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Integrated Health Monitoring of Highway Bridges

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Abstract
Highway bridges constitute major part of today's transport system. A sudden collapse of even a single bridge results not only huge financial losses but loss of human life as well. Hence, proper maintenance of brides is of prime importance. Structural health monitoring (SHM) is an important aspect of maintenance, where, a structure is monitored for any incipient damage or structural abnormality. This paper presents the experimental results of our work on monitoring of highway bridges. Fiber Bragg grating (FBG) sensors, accelerometers and electrical strain gauges (ESG) were used for monitoring of the bridges. As case study, monitoring of Poineer Bridge and Tuas Link has been presented.

Keywords
Structural Health Monitoring, Fiber Bragg Grating, Sensors

1. Introduction

Once a structure is built, its condition is required to be evaluated periodically. This need arises in order to detect any incipient damage so as to mitigate potential hazards to the general public. With the passage of time, some flaws or localized damages are bound to occur in the structure. These could be the result of normal usage or could be due to extreme load cases like the earthquake and the wind. So, the improved safety and optimized maintenance requirement necessitate installation of structural health monitoring systems on structures (Aktan et. al, 1998).

Conventional ESG is one of the available sensing technologies for SHM. Another technology that offers great advantage for SHM is optical fiber based sensors (Moyo et. al, 2005). Especially, fiber Bragg grating (FBG) sensor offer unique potential for SHM because of its advantages over conventional sensors such as immunity to electromagnetic interference and capability of multiplexing a number of sensors in one fiber.

This paper presents the experimental results of our work on monitoring of highway bridges in Singapore Bridges were installed with ESG, accelerometers and FBG strain and temperature sensors. A brief theory of ESG and FBG sensors have been presented, which is followed by the application of the sensors in monitoring of bridges. As case study, monitoring of Poineer and Tuas Link bridges have been presented.

1. Theory of Sensors

ESG consists of a grid of fine array of wires bonded to a backing material. The electrical resistance of this grid varies linearly with applied strain.

FBGs are narrow band reflection filter permanently written into the core of the single mode optical fiber. Once the gratings are in place, light is partially reflected at each grating. Maximum reflection occurs when each partial reflection is in phase with its neighbors. This occurs at the Bragg wavelength, given by (Kashay, 1998),

$$\lambda_b = 2\, n_{eff} \Lambda \quad (1)$$

where λ_b is Bragg wavelength which will be reflected back, n_{eff} is the effective index of the corresponding mode and Λ is the period of the grating. Any external perturbation that can change the grating periodicity or effective refractive index will alter the Bragg wavelength. This shift in Bragg wavelength will be a measure of the applied perturbation. When the fiber is strained, the Bragg wavelength varies due to the change in the grating periodicity and the photoelastic induced change in the refractive index. A sensitivity of 1.06pm/$\mu\varepsilon$ has been observed (Tjin et. al, 2002). A change in the temperature of the fiber also produces a shift in the Bragg wavelength due to thermal expansion, which changes the grating spacing, and a change in index of refraction with temperature. Temperature sensitivity of the order of 25 pm/^{o}C has been reported (Tjis et.al, 2002). The shift in Bragg wavelength with strain and temperature can be described in the following equation,

$$\Delta\lambda_b/\lambda_b = \varepsilon[\, 1\text{-}0.5\, n_{eff}\{\rho_{12} - \nu\,(\rho_{11} + \rho_{12}\,)\}] + \xi\Delta T \quad (2)$$

where ε is the axial strain in the core, ΔT is the change in temperature, ρ is the strain optic co-efficient, ν is the Poisson's ratio and ξ is the thermo–optic co-efficient. Most of these parameters are constants for a specific type of fiber, except the thermo optic co-efficient. Hence simplification can be done as follows,

$$\Delta\lambda_b = k_\varepsilon\, \varepsilon + k_T \Delta T \quad (3)$$

where k_T and k_ε are the linear coefficients of wavelength shift versus temperature and strain respectively at zero strain and 25 ^{o}C respectively. As given in Eq. (3) the reflected Bragg wavelength will be changed with the variation of the strain and the temperature. This property of FBG is used in the development of sensors.

2. FBG Sensor Configuration

A bare fiber is fragile and its response with strain is non linear. For application in civil structure, factors such as measurement range, required sensitivity, linearity as well as sensors survival during cement casting must be taken into account. For these reasons, FBG was embedded within several layers of carbon composite material (CCM). It was found that this process linearizes the FBG response to strain, it also makes the load measurement data repeatable. After embedding to CCM, FBG can take strain changes up to 4000$\mu\varepsilon$, which is larger than the strain change that a conventional concrete structure goes through before the whole structure fails or before the structure reaches an irrecoverable state.

For temperature compensation, FBG was packaged within a small metal tubing. The packaged FBG was found to respond in a linear fashion. This design makes FBG insensitive to strain and it can be used for temperature compensation. Fig. 1 shows the strain and temperature sensors.

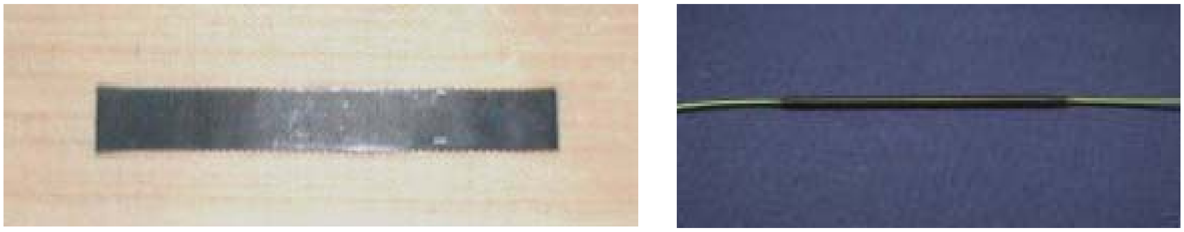


Fig. 1 FBG sensors (a) strain sensor (b) temperature sensor

3. Experimental evaluation and results

The section explains the experimental work on the monitoring of bridges. As case study, monitoring of Tuas Second Link and Pioneer bridges are presented.

3.1.1 SHM of the Tuas Second Link bridge

The Second Link Bridge is a post-tensioned concrete box girder bridge. The overall length of the bridge is about 1.9km comprising 27 spans with cross-sections of the box girder varying in depth in each span. FBG strain and temperature sensors, ESGs and accelerometers were installed in the bridge at the construction in order to monitor its short- term and long-term performance under construction loads, environmental loads and vehicular loads (Fig 2).

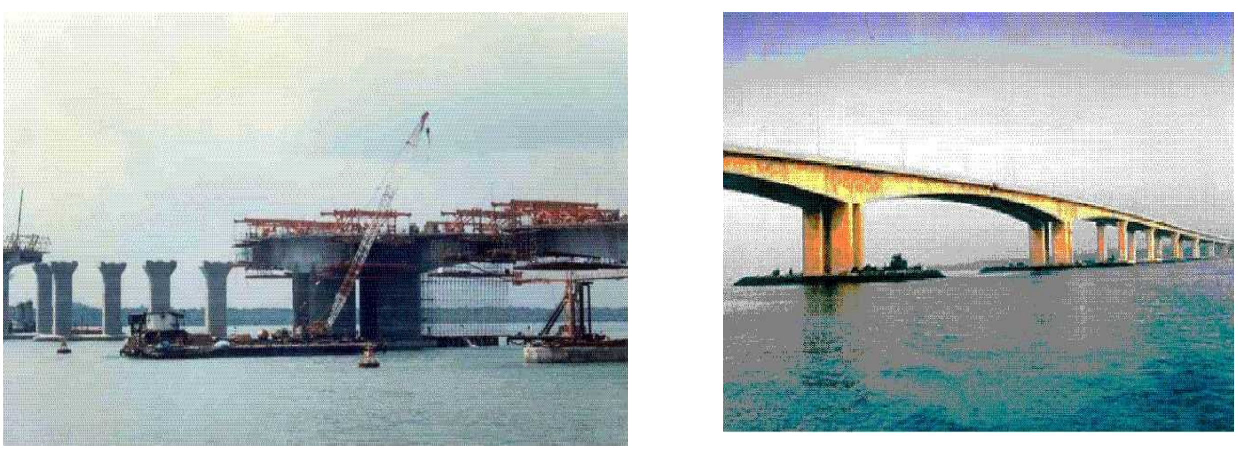


Fig. 2 Tuas bridge (a) under construction (b) under use

Figs. 3 and 4 show the strain values recorded at a particular segment during the construction and over a span of four years post construction.

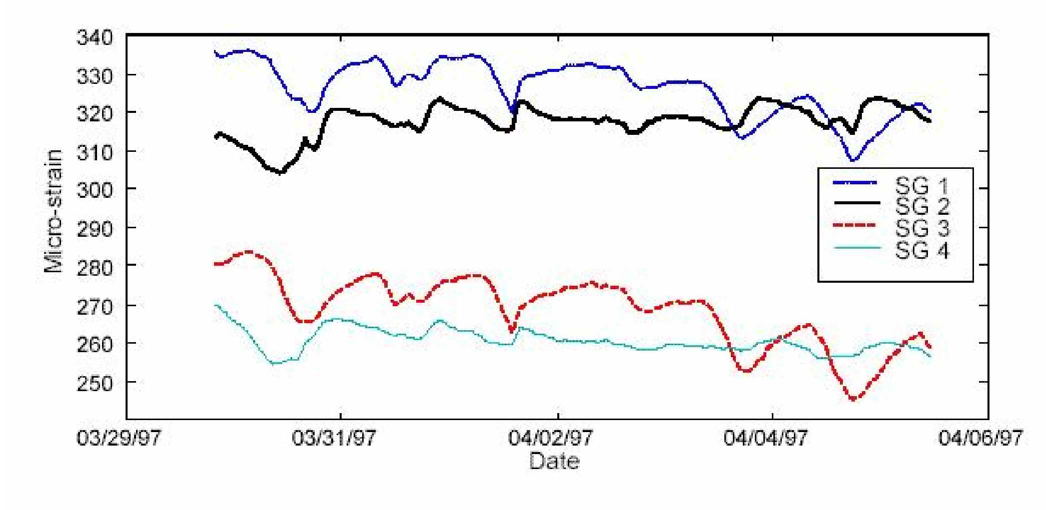


Fig. 3 Strain recorded at a particular segment during construction (concrete curing)

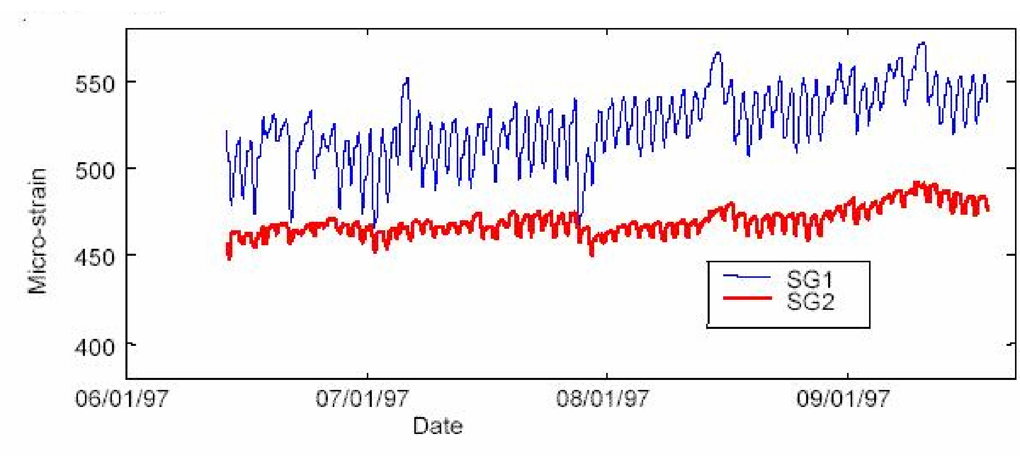


Fig. 4 Post construction strain recorded in 1997

Temperature was also recorded during construction and post construction period. Fig. 5 shows the temperature recorded during construction. Fig. 6 shows the post construction temperature data recorded in a particular segment.

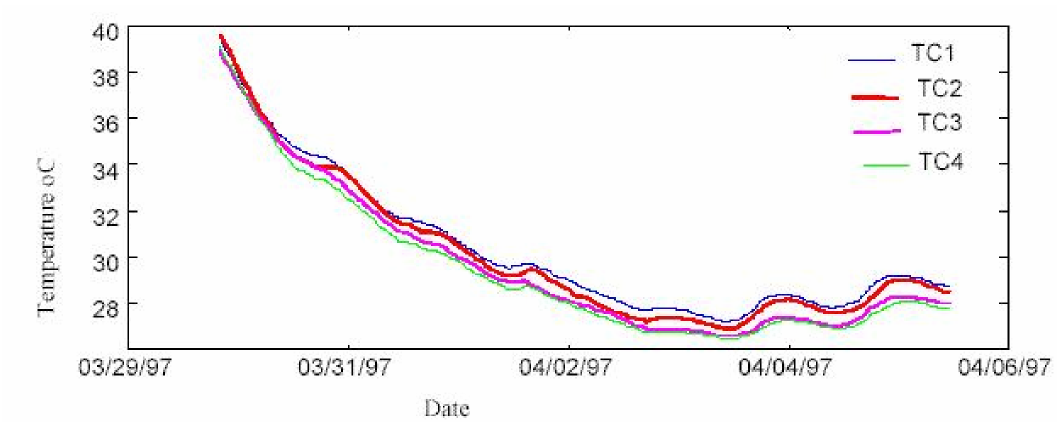


Fig. 5 Temperature recorded in a particular segment during concrete curing.

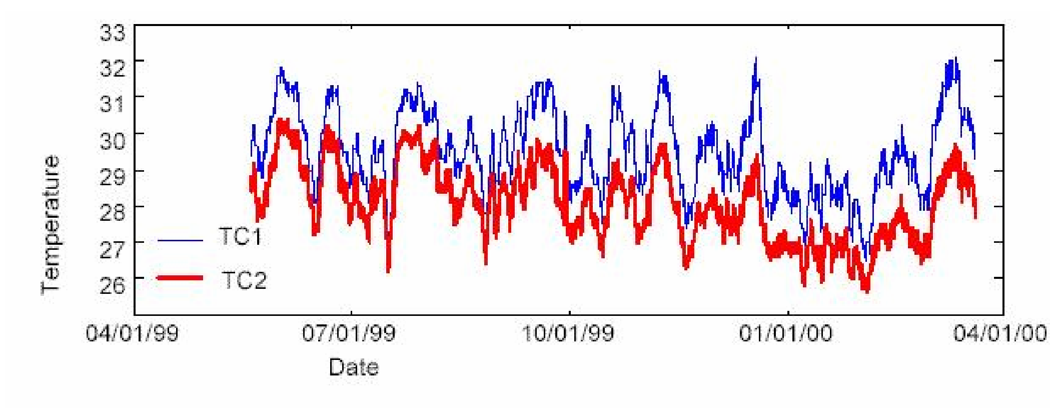


Fig. 6 Post construction temperature record.

Using the data recorded, the effect of post tensioning, concreting and shifting from traveller on strain variation can be found. This information can be used as a reference and any abnormal response observe may serve as an indication of damage.

3.1.1 SHM of Pioneer Bridge

Pioneer bridge (Fig. 7) was installed with FBG sensors, ESG and accelerometers to monitor its improved health after retrofitting. Fig. 8 shows surface munted fbg sensors.

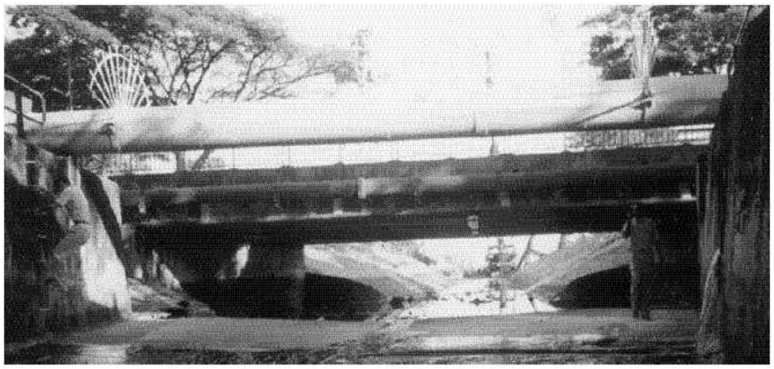
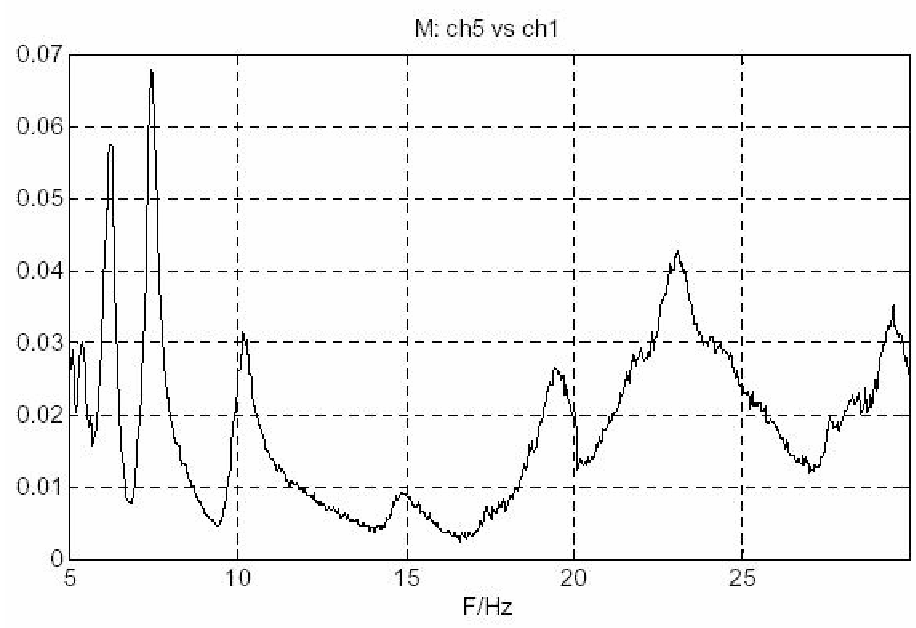


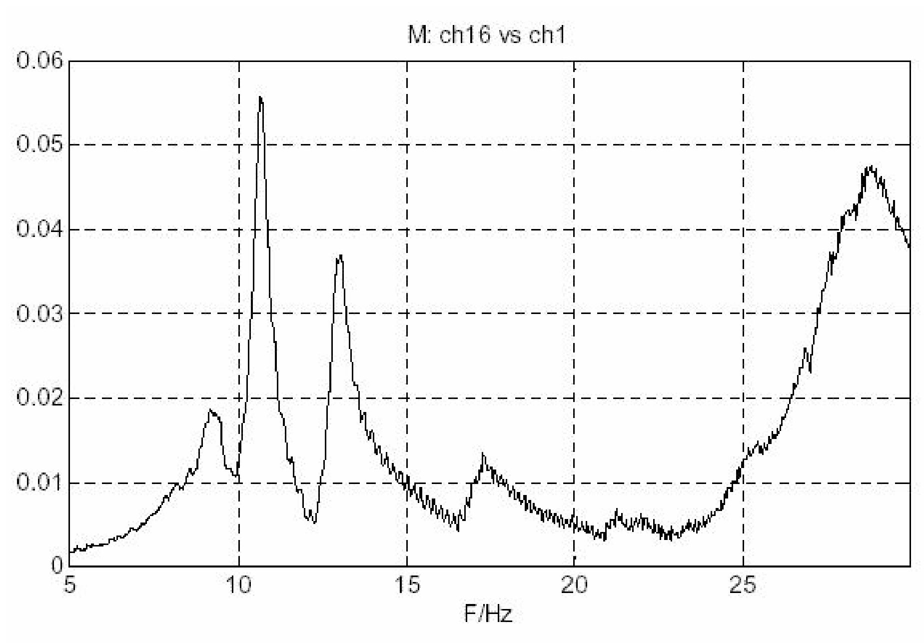
Fig. 7 Pioneer bridge

Fig. 8 Surface mounted FBG strain sensors

Fig. 9 shows the frequency response function (FRF) before and after the upgrade, indicating a considerable increase in stiffness and damping capacity due to the upgrade. Fig 9 (a) and (b) indicate a change of stiffness and damping capacity before and after the upgrading.



(a)



(b)

Fig. 9 Monitoring of Pioneer Bridge (a) before upgrading (b) after upgrading

4. Conclusions

Experimental work on monitoring of highway bridges has been presented. FBG, ESG and accelerometers were used for monitoring of strain and temperature. Monitoring of Tuas bridges was carried out during and post construction over a span of four years. The data obtained can be used as reference for monitoring any abnormality in future. For monitoring of Pioneer Bridge, surface mounted FBG sensors were used as surface mounted. The results obtained, verified the improved health of the bridge after retrofitting.

5. References

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