

Intelligent Skyscraper Monitoring System Based on GPS and Optical Fibre Sensors

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BIOGRAPY

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ABSTRACT

The collapse of the World Trade Center (WTC) has reminded us of the importance of structural integrity monitoring for improving disaster preparedness and response. A real-time system based on GPS and optical fibre sensors for monitoring structural integrity of the skyscraper has been proposed.

In the designed system, there are 4 RTK GPS receivers atop the skyscraper on the vertices and 4 groups of several strings of optical fiber Bragg grating (FBG) sensors deployed along the 4 edges of the perimeters. The GPS sensors are used to measure the 3D positions of the vertices so that strain, tilt and rotation of the skyscraper can be determined. The vibrations of the skyscraper can be measured directly if an external reference GPS receiver is used together with the rover receivers atop the skyscraper at high sampling rate. The optical fiber Bragg grating (FBG) sensors are used to measure both strain and temperature.

The conceptual design of the combined system of GPS and optical fiber sensors was based on the dimensions of the WTC. Then the first experiment involving Trimble MS750 GPS receivers, velocimeters and accelerometers indicates that the GPS RTK results are in good agreement with the results of velocimeters and accelerometers integrated once and twice respectively. The GPS

resolutions for strain, tilt and rotation of the skyscraper are 50 micro-strain, 5", and 45" respectively. In the second experiment involving the optical fiber Bragg grating (FBG) sensors, resolutions of one micro-strain change and 0.1 degree temperature change have been demonstrated.

The system proposed here may also prove to be useful for the monitoring of other structures.

INTRODUCTION

The collapse of the World Trade Center (WTC) twin-tower has caught many people by surprise and has reminded us of the importance of structural integrity monitoring for improving disaster preparedness and response. "Nobody thought it (WTC) would collapse!" The sentence has been repeated many, many times in the media on the first anniversary of 11 September 2001.

The events following the 11 September 2001 attacks in New York City were among the worst building disasters in history and resulted in the largest loss of life from any single building collapse in the United States. Of the 58,000 people estimated to be at the WTC Complex, over 3,000 lost their lives that day, including 343 emergency responders. Two commercial airliners were hijacked, and each was flown into one of the two 110-story towers. The structural damage sustained by each tower from the impact, combined with the ensuing fires, resulted in the total collapse of each building. As the towers collapsed, massive debris clouds consisting of crushed and broken building components fell onto and blew into surrounding structures, causing extensive collateral damage and, in some cases, igniting fires and causing additional collapses. In total, 10 major buildings experienced partial or total collapse and approximately 30 million square feet of commercial office space was removed from service, of which 12 million belonged to the WTC Complex.

The collapse of the twin towers astonished most observers, including knowledgeable structural engineers, and, in the immediate aftermath, a wide range of explanations were offered in an attempt to help the public

understand these tragic events. However, the collapse of these symbolic buildings entailed a complex series of events that were not identical for each tower.

To determine the sequence of events, likely root causes, and methods or technologies that may improve the building performance observed, the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE), in association with New York City and several other Federal agencies and professional organizations, deployed a team of civil, structural, and fire protection engineers to study the performance of buildings at the WTC site.

Although the team conducted field observations at the WTC site and steel salvage yards, removed and tested samples of the collapsed structures, viewed hundreds of hours of video and thousands of still photographs, conducted interviews with witnesses and persons involved in the design, construction, and maintenance of each of the affected buildings, reviewed construction documents, and conducted preliminary analyses of the damage to the WTC towers, with the information and time available, **the sequence of events leading to the collapse of each tower could not be definitively determined.** Because of lack of built-in monitoring system and there was not time to deploy an external one, it is unfortunate that the studies had to rely on some subjective information as well, in addition to field observations. Therefore, from our opinion, objective, uniform, scientific data is missing about what actually happened during the collapse of the WTC.

Let's remember that after September 11 similar attacks to high-rise buildings happened again inside as well as outside the US.

Unfortunately, terrorist attack is not the only threat to such structures. For example, if a high-rise building or a bridge is partly damaged in a major earthquake, the very first decision we need to make is whether the structure is still safe for rescue personnel to enter (in the case of a building) or for emergency vehicles to pass (in the case of a bridge) in order to carry out rescue work. A real-time monitoring system can function as an early warning system, will provide crucial data for making these decisions, and will help to establish the mechanism if the structure is collapsed.

A real-time system based on optical fibre and GPS sensors for monitoring structural integrity has been proposed in this paper.

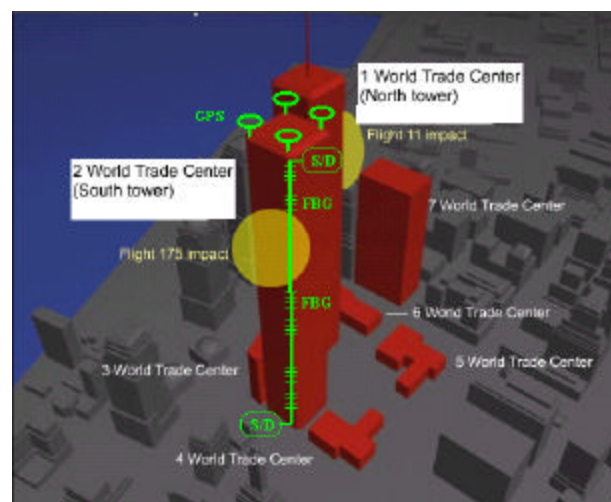
CONCEPTUAL DESIGN OF THE SYSTEM

In the designed system (Figure 1), there are 4 RTK GPS receivers atop the skyscraper on the vertices and 4 groups of several strings of optical fiber Bragg grating (FBG) sensors deployed along the 4 edges of the perimeters. The

GPS sensors are used to measure the 3D positions of the vertices so that strain, tilt and rotation of the skyscraper can be determined. The vibrations of the skyscraper can be measured directly if an external reference GPS receiver is used together with the rover receivers atop the skyscraper at high sampling rate.

The optical fiber Bragg grating (FBG) sensors are used to measure both strain and temperature. In the system 20 FBG sensors connected by optical fiber form one linear array (string) in which they are arranged in 10 pairs of 2 closely located FBG sensors. In each pair, one FBG sensor is in thermal contact with the structure but does not respond to local strain changes while the other FBG sensor responds to both temperature and strain changes so that temperature and strain changes can be discriminated. The length of optical fiber between two adjacent FBG sensor pairs is the same as the height of one storey so that there is one FBG sensor pair at each of the 4 edges on every floor. Hence, one string with 20 FBG sensors will cover 10 storeys of the skyscraper. Therefore, depending on the total number of storeys in the skyscraper, several strings of optical fiber Bragg grating (FBG) sensors will have to be used in each edge. Taking the WTC as an example, 11 strings have to be used at each edge in order to cover all the storeys.

Experiments have been carried out to study the feasibility of using the GPS and FBG sensors in such an integrated system.



FBG: optical fibre grating sensor
S/D: optical source and detector
GPS: Global Positioning System

Figure 1. Conceptual design of the combined optical fibre and GPS monitoring system.

THE GPS COMPONENT

In a joint experiment in Tokyo on 10 August 1999 between the University of New South Wales (UNSW), Australia and the Meteorological Research Institute

(MRI), Japan, two Trimble MS750 GPS receivers were used in the RTK mode with a fast sampling rate of up to 20Hz (Ge 2000). As can be seen from Figure 2, the GPS antenna, an accelerometer, and a velocimeter were installed on a metal plate, which was mounted with bolts and adhesive tape on the roof of an earthquake shake-simulator truck, shown in Figure 3.



Figure 2. The setup of GPS antenna, accelerometer, and velocimeter.



Figure 3. Earthquake shake-simulator truck.

A total of 48 experiment sessions in which vibrations corresponding to earthquakes of different intensities, including past quakes such as the 1923 Kanto Quake and the 1995 Kobe Quake, were simulated. GPS sampling rates used were 20Hz, 10Hz and 5Hz, while the sampling rates for the accelerometers were 100Hz.

The GPS receiver on the truck was used as 'rover receiver' while a reference station was setup 10m away from the truck. The GPS-RTK results for the experiments were recorded on files, in the GGK message format, which includes information on time, position, position type and DOP (Dilution of Precision) values. Acceleration and velocity data from the seismometers were recorded concurrently. According to the MS750 Manual, the accuracy of the MS750 in low latency mode, in which it

was configured for the UNSW-MRI experiment, is 2cm + 2ppm for horizontal and 3cm + 2ppm for vertical.

In the following Figure 4, the GPS-RTK time series of selected segments of the 20Hz session are compared with acceleration integrated twice and velocity integrated once. The later two are bandpass filtered (passband: 0.1 to 8Hz). The three results are in very good agreement in all the experimental sessions (where there were vibrations). But the GPS results indicate that the shaft of the shake-simulator truck did not return to its original position after the sessions, and indeed no effort was made to do so in the experiment.

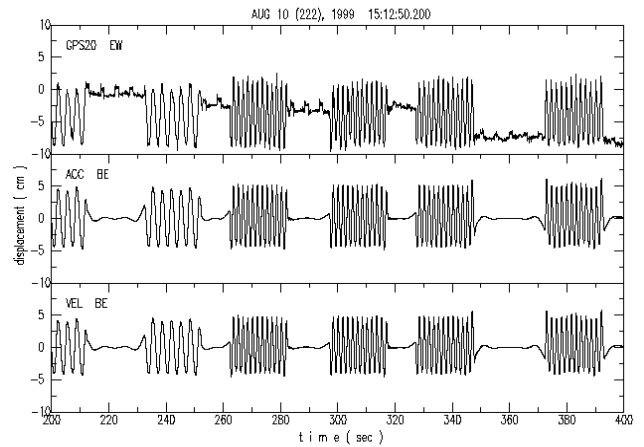


Figure 4. Comparison of GPS results with accelerometer and velocimeter.

In Figure 5 below, the three results were bandpass filtered (passband: 0.1 to 8Hz). The acceleration and velocity results were offset 2cm and -2cm respectively in the vertical axis direction for better viewing. (As a matter of fact, when the results are superimposed in a colour plot they agree with each other very well.) The GPS result is much better than expected (although the origin of the trace offsets in the GPS result that occur every 5 seconds is not clear at present). As can be seen from the figure, sine waves of 10cm amplitude peak-to-peak and 1-5 sec periods were generated by the truck in this session.

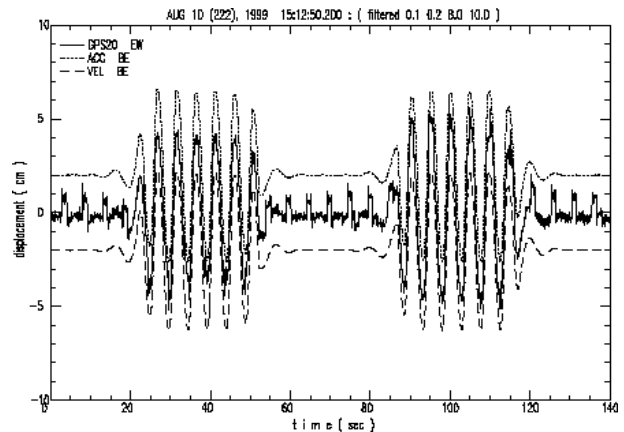


Figure 5. Another comparison of GPS results with accelerometer and velocimeter.

In conclusion, in the joint UNSW-MRI experiment using two Trimble MS750 GPS receivers, operating in the Real-Time Kinematic mode, to detect seismic signals generated by an earthquake simulating truck, the GPS-RTK result is in very good agreement with the results of the accelerometer and velocimeter, indicating that a fast sampling rate (up to 20Hz) GPS system can be used for measuring displacements directly. The vertical displacement divided by the height of the structure will give the strain; the horizontal displacement can be converted to tilt and rotation of the structure.

The advantage of using GPS receivers instead of traditional accelerometers is GPS results can be directly used to derive strain, tilt and rotation of the skyscraper while the accelerometer results have to be integrated twice in order to be converted to displacement, which cannot reflect the true movement of the structure as revealed in Figure 4. Another advantage is that the spectrum response of GPS is flat over the frequency band (0 – 20Hz) most important to structural integrity monitoring.

Since the conceptual design of the combined system was based on the dimensions of the WTC (417m in height and 65m in width), the GPS resolutions for strain, tilt and rotation of the skyscraper are 50 micro-strain, 5", and 45" respectively, assuming the GPS-RTK accuracy as 1cm + 2ppm for horizontal and 2cm + 2ppm for vertical.

THE OPTICAL FIBRE SENSOR COMPONENT

A Fiber Bragg Grating (FBG) sensor is a periodic or non-periodic perturbation of the refractive index along the fiber length which is formed through photosensitivity by exposure of the core to an intense optical interference pattern. The index perturbation in the core is similar to a volume hologram or a crystal lattice, that acts as a stop-band filter. A narrow band of the incident optical field within the fiber is reflected by successive, coherent scattering from the index variations.

The following Figure 6 shows Bragg resonance for reflection of the incident mode occurs at the wavelength for which the grating pitch along the fiber axis is equal to one-half of the modal wavelength within the fiber core. The back scattering from each crest in the periodic index perturbation will be in phase and the scattering intensity will accumulate as the incident wave is coupled to a backward propagating wave.

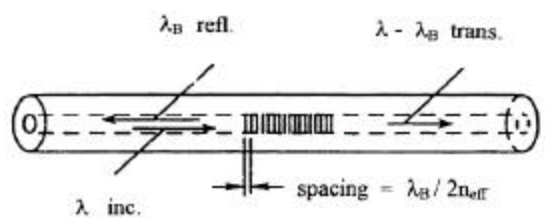


Figure 6. A FBG sensor.

For short period fiber grating or FBG, the strongest interaction or mode-coupling occurs at the Bragg wavelength given by (Alan et al, 1997; Kenneth and Meltz, 1997; Nellen and Sennhauser, 2000)

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

where n_{eff} is the modal index and Λ is the grating period (usually $< 1\mu\text{m}$).

Figure 7 shows that with FBG it is possible to detect both the reflected and transmitted signals. The basic principle is the changes in the measurand (e.g., strain, temperature) will change the grating pitch or refractive index which induce a shift in the Bragg wavelength, linked by resonance condition of a grating. Therefore, the change of the measurand can be obtained by monitoring shift in the Bragg wavelength of the FBG sensor. If spectrally broadband source of light is injected into the fiber, a narrowband spectral component at the Bragg wavelength is reflected by the grating. In the transmitted light, this spectral component will be removed. **Both the reflected and transmitted light can be used for sensing.**

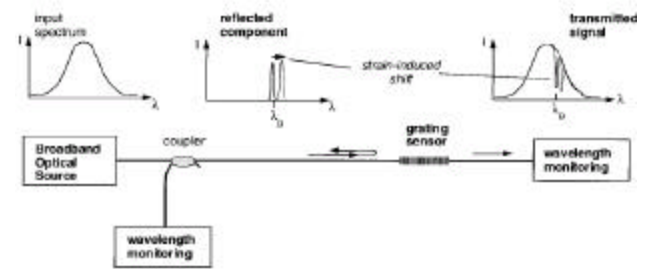


Figure 7. FBG sensing principle.

Any change in fiber properties, such as strain, temperature, or polarization which varies the modal index or grating pitch, will change the reflected (Bragg) or transmission wavelength. The grating is an intrinsic sensor which changes the spectrum of an incident signal by coupling energy to other fiber modes. In the simplest case of FBG, the incident wave is coupled to the same counterpropagating mode and thus reflected.

Differentiate Eq. (1) we have

$$d\lambda_B = 2n_{eff} d\Lambda + 2\Lambda dn_{eff} \quad (2)$$

From Eq. (1) and (2) we obtain

$$\frac{d\lambda_B}{\lambda_B} = \frac{2n_{eff} d\Lambda + 2\Lambda dn_{eff}}{2n_{eff} \Lambda} = \frac{d\Lambda}{\Lambda} + \frac{dn_{eff}}{n_{eff}} \quad (3)$$

The sensitivity is governed by the fiber elastic, elastooptic and thermooptic properties and the nature of the load or

strain which is applied to the structure that the fiber is attached to or embedded within. Strain shifts the Bragg wavelength through dilating or compressing the grating and changing the effective index. Using Eq.(3) the amount of wavelength shift is given by

$$\frac{\delta\lambda_B}{\lambda_B} = \epsilon_1 - (n^2/2)[p_{11}\epsilon_t + p_{12}(\epsilon_1 + \epsilon_t)] \quad (4)$$

where the principal strains are \hat{a}_l along the fiber axis and \hat{a}_t transverse to the fiber axis and the fiber Pockel's coefficients are p_{11} and p_{12} . For simplicity n_{eff} is replaced by n . A more complicated loading might be triaxial which would introduce a third strain component, normal to both the direction of fiber polarization and wave propagation. If the strain is homogeneous and isotropic, then Eq.(4) simplifies to its more common form

$$\frac{\delta\lambda_B}{\lambda_B} = [1 - p_e]\epsilon \approx 0.78\epsilon \quad (5)$$

where we have subsumed the photoelastic contributions into p_e , which is defined by

$$p_e = (n^2/2)[p_{12} - \mu(p_{11} + p_{12})] \quad (6)$$

in terms of the fiber Pockel's coefficients p_{11} and p_{12} and the Poisson ratio μ . Typical values for the sensitivity to an applied axial strain are 1 nm/millistrain at 1300 nm and 0.64 nm/millistrain at 820 nm. The strain response is linear with no evidence of hysteresis at temperatures as high as 370 °C. **Therefore, the FBG strain resolution can be as high as 1 istrain considering the wavelength resolution is better than 0.001 nm.**

The temperature sensitivity of a bare fiber is primarily due to the thermo-optic effect. It is given by

$$\frac{\delta\lambda_B}{\lambda_B} = \alpha + \frac{1}{n} \frac{dn}{dT} \approx \frac{6.7 \times 10^{-6}}{^{\circ}\text{C}^{-1}} \quad (7)$$

up to 85 °C. α is the coefficient of thermal expansion (CTE) of the fiber material (e.g., silica), and dT is the temperature change. A typical value for the thermal response at 1550 nm is 0.01 nm/°C. At higher temperatures, the sensitivity increases and the response becomes slightly nonlinear. If the fiber is jacketed or embedded in another substance then the sensitivity can be enhanced by the proper choice of material. This is clearly desirable if the grating is to be used as a sensor. **Therefore, the FBG temperature resolution can be as high as 0.1°C considering the wavelength resolution is better than 0.001 nm.**

A very important advantage of an FBG sensor is that it is wavelength-encoded. Shifts in the spectrum, seen as a narrow-band reflection or dip in transmission, are independent of the optical intensity and uniquely associated with each grating, provided no overlap occurs in each sensor stop-band. With care in selection of the Bragg wavelengths, each tandem array of FBG sensors only registers a measurand change along its length and not from adjacent or distant transducers.

Several individual FGB sensors can be connected to form an array for quasi-distributed monitoring as shown in Figure 8. Moreover, the use of an optical switch shown in Figure 9 allows such an instrumentation system to address several "strings" or "arrays" of FBG sensors as described in Figure 8. In the system, single-mode optical fiber switches driven under PC control are utilized to allow the measurement of strain along independent strings of FBG sensors.

This approach can bring significant cost-reduction to the monitoring system because several FBG arrays can share the same opto-electronic system.

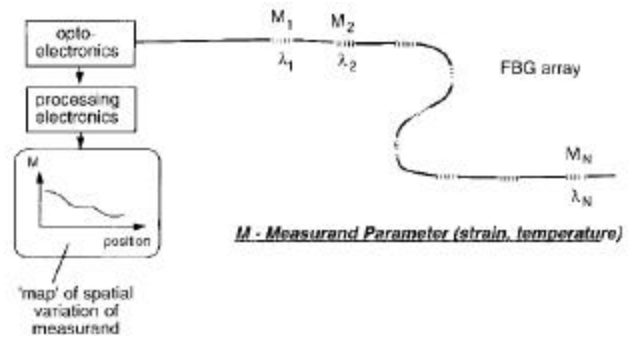


Figure 8. A single string FBG array.

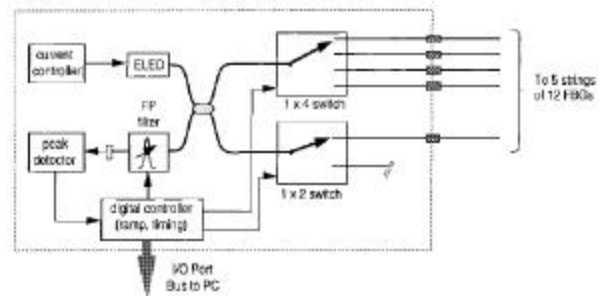


Figure 9. A multi-string FBG array.

An experiment involving the optical fiber Bragg grating (FBG) sensors was carried out in Sydney by the Optical Communications Group (OCG) in the School of Electrical Engineering & Telecommunications, the University of New South Wales, Australia.

First, the two FBG sensors (FBG1 and FBG2) were tested using the optical spectrum analyzer. In Figure 10 the first

plot is the reflective spectrum of the two FBGs. The second plot shows the reflective spectrum of FBG1 and transmissive spectrum of FBG2. It can be seen that the Bragg wavelengths of the two are very close.

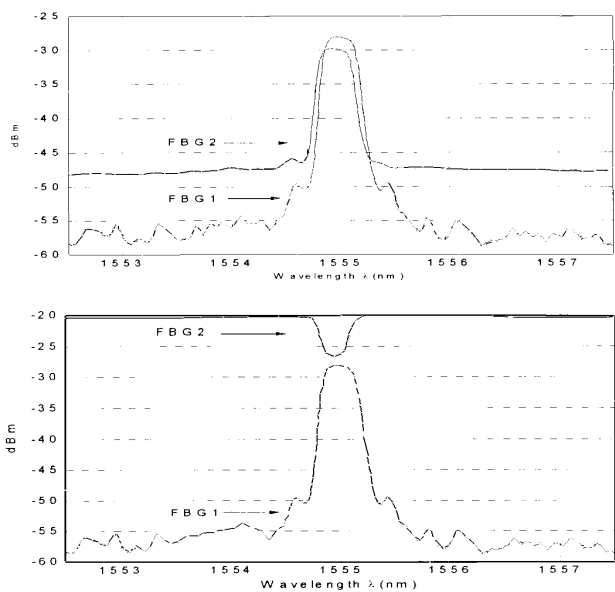


Figure 10. Reflective and transmissive spectrums of FBG.

Using the optical spectrum analyzer, FBG1 was further tested in various load conditions. In Figure 11 below the wavelength shift is plotted against strain assuming a sensitivity of one micro-strain per pm wavelength shift.

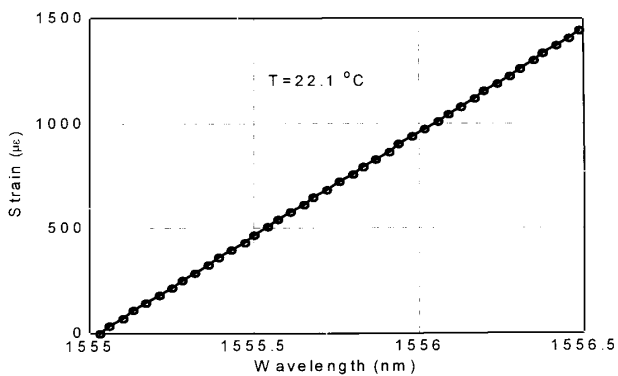


Figure 11. FBG wavelength shift against strain.

Then the two FBG sensors were used together in an experimental system as depicted in the Figure 12. Broadband light was launched into the sensing FBG1 through an adapter, an isolator and a 3-dB fibre coupler. Light reflected by FBG1 was split into two arms. One arm was directly detected by photodetector PD1 (V1) while on another arm light passed through FBG2 and was detected by photodetector PD2 (V2).

At different ambient conditions (23.2 and 25.2 °C of temperature), FBG1 was tested in various strains. The results are given in the Figure 13. It can be seen that the linearity in 0 ~ 250 micro-strain range is very good.

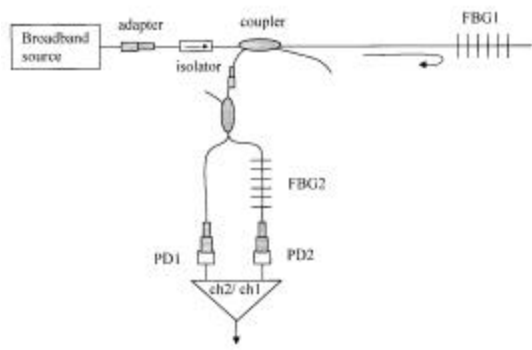


Figure 12. Dual FBG experiment system.

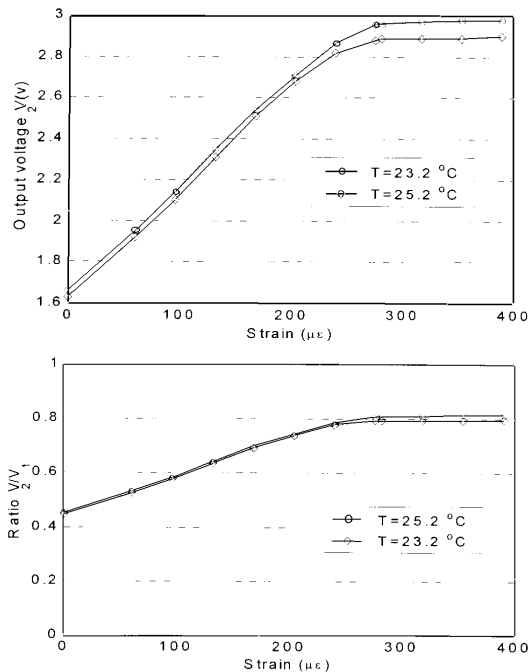


Figure 13. FBG strain sensitivity test under different temperature conditions.

In conclusion, the temperature and strain resolutions of FBG can be as high as 0.1°C and 1 µstrain respectively and the advantages of FBG sensing are,

- electrically passive operation
- EMI immunity
- high sensitivity
- multiplexing capabilities
- distributed sensing
- inherent self referencing

The last two are unique to FBG sensing while the rest are the advantages normally attributed to fiber sensors in general.

THE INTEGRATION OF GPS AND OPTICAL FIBRE SENSOR COMPONENTS

On 11 September 2001, some communications technology was put to extreme tests and failed. Hence, we have to focus on redundancy and security in designing the integrity monitoring system.

In the combined GPS and FBG system, both local strain at the individual FBG sensors and integrated strain between FBG sensors can be monitored. The strain measured by GPS is essentially an integration of all these FBG measured strains over the whole height of the skyscraper.

As a redundancy within the FBG sensing component optical sources and detectors (S/D) have been placed both on top and at the bottom of the skyscraper as shown in Figure 1. With such a design, even if the building is suffered an attack mid-way the FBG arrays will still be functional using the reflective sensing scheme before a total collapse.

In order to send the monitoring data to a safe location, various data communications schemes such as internet, radio and satellite have to be used. The FBG arrays themselves can also be used as data links, because a FBG sensor is merely a perturbation of the refractive index along the fiber length which is formed through photosensitivity by exposure of the core to an intense optical interference pattern.

For example, Figure 14 shows the FBG reflection growth in a polymer optical fibre manufactured in UNSW under the exposure of 4.6mJ ultraviolet laser. Figures 15 and 16 show the FBG reflection and transmission growth respectively after laser writing. Therefore, in principle data communications in the FBG arrays can be carried out on any wavelength outside 1572-1574 nm. However, considering the variations in the central FBG wavelength as illustrated in Figures 17, 18 and 19 of three FBGs all produced in UNSW, especially between FBG1 (1572.25nm) and FBG2 (1573.25nm), the wavelength used for data communications should be selected further away from the Bragg wavelength. Unlike Figure 14, the reflection spectrums in Figures 17-19 have been vertically shifted -6dBm consecutively for clarity.

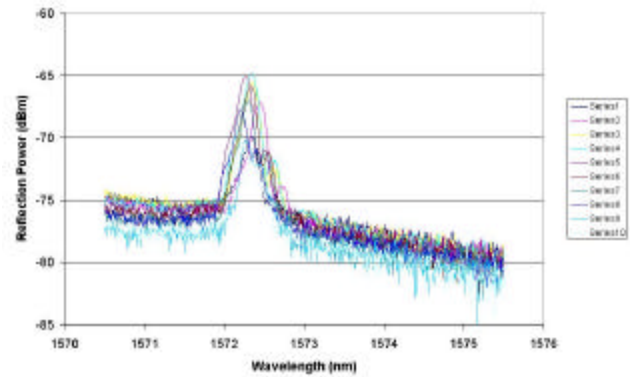


Figure 14. FBG reflection growth during laser writing.

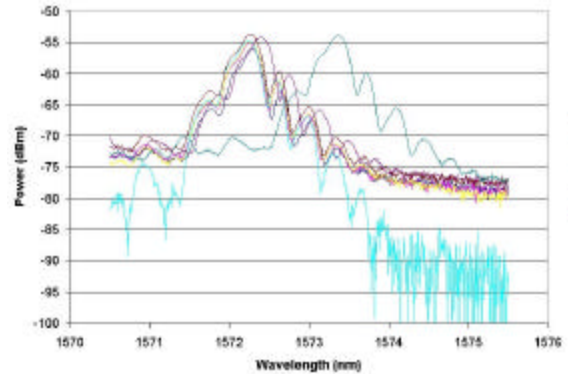


Figure 15. FBG reflection growth after laser writing.

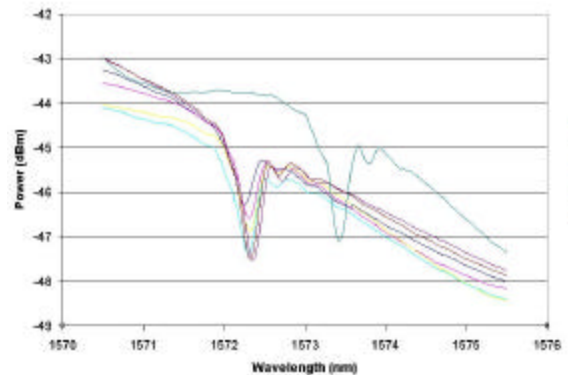


Figure 16. FBG transmission growth after laser writing.

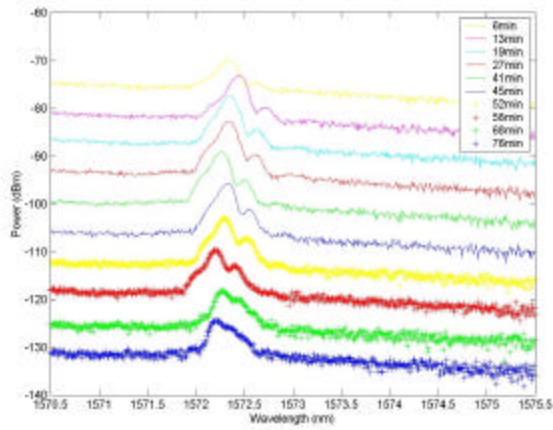


Figure 17. FBG1: reflection growth during laser writing.

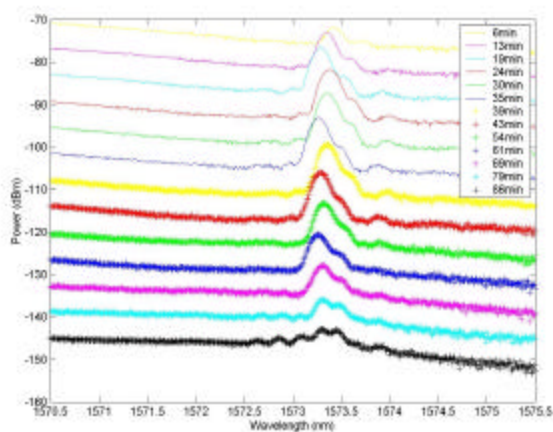


Figure 18. FBG2: reflection growth during laser writing.

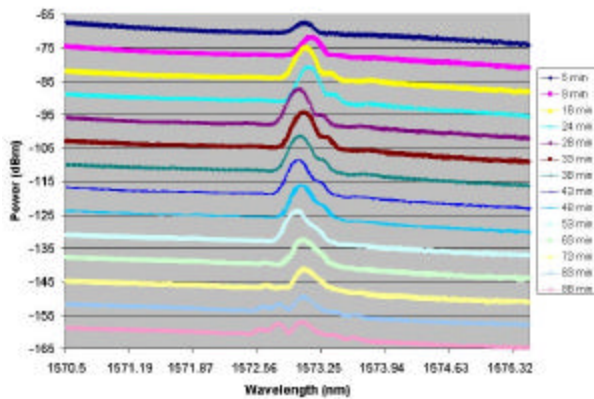


Figure 19. FBG3: reflection growth during laser writing.

CONCLUDING REMARKS

In the wake of the September 11 attack, a real-time system based on GPS and optical fibre sensors for monitoring structural integrity of the skyscraper has been proposed.

The conceptual design of the combined system was based on the dimensions of the WTC. Then the first experiment involving Trimble MS750 GPS receivers, velocimeters and accelerometers indicates that the GPS RTK results are in good agreement with the results of velocimeters and accelerometers integrated once and twice respectively. The GPS resolutions for strain, tilt and rotation of the skyscraper are 50 micro-strain, 5", and 45" respectively. In the second experiment involving the optical fiber Bragg grating (FBG) sensors, resolutions of one micro-strain change and 0.1 degree temperature change have been demonstrated.

The system can function as an early warning system, will provide crucial data for making decisions for rescue, and will help to establish the mechanism if the structure is collapsed. The system proposed here may also prove to be useful for the monitoring of other structures.

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