Cover page

Title: Practical issues in using novel sensors in SHM of civil infrastructure: problems and solutions in implementation of GPS and fibre optics

Authors: James M. W. Brownjohn
Pilate Moyo
Chris Rizos
Tjin Swee Chuan

ABSTRACT

Two contemporary research programs have explored the use of newer type of sensors believed, and advertised, to have potential in future implementation of SHM system for civil structures. Fibre optic sensors have the possibility to record a range of physical parameters simultaneously and at high speed through multiplexing capabilities of the fibre Bragg grating (FBG); GPS has the advantage to measure absolute displacement of slowly moving flexible structures without need for optical line of sight.

FBG sensors have been tested in laboratory situations and have finally been implemented for strain measurements in an expressway viaduct construction program. Meanwhile, a twin-rover GPS system mounted on top of one of Singapore's tallest buildings has recently provided real-time static and dynamic response data as part of an existing monitoring system designed to study structural performance during wind and earthquake loading. Some of the first results of these two programs will be presented.

Both implementations have been problematic in different ways and the paper will identify some of the difficulties and the solutions adopted. The practical limitations and optimal applications can thus be identified.

INTRODUCTION

Structural Health monitoring is a multi-disciplinary research area that merges expertise within the fields of structural analysis and dynamics, with (inter alia) various forms of information technology (IT) such as database management, signal processing, data mining, expert systems and heuristics. Between the structure and the IT lie applications for sensors and the systems for communication of raw or

JMW Brownjohn, NTU Singapore, School of CEE, 50 Nanyang Avenue, Singapore 639798
Pilate Moyo, Department of Civil Engineering, University of Cape Town
Chris Rizos, University of New South Wales
Tjin Swee Chuan, NTU Singapore, School of EEE

semi-processed data. In some cases the link of IT and sensor/communications technology to the structural application is ‘simple’ technology transfer, for example statistical process control procedures common in manufacturing industry that are now used for anomaly detection (1). Mostly such applications can be pursued from the comfort of a computer room, and to some extent research on sensors and communications can be tested in a laboratory.

Probably the greatest challenges for SHM of civil infrastructure lie in the development of appropriate sensing, local data management and communication techniques for field application. Outside the artificial laboratory environment workers, the public or even animals deliberately or unintentionally vandalise equipment, environmental factors push the equipment to the limit of their specifications, noise takes on a completely different and unpredictable form compared to the synthetic computer room equivalent, power fails, telephone or wireless links are interrupted and the SHM system that is designed to ease the burden of inspection and maintenance becomes a burden in itself.

It is for this reason that there is much talk and relatively few field applications of SHM. The very practical problems of designing, implementing and maintaining a SHM system are an equal if less glamorous challenge in comparison to the developments at the IT end of the spectrum.

Part of the attraction of conducting SHM research is the challenge of technology transfer and the collaborations it facilitates. Two small areas of sensor technology in particular have attracted considerable interest for SHM: Global positioning systems (GPS) for absolute deflection monitoring and fibre optics sensing (FOS) for strain, pressure, temperature and other parameters. This paper describes our experience in their application.

GPS in SHM

Conventionally a major effort in SHM research has been devoted to interpreting acceleration signals. The popularity of accelerometers in SHM is in part due to their wide range of specifications including applications for rugged conditions. They can simply be placed on the structure and signals are immediately available, without need for embedment or rigid fixing. Their versatility results in heavy usage, and large-scale research in ‘vibration based damage detection’ (VBDD) still continues to search for the holy grail of a reliable procedure for detecting, locating and even quantifying damage in a real civil structure, not just a laboratory test bed or computer simulation.

Dating back to around the same period three of four decades ago when VBDD began to emerge, mandated surveillance programs for dams were using a range of instruments including displacement sensors to track performance and indicate possible unsafe conditions. Arguably the applications in dams were the first true SHM systems incorporating systematic instrumentation, data acquisition and interpretation (2). Displacement sensors have a fundamental problem of needing a physical reference and generally being unable to provide absolute deflection data devoid of interference by movements of the reference or cross-talk from other degrees of freedom.

In the last decade the abilities of GPS to resolve deflections down to ‘millimetre’ accuracy have led to their application for deflection monitoring in dams (3) and suspension bridges (4). A rather small number of publications are available presenting successful applications of GPS to SHM, but these, with notable exceptions generally short-term instrumentation programs (5) and very often they are isolated rather than being integrated into a comprehensive system.

There are several motives and some special challenges in applying GPS within SHM of tall buildings. Within a broad interpretation of the definition of SHM that includes performance monitoring with an aim to identify mechanisms and correlations between loading and response parameters, deflection monitoring of tall buildings is a rare exercise (6) usually applied for calibrating wind loading codes. The problem here is that the wind-induced response of a building comprises three components: a mean component due to mean wind, a background non-resonant component due to turbulence or fluctuation in wind speed and resonant response, usually in fundamental mode. Of these, accelerometers can capture resonant response and that part of background response down to a very low frequency that is highly dependent on the quality of the accelerometer and associated signal conditioning. GPS on the other hand is perfect for recovering the static component, a slowly varying background response up to a frequency dependent on the system accuracy and resonant response where that rises above the system resolution. Hence GPS and accelerometers should in principle provide, in combination, the total structure displacement response to wind.

GPS INTEGRATION FOR SHM OF A TALL BUILDING

A structural (health) monitoring system has been in operation at Republic Plaza (7) a 280m office tower in Singapore since 1995. It has developed from two channels of biaxial accelerations at the roof to sixteen channels of data from

- Biaxial accelerometers at roof and basement (total four channels)
- UVW anemometers at two locations on the roof (total six channels)
- RTK Eastings and Northings from GPS antenna at opposite corners of the roof
- Temperature sensors in the accelerometers for bias correction

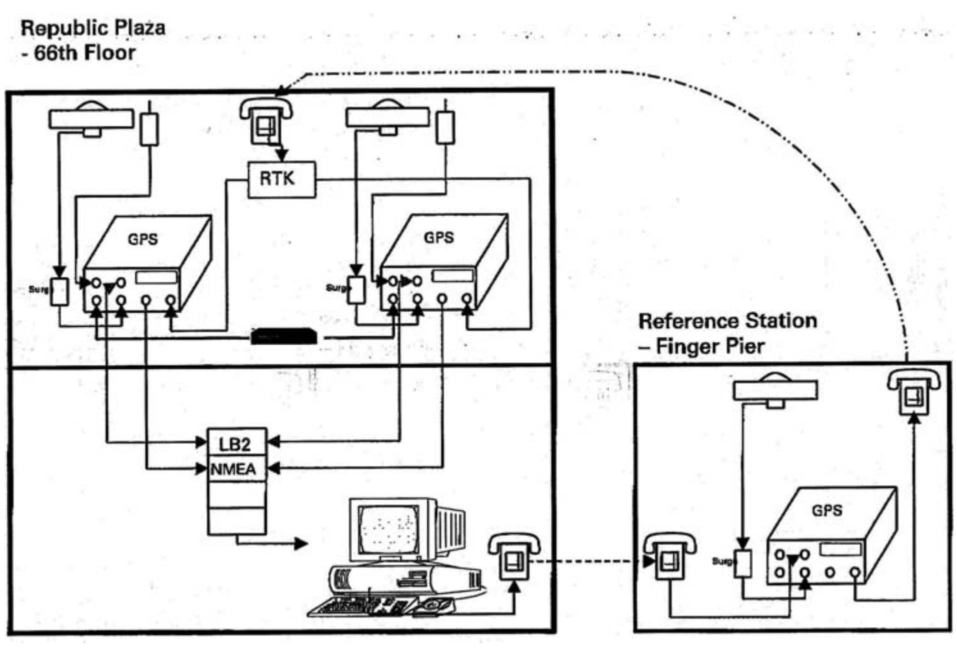

Figure 1 Schematic of GPS system at republic Plaza

Figure 2 Republic Plaza with GPS antenenna and UVW anemometer

Figure 1 shows the schematic of the system and Figure 2 the implementation which is a combination of two linked logging systems. The original logging system that digitised wind and acceleration was reconfigured to acquire additional channels of GPS and to inform the separate GPS system of an event trigger. The new GPS logging system of Figure 1 provides corrections from a base station on a low rise building via a leased line, enabling the two receivers at Republic Plaza to provide real time kinetic (RTK) signals which are converted to analog form for perfect synchronisation with the analog logger. The RTK solution is updated at epochs one second apart and the analog system operates at 8Hz. In addition to the RTK solution, raw GPS data are stored in ring buffers on the three receivers and downloaded, with pre-trigger, for events triggered by the analog system for post-processing with software that may produce a more accurate solution than RTK.

PRELIMINARY RESULTS

The complete system has been in operation only since January 2003, at the beginning of the North-East Monsoon, a period of two or three months during which prevailing north easterly winds are relatively strong (for Singapore) and steady, gusting up to 20m/sec. During this period a number of events were captured and used for debugging the system. Figure 3 shows RTK and post-processed results for a one hour period of strong winds for which the analog system was continuously triggering. Figure 4 shows a minute of the signals during strongest response; upper two plots are GPS signal, lower plots are acceleration (with signs reversed).

The figures reveal much about building response as well as GPS performance. First, the RTK suffers from a periodic and mysterious loss of transmission of corrections via leased line, which takes time to recover and results in data loss. Second (and not shown here) merging of the post-processing of the six 10 minutes raw GPS files fro each event trigger is not always seamless due to a software constrain. Doubtless by the time the paper is read the problems will be solved but there are clearly systems issues in building such an installation.

The deflections of Figure 3 show simple correlation with wind load, indicating that large quantities of data for strong response would be required to establish reliable load-response correlations.

Figure 4 is the first clear indication that the system can recover structural deflections of the order of mm, as the dynamic response is clearly evident in the GPS signal from each direction. What is unknown is the level of noise in the signal and if it matches or improves on the manufacturer specification. Getting clear dynamic GPS data is clearly a far more challenging problem for a tall building than it is for a tower or suspension bridge. Clearer qualification of the system performance along with reliable structural response data will require stronger winds such as occur during the season of thunderstorms and ‘Sumatran squalls’.

FIBRE OPTICS FOR PERFORMANCE OF CONCRETE STRUCTURES

There has been a rapid growth in research in fibre optic sensor (FOS) applications to instrumentation of range of civil structures and materials in and outside the laboratory. For SHM the challenge is field applications and Singapore the material is invariably concrete. The aim has therefore been to develop sensor systems for stress, strain and temperature monitoring (8,9) that benefit from FOS attributes of isolation from electrical interference, good environmental specification and most importantly the ability for high-speed multiplexing. In fact it is the last attribute that sets FOS apart with unique and very attractive capability for SHM, without which the overheads in its use may not justify its use.

It is the fibre Bragg grating (FBG) form of FOS that has greatest appeal to SHM through the ability to impregnate discrete lengths of a fibre to reflect specific narrow ranges of light wavelength; Figure 5 shows the principle of FBG and Figure 6 shows the idealized deployment for a short-span bridge.

PRACTICAL IMPLEMENTATION OF FOS

Our experience with fibre optics began with an invitation to researchers in NTU schools of mechanical and electrical engineering to install fibre optic strain gauges in a 10.5m span reinforced concrete bridge models used in a student training exercise. We purchased a number of expensive Fabry-Perot gauges, including one pre-installed in an embedment device. Other bare fibres were bonded to home-made embedment devices. The local researchers installed their own devices, principally the FBG type prepared in NTU facilities, which were bonded directly ground-down re-bars in the model. The model bridges were tested to failure while reading the signals from the FOS. The FBG gauges worked well, while the expensive Fabry Perot gauges did not work well, largely due to the installation problems. As a result of this experience and because the FBG can be made locally at reasonable cost and have the high-speed multiplexing capability, our research has focused on methods of installing FBG sensors in and on concrete structures.

The research effort in SHM at NTU has revolved around highway bridges because of the accessibility, public ownership and excellent relationship with the bridge management team of Land Transport authority (LTA) in Singapore.

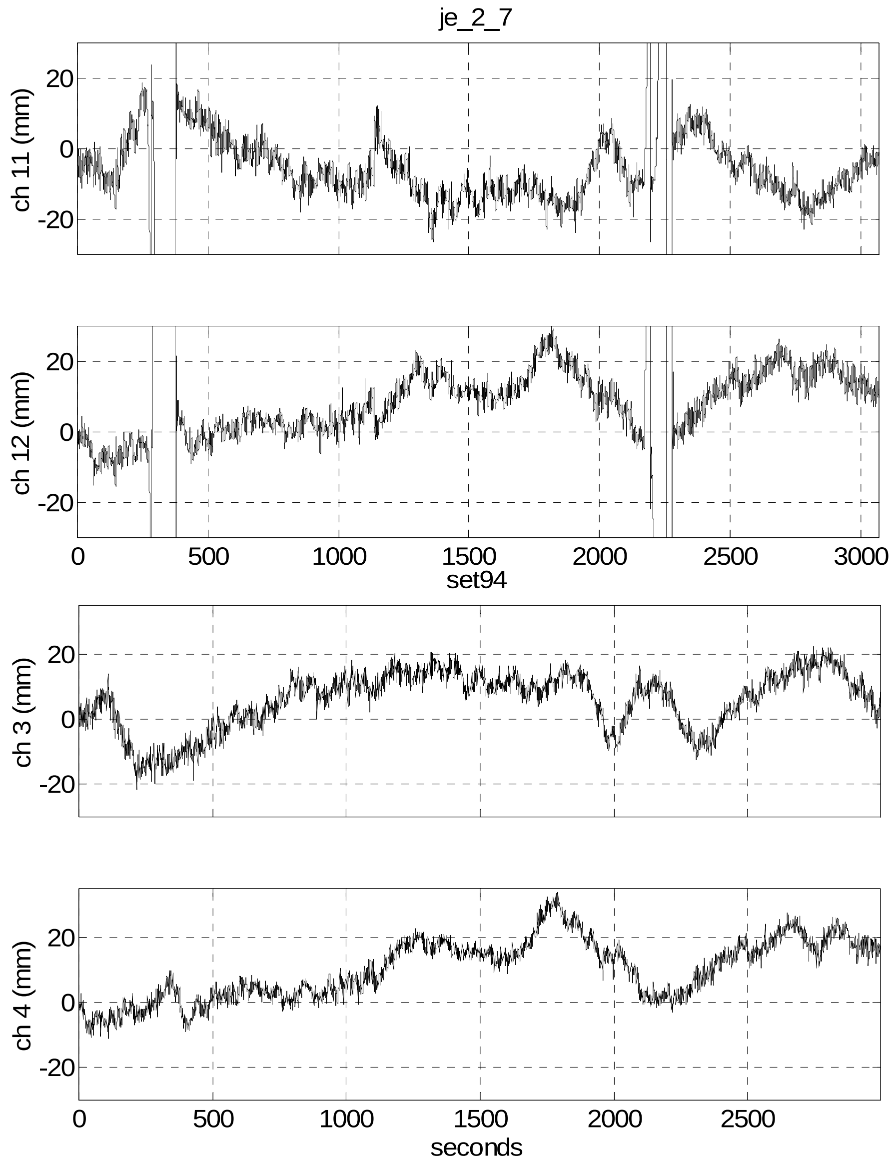

Figure 3 GPS displacements: (top) from RTK solution, (bottom) from post processing

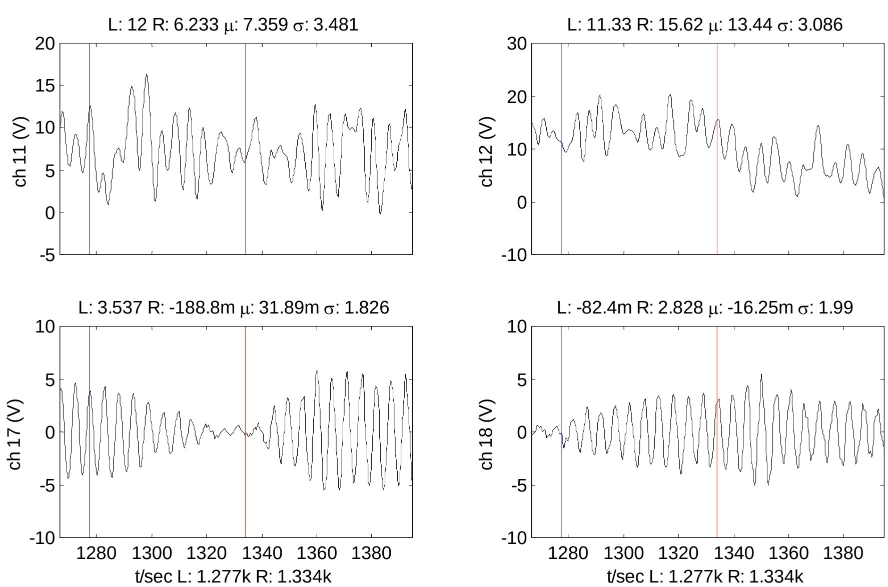

Figure 4 GPS displacements (ch 11,12) and corresponding accelerations (ch 17,18)

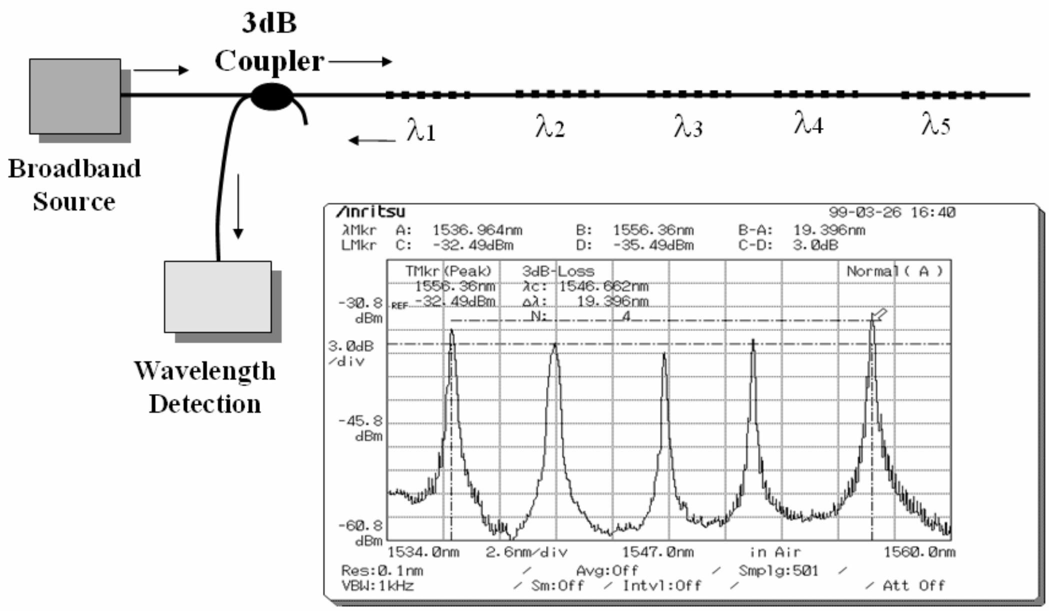

Figure 5 Principle of fibre Bragg grating (FBG)

Figure 6 Concept of FBG deployment

Figure 7 Embedment device

Figure 8 Rebar attachment

Before moving to full-scale applications, extensive laboratory testing of FBG sensors was used to investigate installation and attachment procedures as well as reliability and accuracy of sensors.

Three forms of sensor attachment are employed, as shown in Figure 6, 7 and 8. In each case sensing element is a bare fibre embedded in an optimized sandwich of thin carbon fibre sheets for protection and strain transmission.

Attachment of this sensing element to a redundant slender rebar (Figure 8) embedded in the structure is the preferred procedure as it has been shown by laboratory testing and comparison with electrical gauges (8,9) to be accurate. Provided great care is taken to protect the sheathed fibre and prevent sharp bending anywhere the performance is good. In practical applications where concrete is poured and pokers (vibrators) are used for compaction survival is not 100%.

Because of the practical problems and fragility, a preferred option, particularly for existing structures is surface mounting (Schematic of Figure 6). Limited laboratory tests have shown this method to work well.

Limited tests of the embedment device (Figure 7) have shown that correct design is required for 100% strain transmission and surface preparation for attachment of the carbon fibre sandwich may be tricky. If these issues are resolved, the redundant rebar installation procedure will not be necessary.

The present research is aimed at installations using redundant rebars and surface mounting on a segmental box-girder bridge under construction in Singapore (10). Since the segments are individually cast, multiplexing by redundant rebars is limited practically to a single unit, whereas surface mounting is limited only by accessibility. The hollow segments provide an ideal environment for such mounting.

Given that the installation difficulties can be dealt with a further issue is the logger. Presently a cumbersome light source and manually scanning optical spectrum analyzer is required to read an array of FBG FOS. Development of a field-portable low cost high speed automatically scanning logger is a prerequisite for a practical FOS-based SHM system for use in the real world.

REFERENCES

1. Fugate ML, sohn H, Farrar CR, 2001 “Vibration-based damage detection using statistical process control”. *Smart Materials and Structures* **10**(3) 446-451
2. Salvaneschi P, Cadei M, Lazzari M, 1996 “Applying AI to structural safety monitoring and evaluation” *IEEE Expert-Intelligent Systems and Their Applications* **11**(4) 24-34
3. Rutledge D, Hilman B, “Precise automated monitoring for deformation of dams using the global positioning system (GPS)” *www.3d-gps.com/downloads.htm*
4. Ashkenazi V, Roberts G W, 1997 “Experimental monitoring of the Humber Bridge using GPS” *Civil Engineering, Proceedings, Institution of Civil Engineers* **120** 177-182,
5. Guo J, Ge s, 1997, “Research of displacement and frequency of tall building under wind loading using GPS” *Proceedings GPS ION’97 Missouri 16-19 Sept*, 1385-1388.
6. Dalgleish WA, Rainer JH, 1978 “Measurements of wind induced displacements and accelerations of a 57-storey building in Toronto” *Proceeding, 3rd Colloquium on Industrial Aerodyyamics, Aachen, 14-16 June, Building Aerodynamics* 67-78.
7. Brownjohn JMW, Pan TC, Mita A, Chow KF, 1998 “Dynamic and static response of Republic Plaza” *Journal of the Institution of Engineers Singapore* **38**(2) 35-41.
8. Brownjohn JMW, Moyo P, Wang Y, Tjin SC, Lim TK, 2001 “Experiences with fibre optic Bragg grating sensors in civil engineering” *Proceedings of SPIE* **4317**, 241-247.
9. Wang Y, Tjin SC, Sun X, Lim TK, Moyo P, Brownjohn JMW, 2001 “Simultaneous monitoring of strain and temperature in concrete structures with embedded fibre Bragg gratings” *Proceedings of SPIE* **4317**, 540-545.
10. Brownjohn JMW 2003 “ Sensor and data management technology for structural health monitoring of civil structures” *Proceedings SHMII-1, Japan, November.*