Health monitoring of stay cables by using optical FBG Technology

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ABSTRACT: Stay cables are critical structural components for cable-supported bridges. Under severe environmental influence and load effect, they suffer from corrosion, damage and deterioration easily. Fiber Bragg Grating (FBG) sensors have significant advantages over conventional sensing method including greatly reduce size, reduced weight, flexible, and immunity to electromagnetic interference. It is very suitable for reliable structural health monitoring for detecting damage and deterioration. In this paper, the feasible of using FBG technology to monitor stay cable safety and provide early warning is discussed. Two methods of applying FBG sensor to cables are considered, one is adhering bare FBG directly on steel wire and the other is installing FBG-FRP bar. The application of the two methods are investigated by full-scale specimen tests and engineering application in Sichuan Dadu River Bridge. It is proved that it is feasible to use FBG technology monitoring stay cable safety and providing early warning.

1 INTRODUCTION

The structural efficiency and aesthetics of highly tensioned stay cables have led to a proliferation of cable-supported bridge construction across the China and around the world. The most important elements of these dramatic cable-supported bridges are stay cables, which transfer the loads. It is inevitable that stay cables suffer from corrosion, damage and deterioration subjected to severe environment and accidental influences (e.g. overloads, vehicular impacts, strong earthquakes, hurricanes). How to monitor in-service stay cable safety becomes a hotspot, which has attracted considerable attention. Fiber Bragg Grating (FBG) sensors have significant advantages over conventional sensing method including greatly reduce size, reduced weight, flexible, and immunity to electromagnetic interference. It is very suitable for reliable structural health monitoring to detect damage and deterioration. In this paper, the feasibility of using Fiber Bragg Grating technology to monitor stay cable safety is investigated. Moreover full-scale specimen tests and engineering application of FBG sensors in actual cable are studied.

2 CHARACTERISTICS OF FBG AND FRP-FBG BAR

2.1 *Fiber Bragg Grating*

FBG sensors are spectral filters fabricated within segments of optical fiber. They typically reflect light over a narrow wavelength range and transmit all other wavelengths. The grating is a periodic modulation of the refractive index of a small section of the core of the fiber. When a Bragg grating is subjected to strain at a constant temperature, the reflected wavelength shifts in a manner directly proportional to the strain. Thus, the grating may be used as an optical strain gauge. The relationship between longitudinal strain and Bragg wavelength at a constant temperature is given by Equation (M D Todd et al.2001, Z. Zhou et al. 2003a)

$$\frac{\Delta\lambda_B}{\lambda_B}=\left(1-\frac{n_{eff}^2}{2}\left[p_{12}-v\left(p_{11}+p_{12}\right)\right]\right)\Delta\varepsilon_z \quad (1)$$

Where n_{eff}^2 is the effective refractive index of the core, p_{11} and p_{12} are the strain optic coefficients, v is poisons coefficient, and $\Delta\varepsilon_z$ is the longitudinal strain.

FBG sensor is not only sensitive to strain but also to temperature. Usually, it is not possible to separate the effect of the temperature from the effect

of the strain with only one grating. To prevent temperature from confounding the strain measurement, one can adjust the reflected optical spectrum using the results of a sister grating, which experiences just the temperature event.

2.2 *FBG-FRP bar*

The FBG sensors in the center of die were pultruded with fiber strands in the produce process of Fiber Reinforced Polymer (FRP) bars, and the smart FBG-FRP bars are produced. According to various fiber types, Carbon Fiber Reinforced Polymer-Optical Fiber Bragg Grating (CFRP-FBG) bars and Glass Fiber Reinforced Polymer-Optical Fiber Bragg Grating (GFRP-FBG) bars can be obtained. Z. Zhou (Z. Zhou et al. 2003a) studied the performance of FRP-FBG and found that the FBG don't affect the mechanical properties of FRP bars due to the outer dimension of a standard glass optical fiber is 0.125 mm, which is relative small compared with FRP bar diameter. The tensile behavior of FRP-FBG bars is still a linearly elastic stress-strain relationship until failure. FBG embedded in FRP integrates with FRP well and FRP-FBG bar can serve as perfect sensor. The sensibility factor of FRP-FBG bar is same as bare FBG. The measurement precision is about 1~2 $\mu\varepsilon$, the maximum tensile strain is 1200 $\mu\varepsilon$. The temperature sensing property of FRP-FBG bar is different with bare FBG because the coefficient of thermal expansion of FRP differs from bare FBG (Z. Zhou et al. 2003a).

The FRP-FBG sensor has FRP advantageous properties such as corrosion and fatigue resistance, high strength-to-weight ratio, lightweight and potentially high durability. Moreover, the FRP protects FBG from damage and improves the durability and limit strain of FBG. Furthermore FRP-FBG bar can produced in any length and diameter as a sensor. We can make distributive FRP-FBG sensors from FRP-FBG bars.

3 APPLICATION OF FBG IN STAY CABLES

3.1 *Stay cable*

Several types of cable stays are available for use as stays in cable-supported bridges. Most cable stays are composed of parallel wires, 7 mm in diameter, or parallel strands, approximately 15 mm in diameter. Usually, upset anchorage and grip anchorage are adopted for parallel wire cables and strand cables respectively. Those anchorage interiors are filled with epoxy resin grouts.

The stay cables are highly tensioned structures, and the maximum stress in cable is generally limited to 0.4 UTS (Ultimate Tensile Strength), conforming to JTJ 027-96 of China.

3.2 *Application of FBG*

Dadu River Bridge in Ebian county of Sichuan province is a through concrete-filled steel tubular arch bridge and has a main span length of 138 m. Its suspender consists of 12 multiple seven-wire strands, 15.24 mm in diameter, encased in a steel sheath filled with cement grout. The bridge was constructed in 1995 and found severe corrosive in 2004, which results from the pollution air discharged by yellow phosphor factory beside the Bridge. In order to monitor suspenders safety and provide early warning, FBG sensors are installed along wires of strands in critical suspenders. In this study, a adhesive material 502 glue and a protective and separate material glass cement are applied in the sensor installation applications. The practice proved that every FBG sensors installed in suspenders can work effectively. Figure 1 shows the suspender installed FBG sensor and optical line protection box. Before and after installing sensors, the cable forces are measured by the vibration frequency method.

The Micron Optics Si425 is used to demodulate the Bragg wavelengths. The frequency of collection is 250Hz. Figure 2 is the time-stress graph of NO1 upriver suspender. The stress values should be modified according to FBG installing direction. In this paper, the modified coefficient is 1.022. The dynamic stress of actual suspender can be used to assess safety and estimate fatigue life. Figure3 shows a cycle counting result using rain flow algorithm.

From the engineering application of FBG, we can conclude that it is feasible to install bare FBG sensors on stay cables in service. The strain value measured by FBG sensor can be used to assess stay cable safety and estimate its fatigue life.

Figure 1. Suspender installed FBG sensor

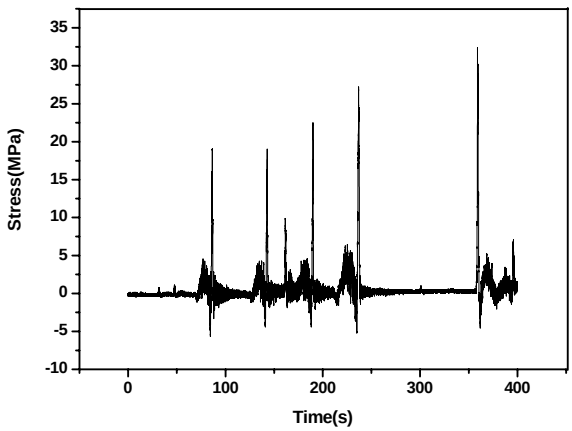

Figure2. Time-Stress graph of suspender

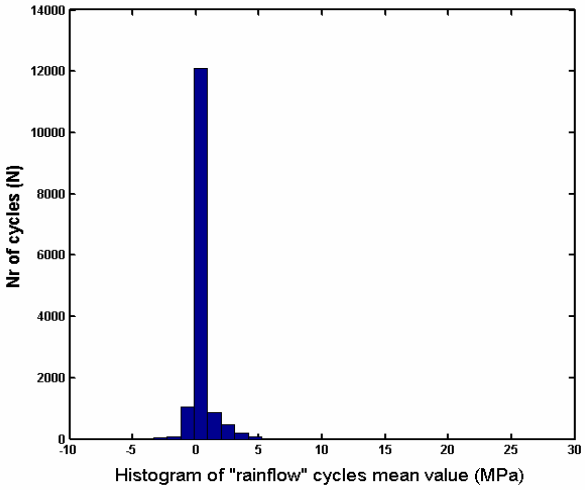

Figure3. Cycle counting results using rain flow algorithm

3.3 *Application of FBG-FRP Bar*

The main idea for smart cables is that FRP-FBG bars are added to cables with each end bonded by epoxy resin grouts in anchors during cable produce. Smart FBG-FRP bars and wires generate coinstantaneous deformation under loading. Thus the smart FBG-FRP sensing bars can measure the stains of smart stay cables. In order to eliminate temperature effect, a sister FBG-FRP bar only expose to temperature should be installed in every cable.

FBG-GFRP bar, showing in Figure 4, has lower elastic modulus, lower price, larger limit strain than FBG-CFRP bar and should be applied to smart cable. When the smart cable bears load, the FBG-GFRP bar bear small force, which is beneficial to bond FBG-GFRP bar.

Harbin Institute of Technology cooperates with Liuzhou OVM Machinery Co., Ltd to develop smart stay cables. Six full-scale specimen cables are produced, in which three cables are parallel wire cables with 85 wires, 4.5m long, shown in Figure5, and the other three cables are 7 multiple seven-wire strands cables, 4.5m long, shown in Figure6.

In order to test the sensing performance of such kind FBG-based smart cables, the static tests are carried out on 12000KN tensile test device at test center laboratory of Liuzhou OVM Machinery Co., Ltd. Test devices including oil pump, jack, anchor-hold force sensor, Optical Sensing Interrogator Si425, show in Figure 7.

Figure 4. FBG-FRP bar

Figure 5. Smart parallel wire cable

Figure 6. Smart strands cable

Three smart parallel wire cables are taken into account. The FBG-GFRP bars, 7 mm in diameter, are installed into stay cable according to the installation method mentioned above. The number of FBG-GFRP bars in three smart cables is one, one and three respectively. Each FBG-GFRP bar has two FBG sensors. Partial FBG sensors are temperature sensors. Experimental results are given as figures 8~11.

From the experimental results given as above, Figure 8~10, we can find that the FRP-GFBG

sensors installed in the steel wire cables show perfect strain sensing properties: good linearity, good repetition and high strain limit. From the comparison figure 11, we can find that the strain gotten from different FBG-FRP bars are different, which gives the information that there is a lag between FBG-GFRP bar strain and practical strain of cables. The calibrate coefficient of bars from NO1 to NO5 are 1.07,1.43,1.39,1.44 and 1.51 respectively. The five calibrate coefficient aren't equal. Therefore stay cables embedded FBG-FRP bars should be tensioned to calibrate sensing characteristic before applied in engineering.

At the same time, figure11 shows the limit sensing strains of FBG-FRP bars in three specimen cables. From this Figure, we can conclude that the limit sensing strains of FBG-FRP bars is about 0.006~0.007, and the limit monitored forces is 45% to 80% UTS. Test results proved that it is feasible to use FBG-FRP bar monitoring stay cables safety and providing early warning.

Figure 7. Static test device of cable

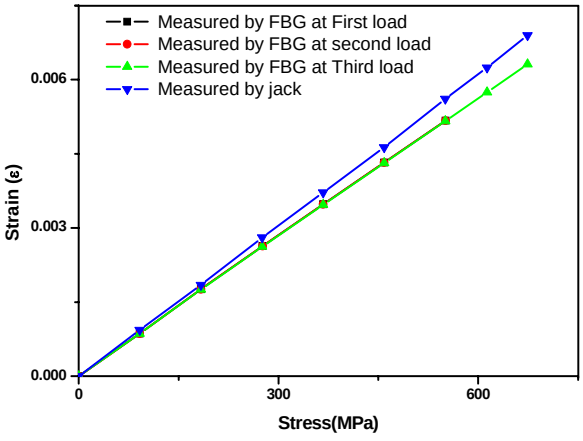

Figure 8. Contrast measured Strains by FBG-FRP with that by jack in cable 1#

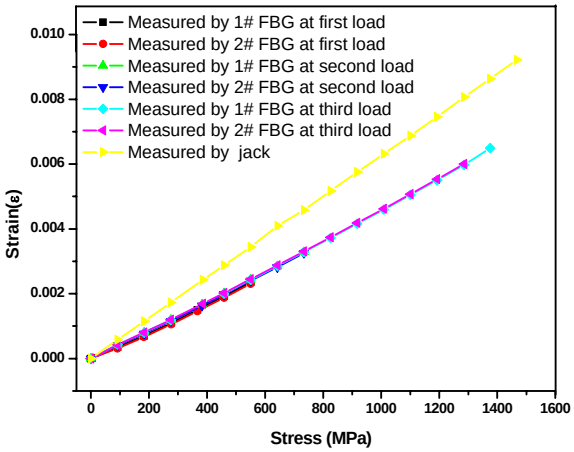

Figure 9. Contrast measured Strains by FBG-FRP with that by jack in cable 2#

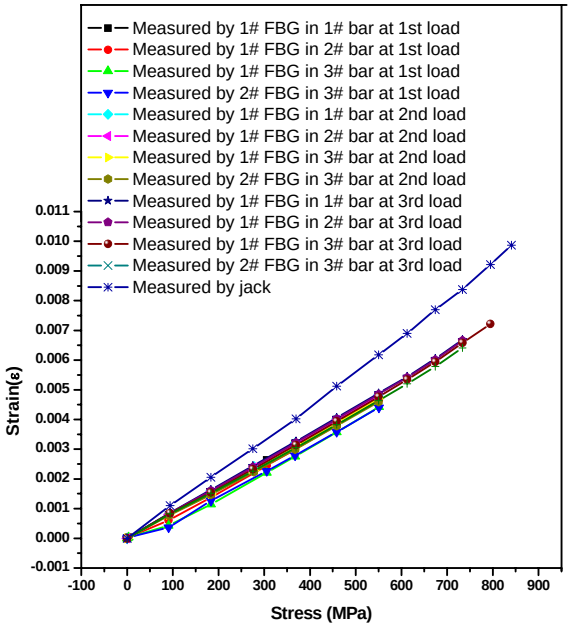

Figure 10. Contrast measured Strains by FBG-FRP with that by jack in cable 3#

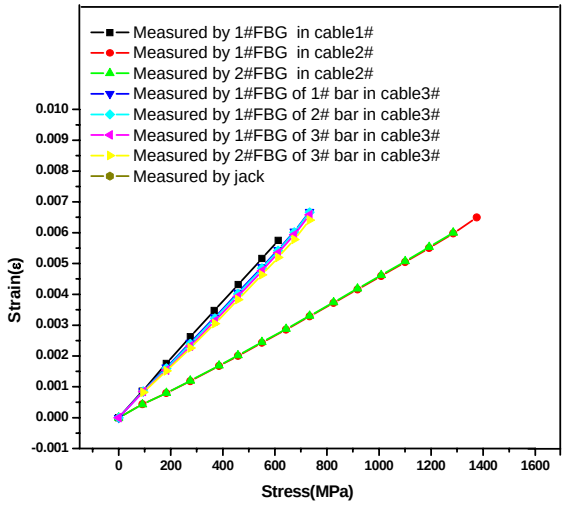

Figure 11. Limit sensor strains of FBG-FRP bars in three specimens

4 CONCLUSIONS

In order to monitor stay cables safety, two application manners of FBG sensors are discussed in this paper. One method is adhering bare FBG, and the other is installing FBG-FRP bar. Full-scale specimen tests and engineering applications are carried out and proved that it is feasible to use Fiber Bragg Grating technology monitoring stay cables safety and providing early warning. Some conclusions are educed as follows:

- The limit strain of bare FBG is small about 3000 $\mu\varepsilon$ ~4000 $\mu\varepsilon$ and can't survive in super-tension of new cable. However it can be adhesive conveniently to in-service stay cable for its small diameter.
- The FBG-FRP sensing bar improves greatly the limit strain of FBG up to 7000 $\mu\varepsilon$ ~12000 $\mu\varepsilon$ and can be embedded conveniently into stay cable during cable produce process. It is suit for new stay cable and may monitor the elastic phases of cable.
- The method of installing FBG-FRP bar is more predominant than the method of adhering bare FBG directly because the former monitors the strain of whole cable and the latter monitors local strain of cable.
- The stay cable embedded FBG-FRP bar should be tensioned to calibrate sensor characteristic before applied in engineering.
- FBG provides a means for high-speed data acquisition. The dynamic strains of stay cable under environmental and vehicle load can be obtained and can be used for safety assess and fatigue life estimate of cable.
- FBG technology not only can be used to real time monitoring but also can be used to off-line monitoring of stay cable.
- Applying FBG technology to monitor stay cable has all advantage of FBG sensing.
- FBG sensor is not only sensitive to strain but also to temperature. In order to eliminate temperature effect, a sister grating should be used.

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