Experimental Research of the Smart Composite Reinforcement

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ABSTRACT: In order to make the composite reinforcements equipped with sensors, the optical fiber-composite smart reinforcements and resistance strain gage-composite smart reinforcements were designed and made. Based on experiments and finite element analysis, the resistance strain gage-composite reinforcements pasted on composite beams played a good role in reinforcement and normal stress monitoring. The result shows that, after double-sided reinforcing, bearing capacity of composite beams increased, while stress values of reinforcement sections decreased by about 50%, providing a reference to the smart composites used for structural reinforcement and health monitoring.

1. INTRODUCTION

Structural reinforcement and health monitoring plays an important role in ensuring the safety of the structure [1]. Fiber Reinforced Polymer (FRP) with its advantages such as lightweight, high strength, good corrosion resistance and excellent designable becomes popular in the field of structure strengthening materials [2,3]. New research achievements have been applied to the field of structural health monitoring with the development of the optical fiber sensing technology [4]. Optical fiber sensor which is a kind of modern monitoring method is one of the important components in structural health monitoring system. The intelligent reinforcement, which has the function of structure reinforcement and health monitoring, designed by the combination of fiber optic sensor or other components with sensing function and fiber reinforced composite would have a broad application prospect in engineering [5].

Design of intelligent reinforcement considered the following aspects: 1. Designing the strength and stiffness of reinforcement according to actual stress distribution of the reinforced object; 2. Determining the species, quantity, measuring parameters, measuring point position and fabrication process of sensing element; 3. Considering the effects on the mechanical properties of the patch after embedding sensors, and the patch and encapsulation process affect the performance of sensing element.

This paper studied measuring and analyzing the stress of composite beams pre and post intelligent reinforcement in order to verify the role of reinforcement and stress monitoring of smart reinforcements.

2. THE OPTICAL FIBER-COMPOSITE SMART REINFORCEMENTS EXPERIMENT

At present, the most researchers focus on the overall mechanical performance of FRP embedded optical fiber and the influence of embedded fiber on FRP mechanical properties. FRP for optical fiber is a kind of encapsulation process
which forms protection related to the survival rate and the working life of optical fiber. It would lose monitoring effect once the fiber before structure and FRP damage occurred. Therefore, in this paper, the research is necessary to explore the experimental method of whether optical fiber damage before FRP damage.

2.1 Specimens making

Specimen size: Length × width is 150mm×15mm and thickness is 2.04mm. The type of unidirectional Glass Fiber Reinforced Plastic (GFRP) prepreg is G20000#. Per layer thickness is 0.17mm. A total of 12 layers were laid along 0° direction. Along the fiber 0° direction, a common single-mode optical fiber was buried into the middle of the two prepreg layers in tension side of the specimen surface (Fig.1).

![Figure 1. The optical fiber-composite smart reinforcement specimen.](image)

Specimen making process: (1)Tailoring prepreg; (2) Laying prepreg and optical fiber; (3) Vacuum bag molding process; (4) Curing temperature 130°C, and curing time 2.5h; (5) Cutting specimens. The survival rate test of optical fiber in the specimen is necessary after the specimens making. The bare fiber which is set aside both ends of the specimen is connected to jumper through the optical fiber fusion splicer. It proves optical fiber in good working condition after jumper is connected to light source with wavelength 1550nm and optical power meter displays 1328uW.

2.2 Experimental program

Three-point bending experiment was carried out according to GB/T3356-2014 in order to test the survival rate of optical fiber. Loading speed was 1 mm/min and span was 32 mm (Fig.2). Light source and optical power meter kept turning on in the experiment. When optical power meter displayed 0, the optical fiber was failed completely and loading stopped.

![Figure 2. Loading mode.](image)

2.3 Experimental analysis

Fiber breakage sound of specimens appeared in the experiment. A small amount of fiber gradually broke at the beginning and power meter readings occasionally reduced with the slow speed. The loading-deformation curve appeared maximum peak (Fig.3) with GFRP and resin fractured. However, the
fact that power meter readings remained virtually unchanged proved optical fiber was relatively intact. After maximum peak appeared, test force had a rapid descent and then power meter readings reduced rapidly because of optical fiber damage. When optical power meter displayed 0, the optical fiber was failed completely. In Fig.3, the maximum load was 1352N and bending strength calculated of the specimen was 1040 MPa.

![Figure 3. Loading-deformation curve.](image)

The finite element model was established according to the experimental load 1352N and constraints for analysis of three-point bending experiment phenomenon. The model was built by 3D solid element (Fig.4.a) which included composite materials, fiber core and cladding, and fiber jacket (Table 1).

**Table 1. Material parameters of the bending specimen.**

<table>
<thead>
<tr>
<th>Composition</th>
<th>Material</th>
<th>External diameter</th>
<th>Elastic Modulus</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber core and cladding</td>
<td>SiO₂</td>
<td>125µm</td>
<td>72.2GPa</td>
<td>0.17</td>
</tr>
<tr>
<td>Fiber jacket</td>
<td>Polymide</td>
<td>250µm</td>
<td>4.5GPa</td>
<td>0.34</td>
</tr>
<tr>
<td>Composite</td>
<td>Glass fiber /Epoxy</td>
<td>150×15×2.04mm</td>
<td>1GPa</td>
<td>0.3</td>
</tr>
</tbody>
</table>

![Figure 4. Normal stress distributions of the optical fiber: (a) Model graph; (b) Fiber core and cladding; (c) Fiber jacket.](image)

The tensile strength of optical fiber was tested about 4.07 GPa, and when the beam tensile stress reached 240 MPa, optical fiber coating layer and the interface between the cladding occurred shear failure [6]. In Fig.4.b and Fig.4.c, when the beam reached ultimate strength, the fiber core and cladding maximum normal stress was 1.51 GPa less than fiber breaking strength. The coating layer lost protective effect on fiber core and cladding because it was destroyed before...
beam damage occurred, but that would not impact on optical fiber transmission signal power because of the intact beam. After the stress of the beam achieved ultimate destructive strength, fiber damage was caused by sharp increase of the deformation.

3. RESISTANCE STRAIN GAGE-FIBER-COMPOSITE SMART REINFORCEMENTS IN COMPOSITE BEAMS

Optical fiber sensor in accordance with the different modulation types can be divided into three categories: fiber interferometric sensor, fiber non-interferometric sensor, and distributed sensor [7]. Because of experimental conditions, resistance strain gauge was used instead of optical fiber as the sensing element. Resistance strain gage-fiber-composite smart reinforcements were used in the experiment of composite beams reinforcement.

3.1 Resistance strain gage-fiber-composite smart reinforcements making

Reinforcement size: Length × width is 400mm×40mm and thickness is 0.4mm. The type of unidirectional GFRP prepreg is G12500#. Per layer thickness is 0.1mm. A total of 4 layers were laid along 0 ° direction. Curing temperature is 130°C and curing time is 2.5h. One side of the patch is smooth, the other side is rough. Strain gauge pasted on the smooth surface and composite beam pasted with the rough surface (Fig.5).

![Figure 5. The resistance strain gage-fiber-composite smart reinforcement.](image)

3.2 Composite beams reinforcing experiment

Many researchers had researched related normal stress distribution on mid-span cross section of composite beams under pure bending loads [8,9]. In this paper, the combination of the low carbon steel beam and aluminum alloy beam in different ways (Fig.6) was reinforced by double-sided reinforcement with the smart patch. Compared the normal stress distribution of composite beam pre and post intelligent reinforcement in order to verify the intelligent patch effect of reinforcement and monitoring.

![Figure 6. Cross-sections of the composite beams after reinforcing: (a) Full-width bonding beam; (b) Half-width bonding beam; (c) Fold bonding beam.](image)

Four-point bending experiment was carried out pre and post intelligent reinforcement of the composite beams. The beam between the two concentrated forces is pure bending. Some sizes: h=b=20mm, a=100mm, L=100mm. Eight measuring points were decorated on the beam (Fig.7) and measured by
electrical measuring method. According to the displacement loading, the speed is 0.1mm/min. The first data acquisition was 250N and the last was 3000 N. Each data acquisition was recorded with every increase of 250N. The data were measured by static strain gauge according to the single sampling. After collecting a group of data, the experiment would be repeated for three times. Calculating the average value of three groups of data was for working out the experimental stress on the basis of generalized Hooke’s law.

3.3 Result Analysis
Stress was measured by the strain gauge on composite beams before the reinforcement and glued on GFRP patch after the reinforcement. The interface of two beams is y=0. The beam upward direction is the y positive direction. In the half-width bonding beam, fracture plane is side A and adhesive surface is side B. The mid-span cross section normal stress distribution along the height in composite beams before and after double-sided reinforcement is shown in Fig. 8.
Figure 8. Experimental Stress of composite beams pasted smart composite reinforcements: (a) Full-width bonding beam; (b) Half-width bonding beam; (c) Fold bonding beam; (d) Stress of all beams after double-sided reinforcing.

The finite element model was established by 3D solid element in order to compare with the experimental data. Related material parameters are shown in Table 2.

### Table 2. Material parameters of the smart composite reinforcement.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Material</th>
<th>Size</th>
<th>Elastic Module</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel beam</td>
<td>low carbon steel</td>
<td>650×20×20mm</td>
<td>208GPa</td>
<td>0.27</td>
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<tr>
<td>Aluminum beam</td>
<td>aluminum alloy</td>
<td>650×20×20mm</td>
<td>71GPa</td>
<td>0.31</td>
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<tr>
<td>Adhesive 1</td>
<td>Cyanoacrylate</td>
<td>650×50×0.15mm</td>
<td>1GPa</td>
<td>0.3</td>
</tr>
<tr>
<td>Adhesive 2</td>
<td>Cyanoacrylate and Double-sided adhesive</td>
<td>650×20×0.35mm</td>
<td>0.3GPa</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Adhesive 1 was used in full-width bonding beam, and adhesive 2 was used in half-width bonding beam. The simulation results are shown in Fig.9.

Figure 9. Simulation stress of composite beams double-side pasted smart composite reinforcements: (a) Full-width bonding beam; (b) Side A of half-width bonding beam; (c) Side B of half-width bonding beam; (d) Fold bonding beam.
As is shown in Fig.8. and Fig.9.: Only tension was observed for the bottom beam in Fig. 8.(a) coincided with [10] while in Fig.8.(c), both tensile and compressive stress were observed for the bottom beam in the unreinforced situation which was agreed well with [11]. In Fig.8(b), the stress distribution of half-width bonding beam was similar to fold bonding beam before reinforcing because of the slip in interface and the two beams had an average difference (19%) in stress value of every point. The stress distribution of two sides (A and B) of half-width bonding beam differs little (the average 1%) and it would have a great influence on the stress of two sides of the composite beams once the adhesive layer damage occurred; The maximum stress in every composite beam appeared on the top surface of low carbon steel beam. The carrying capacity of full-width bonding beam was the highest which was 1.43 times of fold bonding beam and 1.25 times of half-width bonding beam and the result was consistent with material mechanics theory; The stress distribution on the GFRP patch was linear which accorded with plane assumption after double-sided reinforcement; The carrying stress of all beams had an improvement such as full-width bonding beam with 3.1 times, half-width bonding beam with 2 times and fold bonding beam with 1.8 times. The fact showed that the smart reinforcements had a good effect on structural reinforcement and health monitoring. The stress distribution trend in simulation results and experimental results was the same, but the error of full-width bonding beam and fold bonding beam was about 24% and that of half-width bonding beam was 1%. Many factors led to the errors such as friction, specimen paste process, elastic modulus values of adhesive, etc.

4. CONCLUSIONS

Three-point bending experiment of the optical fiber composite smart reinforcements and four-point bending experiment of the composite beams with resistance strain gage-composite smart reinforcements were carried out. Regarding the effect of the load, the following results were obtained:

(1) When the ultimate load increased to 1352N in three-point bending experiment of the optical fiber composite smart reinforcements, the optical fiber wasn’t failed. After the beam stress achieved ultimate destructive strength and the load reduced to less than 10N, failure of the optical fiber was occurred because of sharp increase of the beam deformation.

(2) Compared with the stress of beams before reinforcing, the carrying stress of all measuring points was improved after resistance strain gage-composite smart double-sided reinforcing which average increased by 3.1 times in full-width bonding beam, 2 times in half-width bonding beam and 1.8 times in fold bonding beam.

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REFERENCES