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Stay cable vehicle live load effects analysis based on structural health monitoring data

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Summary

Stay cables are some of the most critical structural components of a bridge. However, stay cables readily suffer from corrosion damage and stress corrosion damage. Thus, health monitoring of stay cables is important for ensuring the integrity and safety of a bridge. Glass Fibre Reinforced Polymer Optical Fibre Bragg Grating (GFRP-OFBG) cable, a kind of fibre Bragg grating optical sensing technology-based smart stay cables, is proposed in this study. The fabrication procedure of the smart stay cable was developed and the self-sensing property of the smart stay cable was calibrated. The application of the smart stay cables on the Tianjin Yonghe Bridge was demonstrated and the vehicle live load effects smart stay cables were evaluated based on field monitoring data. Finally, the probability distribution and extreme value distribution of live load effects of the stay cables were established.

keywords: Stay cable, vehicle load effects, structural health monitoring, probability distribution.

Instroduction

Stay cable are some of the most critical structural components of a bridge. However, stay cables readily suffers from fatigue damage, corrosion damage and their coupled effects (Tabatabai, 2006). For bridges, the design life is 100 year or even longer, while for stay cables, the design life is only 20 years in mainland China. In fact, most stay cables have to be replaced after 5-13 years of use due to severe corrosion and breakage in mainland China (Ou, 2006). Therefore, inspection and health monitoring of a stay cables are vitally important to ensure the integrity and safety of a bridge.

Visual inspection is frequently used as a daily inspection technique. However, it is more difficult to quantify damage. Magnetic flux leakage technique, which can identify the extent of damage and its location along the length of cable, has a very long history in the inspection of cables, but cannot identify the location of damage within the cross section. Additionally, this method cannot be used for inspections in the anchorage zones, in the vicinity of anchorage zones, or with large diameter (Christen et al, 2003; Tabatabai, 2006). Ultrasonic testing is one non-destructive technique which sends stress waves into the wire at the anchorage and the reflections are monitored and displayed. Because transmission of stress waves in wires is complex and because stress waves attenuate significantly in wire, this technique

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is not used on practical cables. X-ray is an efficient method to detect the damage of cables, but safety, cost, and portability of equipment have significantly limited their use (Tabatabai, 2006). Acoustic emission monitoring technique is a passive monitoring system and has been used to detect wire breaks in stay cables and cracks of the anchorage. It is worth noting that the vibration-based force measurement technique is the most widely used. This approach is convenient for identifying tension forces through acceleration of the stay cable measured using an accelerometer. However, it can only obtain the tension force in a segment and cannot identify the stress of a stay cable on-line.

Fibre Bragg gratings optical sensing technology provides a potential approach to measure strain and temperature of structures and has been extensively studied in many fields (Ou et al, 2005). However, the OFBG sensors cannot be directly used in civil engineering due to their fragility. Ou (2007) proposed embedding OFBG sensors into Fiber Reinforced Polymer (FRP) to protect the OFBG sensors from breakage. Obviously, FRP-OFBG products simultaneously have self-sensing property and good mechanical performance. Based on this technology, this study presents smart GFRP-OFBG cable, a kind of fibre Bragg gratings optical sensing technology–based smart stay cables. For the smart stay cables, three glass fibre reinforced polymer (GFRP) bars embedded with fibre Bragg grating optical (OFBG) strain and temperature sensors were inserted into the hollows of steel wires and fixed with the steel cable at the two-end anchorages of a cable. Therefore, the GFRP-OFBG bars can consistently deform with the steel wires and the smart stay cable can sense its own strain and temperature. The fabrication procedure of the smart stay cable was developed and the self-sensing property of the smart stay cable was calibrated. The application of the smart stay cables on the Tianjin Yonghe Bridge was demonstrated and the vehicle live load effects smart stay cables were evaluated based on field monitoring data. Furthermore, the probability distribution and extreme value distribution of live load effects of the stay cables were established. Finally, the fatigue load effects of smart cables and fatigue accumulative damage of the smart stay cables was evaluated based on field monitoring strain.

Fabrication and calibration of smart stay cables

Fabrication of smart stay cable

OFBGs were fabricated by standard monomode optical fiber with a diameter of 125 μm, into which Bragg gratings were written. The OFBGs used in this study were provided by T&S Communications Ltd (Shenzhen, China), the OFBG center wavelength ranged from 1520-1570 nm, and the grating length was 10mm. A uniform periodic grating was used to determine the strain averaged over the gauge length. Within limits, this gauge length can be quite short, making the measurement practically a pointwise measurement for large structures.

The principle of OFBG sensors can be described by the following equation

$$\lambda_B = K_\varepsilon \varepsilon + K_T \Delta T \tag{1}$$

where λ_B is the center wavelength of the OFBG sensors, ε is the strain of the OFBG sensors, ΔT is the variety in temperature, K_ε and K_T are the sensitivity coefficients of strain and temperature, respectively, and were equal to 1.20 pm/$\mu\varepsilon$ and 8.9 pm/$^\circ$, respectively, in this study. The maximum allowable percentage elongation of OFBG strain sensors was about 5000 $\mu\varepsilon$. The available range of OFBG the temperature sensor was -100$\sim$200^{o}C.

It is necessary to protect bare optical fiber with FBGs from breakage when used in civil engineering. The authors suggested embedding OFBG sensors into a fiber reinforced polymer (FRP) bar during the fabrication of the bar in order to solve this practical problem. As a consequence, the FRP can protect the OFBG sensors from breakage and the FRP bar with OFBG sensors has self-sensing properties along with good mechanical properties and corrosion-resistance. The FRP bar embedded with OFBGs is referred to as the FRP-OFBG bar.

The fabrication procedure of FRP-OFBG bars can be illustrated using Figure 1. During the fabrication procedure of FRP, bare optical fiber with FBGs was inserted through the concentration panel and the resin solidifies the reinforced fiber and optical fiber together. Here, the optical fiber with OFBG was placed in the center of the mould, where the OFBGs were located at any position along the optical fiber according to preference. Obviously, the OFBG strain sensors consistently deform with the FRP bar and can predict the deformation of the FRP bar. The OFBG temperature sensor was placed into a hollow tube without any connection. Then, the hollow tube was embedded into a FRP bar. Obviously, the OFBG temperature sensor embedded in the FRP bar only senses temperature and does not deform with the FRP bar. The FRP bar embedded with the OFBG strain and temperature sensors has strain and temperature self-sensing properties.

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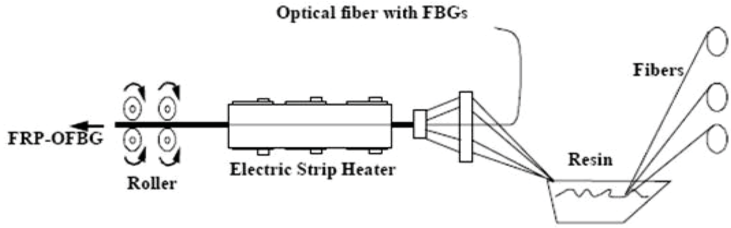

Figure 1: Schematic diagram of FRP-OFBG fabrication procedure

The FRP-OFBG bars incorporated into the smart stay-cables have the same diameter as the steel wires of cables. Obviously, the increase in tension strength of the cable by the additional GFRP-OFBG bars can be neglected.

Calibration of smart stay cables

Before the stay cables were installed on a bridge, pre-stretching test of the cable must be carried out for checking the quality of cables. Calibration of the OFBG strain sensors was simultaneously conducted. One end of the cable was fixed and the other end was pre-stretched by a jack. Each cable was loaded in five load levels and the maximum load was 1.2 times of the designed load. Each level load was sustained for 5 minutes and a compression ring was employed to measure the tension force on the cable, which was installed between the anchor of the cable and the fixed seat. The wavelength of OFBG sensors was measured by a fiber Bragg grating demodulator (made by the MOI. Inc., USA, MOI-425) and then the strain, stress and tension force can be calculated using the collected wavelength of OFBG strain sensors in combination of their sensitivity factor. Because the test was carried out in a short time, the temperature remains constant during testing and the effect of temperature on the length variation could be neglected. The tension forces of three cables measured by the compression ring and the OFBG strain sensors embedded in the cables, respectively. The compression ring was installed between the anchor cup and the jack. The measured stresses by the two kinds of sensors are shown in Fig. 2. The Y-coordinate and X-coordinate of Fig. 2 denote the tension force measured by the OFBG strain sensors and compression ring, respectively. The equivalent area and equivalent elastic module of the cable are 0.001354 m^2 and 199 GPa, respectively. For comparison, the theoretical curve (the slope of the straight line is unit) is also depicted in Fig. 2 (the dotted line).

Application of structural health monitoring of smart stay cables

As mentioned above, stay cables play a critical role in ensuring the integrity and safety of bridges. Smart stay cables incorporated into bridges can record the time-history of their own stress and, thus, the health status of the cables can be diagnosed utilizing the collected time-history of stress. Because the stay cables are

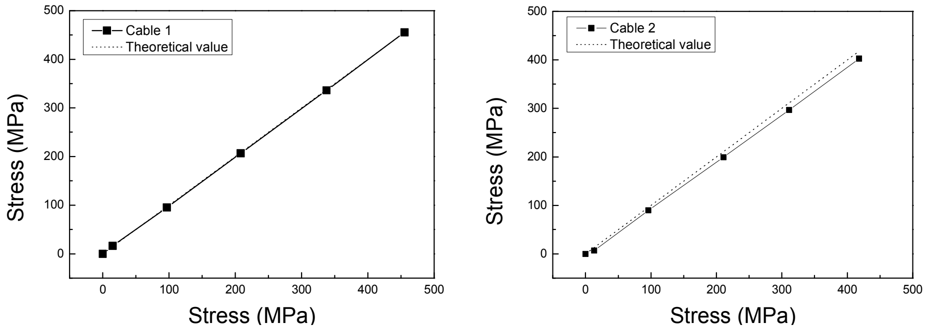

Figure 2: Calibration of smart stay cables

subjected to cyclic traffic loads, accumulative fatigue damage is one of the main failure modes of stay cables in bridges. The accumulative fatigue damage of a stay cable can be assessed using the measured time-history of stress of the cable itself.

Description of Tianjin Yonghe Brigde

The Tianjin Yonghe Bridge, as shown in Fig. 3, is one of the earliest cable-stayed bridges constructed in mainland China. It is comprised of a main span of 260m and two side spans of 25.15+99.85 m each. This bridge opened to traffic in December, 1987. Its girder was damaged after 18-year of operation and was repaired and rehabilitated in 2005. As for the repair and rehabilitation, the girder over the mid-span was re-casted and other segments were repaired and rehabilitated by bonding carbon fiber reinforced polymer sheets to the surface of the girder. At the same time, all stay cables were replaced and some smart stay cables were incorporated into this bridge, as marked in Fig. 3. The strain of the smart cables was automatically and continuously collected using a fiber Bragg grating demodulator (made by the MOI. Inc., USA, MOI-425) and the sampling frequency was 62.5 Hz.

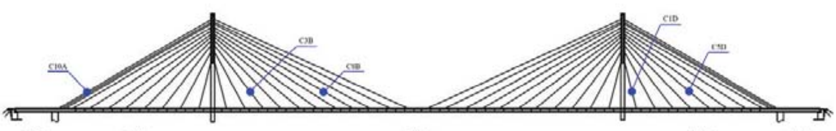

Figure 3: Schematic diagram of smart cables in Tianjin Yonghe Bridge (units: cm)

3.2 Live load effects of smart cable

The measured stress (obtained from the measured strain and elastic module of the cables) of cables C1 and C10 in one day of 2007 is shown in Fig. 4. The effects of temperature had been removed. For the span of the bridge was short and the stiffness was large correspondingly, the action wind load on cable force could be ignored. Therefore, the load effects of cables shown in Fig. 4 were induced only by vehicle load. In Fig. 4, the positive peaks were caused by a vehicle moving near the cable and the corresponding negative peaks were generated by the same vehicle moving near the symmetrical location of the cable about the tower. The reference line denotes the stress of the cable caused by the dead load.

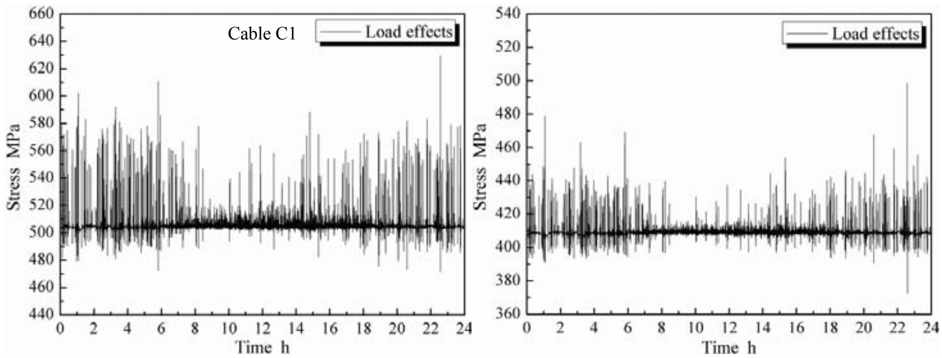

Figure 4: Vehicle live load effects obtained by smart cable

Live load effects analysis

Probability distribution of live load effects

Based on field monitoring data of one week just as shown in Figure 4, the peak values of live load effects are identified and the peak values of live load effects which are less than 5 MPa are ignored. The probability distribution and cumulative distribution of live load effects are shown in Fig. 5. The three-parameter Weibull distribution can be used discribed the probability distribution of live load effects and the cumulative distribution function is

$$F_S(s) = 1 - \exp\left[-\left(\frac{s-\alpha}{\eta}\right)^{\beta}\right] \tag{2}$$

where α, β and η are the parameter of Weibull distribution and are determinded by Maximum Likelihood Estimation (MLE) method based on the field monitoring data. The estimated probabiltiy distribuiton and cumulative distribution of live load effects are also shown in Figure 5 and the estimated parameters can be accepted by Kolmogorov-Smirnov test (KS-test) at the significance level of 1%. The mean values of live load effects are 41.15 MPa, 38.32 MPa, 33.88 MPa, 30.87 MPa, 21.93 MPa respectively from cable C1 to C10. It can be seen that the shorter the cable length is, the lareger the live load effects of cable is.

Extreme value distribution of live load effects

The live load effects process is modeled as a sequence of randomly occuring live load events (i.e., pulses) with random intensities and duration. Based on SHM data, it can be determined that the load event (larger than 5 MPa) occurs at a mean

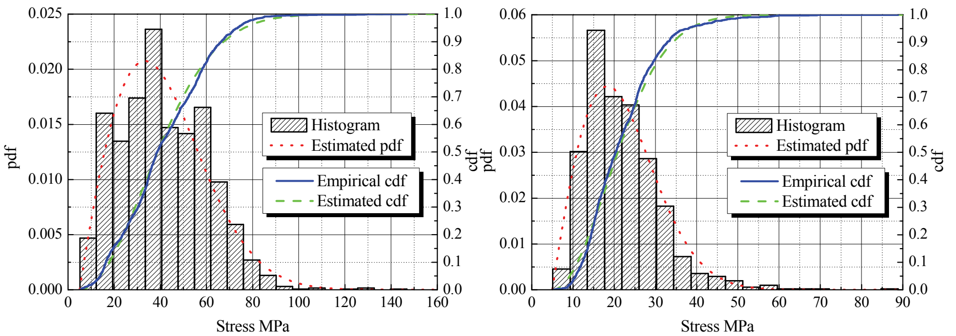

Figure 5: Probability distribution of live load effects

rate of 7000 times each weak. Additionally, it is assumed that the random intensities are statistically independent and identically distributed random variables. Consequently, the vehicle live load is described by a Poisson point process.

The extreme value probabiltiy densities of the live load effects of cable C1 and C10 are shown in Fig. 6. From Fig. 6, it can be seen that as the time interval is increased, the expected value of maximum live load effects in the interval increased, and the dispersion of maximum live load effects in the interval decreases. The distribution changes dramatically within the first year, and increases only slightly beyond $t = 5$ years. The extreme value probabiltiy densities of the live load effects of cable C1 to C10 with $t = 30$ years are shown in Fig. 7. It can be seen that the shorter the cable length is, the lareger the maximum live load effects of cable is.

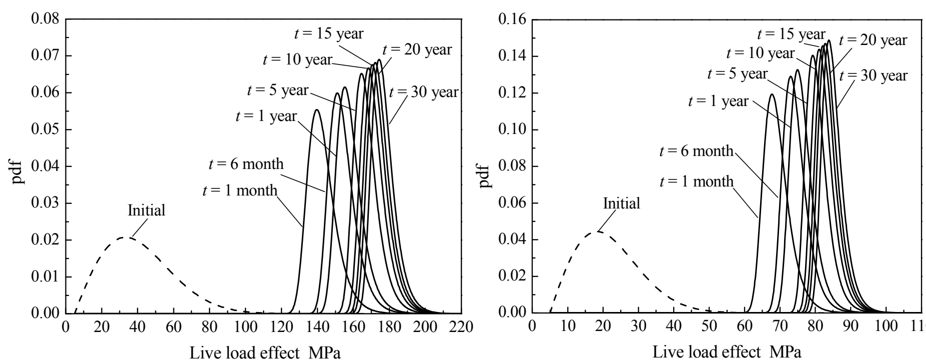

Figure 6: Extreme value distribution of live load effects with different time intervals

Conclusions

This paper proposes a self-sensing smart stay cable and presents its application. The following conclusions are obtained from this study:

- The smart stay cable was fabricated as a common cable and no special process was needed.

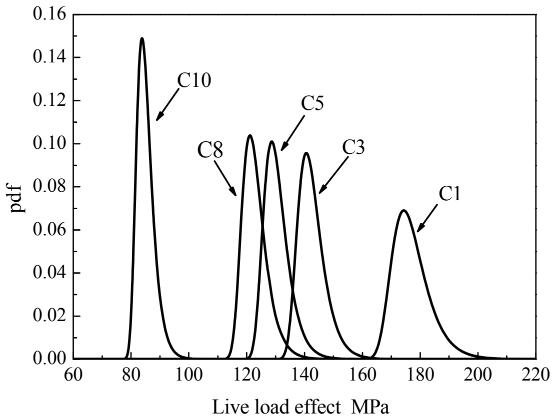

Figure 7: Extreme value distribution of live load effects with t = 30 years

- The smart stay cable has good self-sensing properties and discrepancies between measurement and theoretical values are very small.
- The smart stay cable can record the time-history of its own stress. The measurements indicate that the vehicle live load effects of shorter cables was larger than that of longer cables suffering from the same traffic loads. Therefore, the shorter cables are more sensitive to load effects. It should be cared for the safety of shorter cables.

Acknowledgement

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