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2800</td>
<td>164000</td>
<td>1.7</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>2800</td>
<td>164000</td>
<td>1.7</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>2800</td>
<td>164000</td>
<td>1.7</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optical fiber spacing(mm)</th>
<th>Center wavelength λ_B (nm)</th>
<th>BW@-3dB (nm)</th>
<th>SLSR (dB)</th>
<th>Reflectivity(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1530.968</td>
<td>0.227</td>
<td>20.63</td>
<td>93.41</td>
</tr>
<tr>
<td>300</td>
<td>1531.970</td>
<td>0.258</td>
<td>19.19</td>
<td>94.92</td>
</tr>
<tr>
<td>300</td>
<td>1533.064</td>
<td>0.226</td>
<td>17.81</td>
<td>92.40</td>
</tr>
</tbody>
</table>

OFBG was proved to be a kind of better strain sensing element by strain sensing test of CFRP-OFBG. Smart carbon fiber reinforced plates not only possessed higher tensile strength, but also had higher sensitivity, of which strain sensing sensitivity average value was $1.281 \text{pm/\mu e}$. When smart carbon fiber reinforced plates were
tensile failure, wavelength variation average value of smart carbon fiber plates and ultimate strain average value were 13.8350\text{nm}, 10186\text{\mu\varepsilon}, respectively.

**Experiment on Reinforced Concrete Beams Strengthened with Smart Carbon Fiber Plates**

**SPECIMEN DESIGN**

Five strengthened beams were made in this experiment, and each beam was 2,600-mm long, 150-mm wide, and 250-mm high, with a calculation span of 2,400-mm. The number of beams were JGL1 to JGL5. Compression steel bars and longitudinal tensile steel bars were 2C6 and 2C8, respectively. Besides, each beam had a pure bending region of 600 mm at midspan and a shearing-bending region of 900 mm, achieving a two-point loading procedure by a distribution steel beam. In order to prevent appearing shear failure during the loading process, it needed to place compact stirrups (C6) at shearing-bending region, and spacing of stirrups was 100 mm. Except shearing-bending region, spacing of stirrups was 200 mm, and the stirrup type was the same as the former. On the other hand, strength design grade of concrete was C30 and concrete cover was 30 mm. In this test, CFRP plates embedded length, width and distance to the lower surface of concrete were treated as test parameters. The thickness of CFRP was 2 mm and the strengthened method was symmetric. (1) In the parts of all beams, embedded length of JGL1, JGL2 and JGL3 were 2,200 mm, the distance to the lower surface of concrete all was 40 mm and the CFRP plates width were 10 mm, 15 mm, and 20 mm, respectively. (2) Embedded length of JGL4 was 1,600 mm, the distance to the lower surface of concrete all was 40 mm and the CFRP plates width were 20 mm. (3) Embedded length of JGL5 was 2,200 mm, the distance to the lower surface of concrete all was 60 mm and the CFRP plates width were 20 mm. In general, Figure 2 presents the details of specimen and Table 3 shows the design parameters and primary results of the test beams.
Figure 2. Test beam design and loading schemes.

Table 11. Numbers and reinforced mode of the experimental beams.

<table>
<thead>
<tr>
<th>Strengthened position</th>
<th>number</th>
<th>Ratio of steel bar</th>
<th>Width of CFRP plates (mm)</th>
<th>Embedded length (mm)</th>
<th>Embedded position (distance to the lower surface of beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>on the beam side</td>
<td>JGL1</td>
<td>0.32%</td>
<td>2 × 10mm</td>
<td>2200</td>
<td>40mm</td>
</tr>
<tr>
<td>JGL2</td>
<td>0.32%</td>
<td>2 × 15mm</td>
<td>2200</td>
<td>40mm</td>
<td></td>
</tr>
<tr>
<td>JGL3</td>
<td>0.32%</td>
<td>2 × 20mm</td>
<td>2200</td>
<td>40mm</td>
<td></td>
</tr>
<tr>
<td>(embedded smart plates)</td>
<td>JGL4</td>
<td>0.32%</td>
<td>2 × 20mm</td>
<td>1600</td>
<td>40mm</td>
</tr>
<tr>
<td>JGL5</td>
<td>0.32%</td>
<td>2 × 20mm</td>
<td>2200</td>
<td>60mm</td>
<td></td>
</tr>
</tbody>
</table>

Strengthened Methods

The experiment used the CFRP plates embedded strengthening technique. Compared with external bonding of CFRP, the procedures of surface smooth and polish were avoided by embedding strengthened. The slotting width was 1.5 to 2 times as much as the thickness of CFRP plate. In the test, the thickness of smart carbon fiber reinforced plates, slotting width, and slotting depth were 2 mm, 3 mm and 25 mm, respectively. Following procedures were detailed. (1) slotting on the beams side by mechanical; (2) cleaning impurity and washing the surface of the gap by alcohol; (3) mixing the curing agent and epoxy formed structural adhesive according to the rate of one to two; (4) pouring the adhesive into the gap; (5) embedding the CFRP-OFBG plates in the gap; (6) maintaining 7 days after all procedures were completed. Figure 3 presents the embedded members.
MEASUREMENT CONTENT AND ARRANGEMENT OF MEASURING POINTS

The measurement contents included the steel bars strains of midspan and the loading points, the strains of smart carbon fiber reinforced plates and the strains of midspan concrete from top to bottom. The strains of tensile steel bars and concrete were measured with electrical-resistant strain gauges. The strains of CFRP plates were measured with OFBG. In this test, two gauges were pasted on the tensile steel bars at the bottom of beam midspan, and the distance to midspan was 300 mm. However, arrangement of smart carbon fiber plates measuring points were one point at midspan and two points at the loading position, respectively. In order to measure the displacement deformation of the test beams during loading process, it needed to place a dial gauge on the bottom of midspan and loading points, respectively. At the same time, it also needed to place a dial gauge on the top of concrete at the bearing position, to measure the vertical displacement of bearing both ends. Measuring points layout are shown in Figure 4.

![Smart CFRP sample.](image1)
![Finished beams.](image2)

Figure 3. Reinforced concrete beam strengthened with CFRP-OFBG plates.

LOADING SCHEME

50t hydraulic jack was used in the test, as shown in Figure 5. Test load was allocated at two loading points by a distribution steel beam, and each beam had a pure bending region of 600 mm at midspan. In addition, it needed to place five dial gauges at the bottom of beam midspan, the position of two loading points and bearing both ends, respectively. Loading site is presents in Figure 7. In order to ensure consistence of data-acquisition on the load, strain and displacement during testing, our team placed 70T load sensor at the loading points on the distribution steel beam. Load sensor, dial gauges and strain gauges were connected to data-
acquisition equipment (TST-3826). And then the data was collected automatically by data-acquisition equipment with a frequency of 1 Hz. Data-acquisition equipment is shown in Figure 6.

Before testing, beams were subjected to pre-pressure with 10% of cracking load on the surface of beams to ensure instrumentation normal working. After pre-pressure was finish and the beams were unloaded, it needed to adjust the test instrumentation according to the results of pre-pressure. During testing, step load was used according to the calculated damage load in advance. Following loading procedures were detailed.

(1) The load increment was 3 KN before the beams cracking;
(2) The load increment was 2 KN, when the controlled section appear 0.5 mm crack;
(3) It didn’t take notes when the cracking width was more than 0.5 mm, continuing to load until the final structure was destroyed.

Figure 4. Measuring point location.

Figure 5. Loading test device.

Figure 6. Data-acquisition equipment.
TEST RESULTS AND ANALYSIS

Failure Mode

There were three failure modes of embedded strengthened beams, according to the test results of most strengthened beams from famous researchers. The first category was flexural failure, including the rupture of CFRP (A), the crushing of compression concrete after the longitudinal steel bars yielded (B) and the crushing of compression concrete with the longitudinal steel bars not yielded (C). Flexural failure happen, when the CFRP plates-end anchorage was reliable; The second category was shear failure. Before the strengthened beams were not reaching to flexural capacity and because of insufficient shear capacity, the beams occured shear failure. The third category was debonding failure, including the interface failure of epoxy-concrete (D), debonding failure of CFRP plates-end concrete cracking (E) and the interface failure of plate-epoxy (F). The failure mode type D was caused by the insufficient shear strength of the interface of epoxy-concrete, the failure mode type E was caused by the lower tensile strength of concrete and the failure mode type F was caused by the lower shear strength of the interface of plate-epoxy. In term with this test, there were two failure modes, which were the crushing of compression concrete after the longitudinal steel bars yielded (B) and debonding failure of CFRP plates-end concrete cracking (E). Table 4 shows the test results for each specimen and the failure modes.

Analysis of Bearing Capacity

The bearing values of strengthened beams were collected automatically by data-acquisition equipment. Figure 8 shows load-deflection curve of all beams. Through the analysis of experimental data, some conclusions were given in this test. Under the ratio of steel bars, the embedded length and embedded position were
the same (JGL1, JGL2 and JGL3), the yield load of the beam was increased with the increase of the width of the CFRP plates. It showed that the load bearing capacity of the specimens could be improved during service period by increasing the width of

TABLE IV. FAILURE MODES STATISTICS.

<table>
<thead>
<tr>
<th>Strengthened position</th>
<th>number</th>
<th>Ratio of steel bar</th>
<th>Width of CFRP plates (mm)</th>
<th>Embedded length (mm)</th>
<th>Embedded position (distance to the lower surface of beam)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengthened on the beam side</td>
<td>JGL1</td>
<td>0.32%</td>
<td>2 × 10mm</td>
<td>2200</td>
<td>40mm</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>JGL2</td>
<td>0.32%</td>
<td>2 × 15mm</td>
<td>2200</td>
<td>40mm</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>JGL3</td>
<td>0.32%</td>
<td>2 × 20mm</td>
<td>2200</td>
<td>40mm</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>JGL4</td>
<td>0.32%</td>
<td>2 × 20mm</td>
<td>1600</td>
<td>40mm</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>JGL5</td>
<td>0.32%</td>
<td>2 × 20mm</td>
<td>2200</td>
<td>60mm</td>
<td>B</td>
</tr>
</tbody>
</table>

TABLE V. BEARING CAPACITY ANALYSIS OF EXPERIMENTAL BEAMS.

<table>
<thead>
<tr>
<th>number</th>
<th>Cracking load(KN)</th>
<th>Yield load(KN)</th>
<th>Ultimate load(KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JGL1</td>
<td>12</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
<td>JGL2</td>
<td>12</td>
<td>30</td>
<td>68</td>
</tr>
<tr>
<td>JGL3</td>
<td>12</td>
<td>40</td>
<td>74</td>
</tr>
<tr>
<td>JGL4</td>
<td>12</td>
<td>28</td>
<td>44</td>
</tr>
<tr>
<td>JGL5</td>
<td>12</td>
<td>30</td>
<td>71</td>
</tr>
</tbody>
</table>

Figure 8. Load-deflection curve of all beams.
CFRP plates in a certain range of plates width. With the increase of the width of CFRP plates, the ultimate load was greatly influenced by the width of the plates. However, the ultimate load of the specimen was higher, and the increase of the ultimate load was smaller. That was, the effect of strengthened beams were decreased, subsequently. When the embedded length was shorter (JGL4), the test beams was easy to appear debonding failure in the process of loading. This moment, the bearing capacity of the test beams were not reached the ultimate bearing capacity. Under the ratio of steel bars, the plates width and embedded position were the same (JGL3 and JGL4), the test beams could achieve the desired failure mode with the embedded length in the vicinity of 2,200 mm. Under the ratio of steel bars, the plates width and embedded length were the same (JGL3 and JGL5), the effect of strengthened beams was better with the embedded position of CFRP plates, which was close to the position of tensile steel bars.

**Measurement Data Processing of Smart Carbon Fiber Plates**

Smart carbon fiber reinforced plates contained Optical Fiber Bragg Grating (OFBG), including measurement OFBG and transmission OFBG. For the measurement OFBG, the refractivity could appear cyclical changes because the external environment changed. The central wavelength of the grating ($\lambda_B$), the cycle of the grating ($\Lambda$) and the effective refractivity ($n$) had a such relationship, which was $\lambda_B = 2n\Lambda$, according to the model coupling theory. Because of the relationship of the $\lambda_B = 2n\Lambda$, central wavelength would changed when the external stress was changed. That was to say, the change of the external information could be characterized by the change of the central wavelength of the fiber grating. The sensing principle of Fiber Bragg Grating is shown in Figure 9. A certain width of light from the Broad Band Source rayed into Optical Fiber Bragg Grating by a ring device. Due to the selection of the Optical Fiber Bragg Grating, the selected light was reflected back to the ring device, and then the analysis device received the information from the ring device to measure the new reflection wavelength values. The basic principle was that external variations were feedback by changing gating spacing when external temperature, stress and strain were changed. And then the analysis device detected the change of the wavelength and deduced the change of the outside.

The principle of strain sensor was introduced as follows:

There was a such relationship in the variations of central wavelength ($\Delta\lambda_B$) and longitudinal strain ($\Delta\varepsilon$) of Optical Fiber Bragg grating, as seen in Eq. (1)

$$\Delta\lambda_B = (1 - p_e)\lambda_B\Delta\varepsilon$$  \hspace{1cm} (1)$$

Of which, fiber elastic coefficient $p_e$ was defined, as seen in Eq.(2), an
longitudinal strain sensitivity coefficient of Fiber Bragg Grating \((1 - p_e)\) was defined. Finally, longitudinal strain sensitivity of Fiber Bragg Grating \(((1 - p_e) \lambda_B)\) was defined.

\[
p_e = -\frac{1}{n} \frac{d_n}{d_e} \tag{2}
\]

For the strain sensing sensitivity of Fiber Bragg Gating in this test, Davis et al. gave two sets of data by testing measurement. When the central wavelengths were 800 nm and 1550 nm, the strain sensing sensitivity of Fiber Bragg Grating were 0.64 pm/\(\mu\varepsilon\) and 1.209 pm/\(\mu\varepsilon\), respectively. Wavelength-strain sensitivity of Fiber Bragg Gratings with different central wavelength is shown in Table 6 [21-22].

The drawing was presented as follows, according to the measured wavelength values of smart carbon fiber reinforced plates by OFBG and measured strain values of carbon fiber plates by strain gauges. Among them, the longitudinal coordinate represented wavelength (the unit was nm) and the horizontal coordinate represented the strains of carbon fiber plates (the unit was \(\mu\varepsilon\)).

The analysis of the drawings was indicated that the straight line slope was about 0.0012, converting into the sensitivity coefficient of smart carbon fiber plates was 1.2 pm/\(\mu\varepsilon\). It was close to the sensitivity coefficient of smart carbon fiber plates, which was mentioned originally. According to this test, it was shown that developed smart carbon fiber plates could measure strain of carbon fiber plates and had a considerable accuracy at the same time.
CONCLUSIONS

In this paper, the experimental study investigated the embedded strengthened reinforced concrete beams by developed smart carbon fiber plates. Through the testing, the different failure modes and experimental phenomena were given, and then the variations of bearing capacity of reinforced beams was analyzed. According to the results in this experiment, the following conclusions can be shown:

1. Compared with external bonded CFRPs, using embedded bonded CFRPs to strengthen concrete beams is an effective strengthening method for improving the yield load and ultimate load and reducing deformability of concrete beams.

2. Optical Fiber Bragg Grating as a new type material can effectively measure center wavelength variation of carbon fiber reinforced plates and correctly reflect the strains of carbon fiber reinforced plates by mathematical conversion relationship.

3. Through the experiment, we put measured center wavelength variation of smart carbon fiber plates and measured strain of carbon fiber plates from strain gauges at the same location to be analyzed and plotted by computer. The drawings analysis demonstrated that: both wavelength and strain showed a better linear relationship, and the slope was about $1.2 \text{pm/\mu}e$. It was in a good agreement with the smart carbon fiber strain sensing sensitivity, which was $1.281 \text{pm/\mu}e$.

4. Finally, the results showed that the smart carbon fiber reinforced plates had better applicability in smart monitoring, and there are the widely application prospect and value on structural health monitoring and structural reliability analysis in the future.

<table>
<thead>
<tr>
<th>wavelength</th>
<th>Strain sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.83 $\mu$e</td>
<td>0.64 pm/\mu e</td>
</tr>
<tr>
<td>1.30 $\mu$e</td>
<td>1.00 pm/\mu e</td>
</tr>
<tr>
<td>1.55 $\mu$e</td>
<td>1.20 pm/\mu e</td>
</tr>
</tbody>
</table>
Figure 10. JGL-1 Intelligent carbon fiber board wavelength and strain data.
Figure 11. JGL-2 Intelligent carbon fiber board wavelength and strain data.
Figure 12. JGL-3 Intelligent carbon fiber board wavelength and strain data.
Figure 13. JGL-4 Intelligent carbon fiber board wavelength and strain data.
Figure 14. JGL-5 Intelligent carbon fiber board wavelength and strain data.
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