20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 8 Paper 1848

Performance Surveillance of Gentilly-1 Reactor Building GFRP Repair Using Fiber Optic Sensors and Strain Gauges

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Keywords: Reactor, Ring Beam, Concrete, Aging, Monitoring, Strain gauge, Repair, Fibre reinforced polymers, Fibre optic sensors.

1 ABSTRACT

Gentilly-1, a permanently shutdown CANDU™ 250 MWe Nuclear Power Plant and is currently in the Storage With Surveillance (SWS) phase. At approximately 30 years old it underwent repair of the prestressed containment concrete ring beam. In order to meet SWS phase requirements of maintaining the structure, and to assess the long-term performance of the first Glass Fibre Reinforced Polymer (GFRP) repaired CANDU structure, an instrumentation and monitoring program was implemented.

Instrumentation was embedded to monitor the concrete repair material and also the GFRP sheets. The program included the usage of Fibre Optic Sensors (FOS), Vibrating Wire Strain Gauges (VWSG) and thermocouples. Fifteen VWSGs were embedded in the repaired concrete. Twelve Fabry-Perot (FP) FOS were installed. Eight of them were installed on the GFRP sheets with two layers of protection, while the other four sensors were installed in smart patches made of strips of Carbon Fibre Reinforced Polymer (CFRP).

The primary purpose of this paper is to present the 8-year performance of the repaired concrete and the sensor technologies used. The outcome of this study does promote confidence in the new repair technologies adopted in the Gentilly-1 containment ring beam.

2 INTRODUCTION

Gentilly-1 was designed in 1960s and went into operation in 1972. It is currently in a safe shutdown state, which is referred to as Storage With Surveillance (SWS) phase. The objective of this phase is to maintain integrity of the structure to allow for decay of radioactive materials. During visual inspection of the Gentilly-1 containment structure in the 1990s, deterioration in the form of cracking, spalling and delamination of concrete was observed predominantly in the ring beam. An evaluation of the structure to determine the cause and extent of deterioration consisted of the following activities:

- non-destructive tests and laboratory analysis of concrete cores;
- overcore concrete stress measurements; and
- in-situ stress measurement and inspection of post tensioned cables.

In the areas of post-tensioning anchorages, concrete serves mainly a secondary function of protecting anchorage heads from corrosion. Despite the very poor concrete quality of the concrete in the post-tensioned recesses, the anchorage heads were in a reasonably good condition. Deterioration was mainly due to Alkali Aggregate Reaction (AAR).

To minimize future expansion due to AAR and to protect reinforcing and prestressing steel from corrosion, water ingress had to be prevented. Deteriorated concrete of the ring beam was replaced using cement based grout material. Subsequently, GFRP sheets were applied using the pattern shown in Figure 1.

Prequalifying work was carried out to test the repair method prior to application. Figure 2 shows condition of the ring beam before and after repair.

In order to provide assurance of structural integrity and to investigate suitability of instruments for long-term monitoring, instrumentation was embedded within the new concrete repair patches, and also mounted on the exposed surface of the GFRP material. The design and implementation of the instrumentation package was a joint effort by Atomic Energy of Canada Limited (AECL) and Intelligent Sensing for Innovative Structures (ISIS) Canada. This study discusses the usage, temperature and strain data retrieved from the FOSs, VWSGs and thermocouples.

The primary purpose of this paper is to present experience gained in order to promote confidence in new experimental technologies adopted in the Gentilly-1 containment ring beam repair. This paper presents the eight-year performance of the repaired concrete and the sensor technologies used. Four key aspects of the Gentilly-1 repair surveillance program are discussed:

i) strains and temperature variations of the repaired concrete and the GFRP
ii) effectiveness and performance of the GFRP for concrete repair
iii) testing and validation of fiber optic sensor technology, and
iv) effectiveness of the remote monitoring system.

3 INSTRUMENTATION MONITORING PROGRAM

As part of the Aging Management Program (AMP), the instrumentation measurements are collected periodically to evaluate the integrity of the concrete repair, and to satisfy the SWS phase requirements of maintaining the structure. Furthermore, assessment of the instrumentation data is necessary in order to evaluate the long-term performance of the first GFRP repaired CANDU[1] structure.

VWSGs were installed inside the new concrete after the deteriorated concrete was removed and before the new concrete was placed. FOS were mounted on the outside surface of GFRP sheets. The initial data of the embedded VWSG in the concrete reflects the hydration reactions of the repaired material.

3.1 Vibrating Wire Strain Gauges (VWSG)

Fifteen IRAD Model EM-5 VWSGs were embedded in the repaired concrete. Measurements captured strains induced by early age concrete hydration processes and also hardened concrete strains and temperature effects. Data from the VWSGs is collected manually using software prepared by Aiello Engineering. Collected raw data consists of frequency and temperature measurements for each gauge at a given time. To compensate for temperature effect on the gauge body and to estimate concrete strain due to temperature variations, temperature is measured by the thermistors provided within the body of the gauge. Of the fifteen VWSGs, all continue to be functional with the exception of only one. The principle of VWSG as well as the process of data interpretation is described below.

3.1.1 Principle of VWSG

A typical VWSG consists of a hollow tube containing a tensioned steel wire anchored at both ends of the tube with an electromagnetic coil. This coil excites the wire, causing it to vibrate at natural frequency. The frequency of the wire is a function of wire length, diameter, density, and the amount of tension provided in the wire. For a given wire with a specified length, diameter, and density, the frequency (f) of the wire is proportional to the square root of its tension (T) (strain), as shown below:

$$f \propto \sqrt{T}$$

A VWSG enables measurements of local strain of concrete in the vicinity of the gauge. The strain variation is calculated by measuring the change in resonant frequency of the wire, which varies with changes in its tension, against a datum value.

3.1.2 Analysis of VWSG Data

Although some local cracking has occurred during hydration of concrete, this analysis is performed based on the assumption of uncracked concrete. Figure 3 illustrates temperature variations measured by thermistors

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[1] CANDU is a trademark of Atomic Energy of Canada Limited (AECL).

incorporated in the bodies of the gauges. In the designation of the VWSGs, the first letter is the position (North, West, South and East) while the ratio xx/xxx is the depth of the sensor over the depth of the repaired concrete.

All gauges show similar temperatures. When the temperature rises, the wire in the VWSG tries to expand which decreases the tension in the wire lowering its frequency, hence strain. After the temperature effect on the gauge body has been accounted for, the general trend of total concrete strain versus time graph shown in Figure 4 follows the trend of the temperature graph.

After the value of concrete strain due to temperature has been subtracted from total strain, assuming a coefficient of thermal expansion of 10 με/°C, the strains due to other factors (i.e. stress, creep, shrinkage) shown in Figure 5 exhibits more uniformity by comparison to the data plotted in Figure 4. This means that temperature variation is the main factor, which causes strain in concrete (i.e. concrete contracts with decrease in temperature and expands when temperature increases). The results indicate that no significant change in strain readings have occurred in the last five years.

3.2 Fibre Optic Sensors

Twelve Fabry-Perot FOS were installed after repair was completed in 2001. Eight FP-FOS sensors were installed on the GFRP wraps with two layers of protection as shown in Figure 6. The first layer is a fast set epoxy and then a polyurethane protection was applied as a second layer. Four sensors were installed in the 'smart patches' made of a carbon FRP strips (two gauges in each strip). To estimate concrete strain due to temperature variations, temperature has been measured by four thermocouples bonded to the GFRP wrap in close proximity of the FP-FOS in four locations (North, South, East and West). Two thermocouples are located inside the reactor building (North and South direction).

3.2.1 Principle of FOS

The FP-FOS measure strains as a result of a phase change of the reflected light resulting from length variation of the cavity between two mirrors at the end of the optic fibre. The FP-FOSs are read with units linked to a computer with a serial port and controlled by an executable program. The software is used to define the time and rate of data acquisition and also to store the data on the computer hard disk.

3.2.2 Analysis of FOS Data

The FP-FOS measured strains are illustrated in Figure 7, where all initial values are set equal to zero in October 2003. The coefficient of thermal expansion of the FP-FOS is small (–0.5 με/°C). Thus, the trend of measured strain shown in Figure 7 is similar to the temperature variations (Figure 8) even without compensation for temperature effect of the FP-FOS. The temperature measured inside the reactor building (shown with thick lines in Figure 8) does not change as fast as temperature outside, which reflects variations in rapidly changing weather conditions, such as presence of sunlight. The difference between inside and outside temperatures indicate a significant temperature gradient; hence the associated stresses in the ring beam.

The approximate concrete strain induced due to temperature effects is subtracted from total concrete strain, yielding a relatively uniform strain (oscillating between -100 and 100 με). This is shown in Figure 9, revealing that the gauge sensor measurements are strongly controlled by temperature variations causing strain in the concrete. In general, sensors located on North and East side indicate lower strain than those located on the South and West side because of higher temperatures observed on the South and West. It should be noted that the frequency of data collection varies greatly between VWSG and FOS: Figure 5 shows a plot of VWSG data on a monthly and then semi-annual basis, while FOS data in Figure 9 is plotted on a weekly basis.

Sensors located on the horizontal strip (designated H) do not indicate the same strain as those located on the horizontal and vertical GFRP strip (designated H+V) although general trend is similar. It is likely that additional layer of the GFRP provides extra insulation, resulting in different temperature variations, thus strain. The FP sensors in the smart patches are designated SPe and SPw and show similar strain as the other FP sensors.

In Figure 9, the behavior of one sensor, as shown with thick line, is somewhat different from the other sensors. It is located on the North side of the ring beam. This unique behavior is speculated to be attributed to the different coefficients of thermal expansion for different concrete mixes. The coefficients range from 6 to 13 με/°C. The value of 10 με/°C has been used in the calculations. However, repair pockets were shallow on the North side and in some places old concrete that (at the time of the repair) did not show significant deterioration was left in place.

4 CONCLUSIONS

The key objective of this study was to assess the performance over an eight year period of the experimental technologies applied to the Gentilly-1 containment ring beam repair specific to the repair materials used and also the sensor technologies. The primary findings from this study are summarized as follows:

Strains and temperature variations of the repair concrete and the GFRP:

The structural strain in the ring beam concrete was indicated by most gauges is small and indicates no cracking. The trend of strain is similar for the last five years, thus no significant measurable changes are occurring within the repair. The large component of strain measured by both VWSGs and FOSs is attributed to the temperature variations throughout the year.

Effectiveness and performance of the GFRP for concrete repair:

Analysis from the instrumentation data is also supported by a visual inspection conducted in August 2007, which revealed local cracking in two locations, the North-East and the South face. In general, the instrumentation data, which is reported from August 2000 to the present, indicates that the GFRP has been effective in protecting the concrete from further AAR damage, but it is highly recommended to continue with periodic inspection and monitoring.

Testing and validation of instrumentation (VWSG and FOS):

Based on the assessment of instrumentation data most of the gauges are in good working condition. To date, there is only one of the fifteen VWSGs, which is not functioning.

Implementation of an effective remote monitoring system:

Both VWSG and FOS technologies are practical and effective in monitoring, however, some difficulties were encountered with the continuity of remote monitoring since the connection has been lost and re-established a few times over the years.

Acknowledgements. *Endeavours of all participants taking part in the reported work are acknowledged. Encouragement and support from Rick Janzen (AECL) in development and implementation of Aging Management Programs for Gentilly 1 is greatly appreciated. Continuous help with implementation of the monitoring program provided by Jean Vezina and Danielle St Louis (AECL Gentilly 1 site personnel) is particularly acknowledged.*

Abbreviation

AECL	Atomic Energy of Canada Limited
CFRP	Carbon Fibre Reinforced Polymer
FOS	Fibre Optic Sensor
FP	Fabry - Perot
FRP	Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced Polymer
ISIS	Intelligent Sensing for Innovative Structures
SWS	Storage With Surveillance
VWSG	Vibrating Wire Strain Gauge

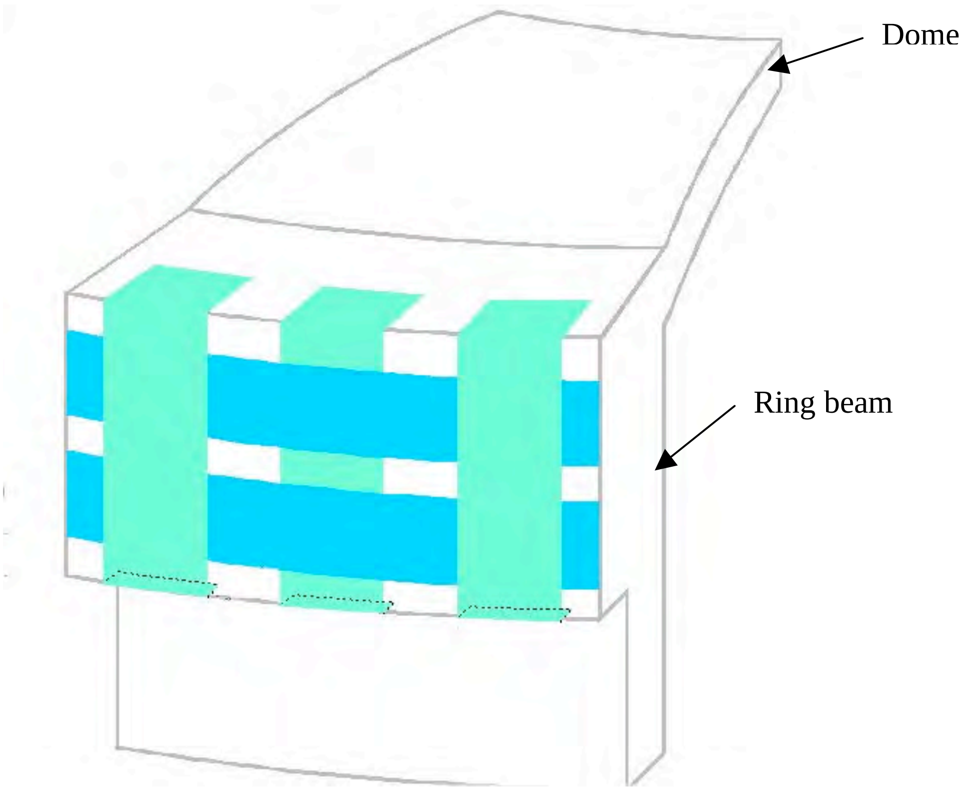

Figure 1 Application Pattern of GFRP sheets to the Ring Beam

a) Before repair, 1999 **b) After repair, 2008**

Figure 2 Ring Beam Before and After Repair

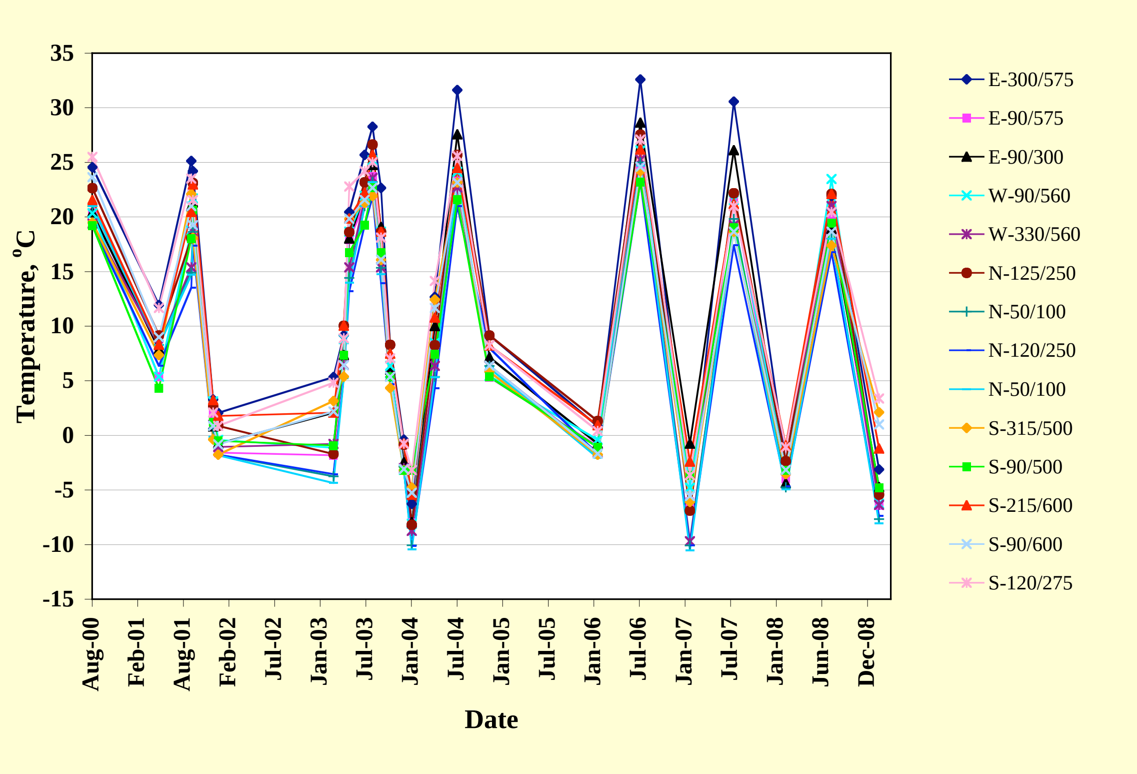

Figure 3 VWSG – Temperature Variations over 8 Years

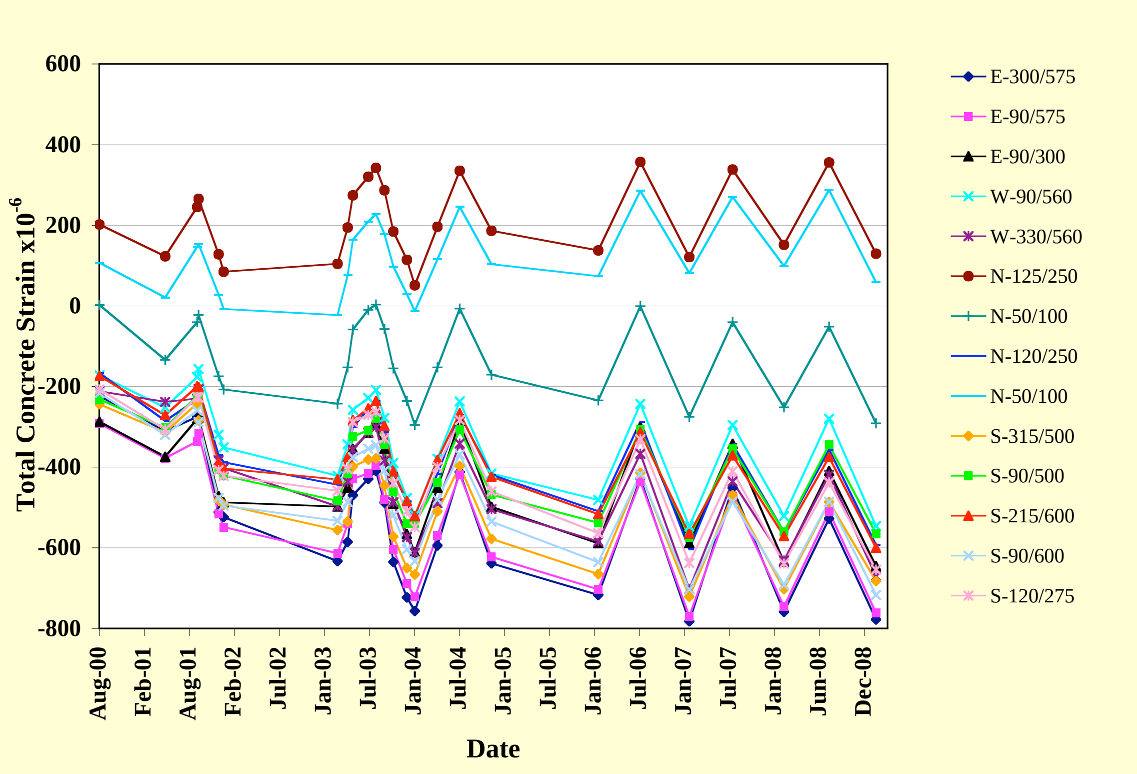

Figure 4 VWSG - Total Concrete Strain before Temperature Compensation

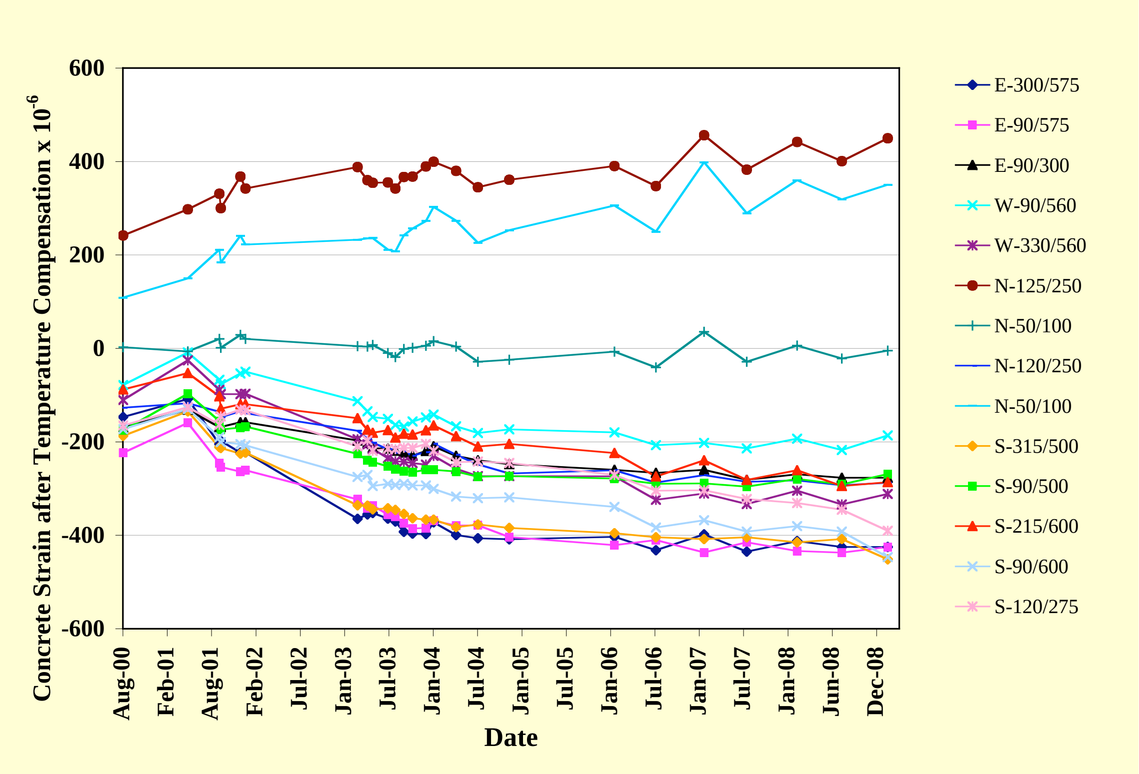

Figure 5 VWSG - Concrete Strain after Temperature Compensation

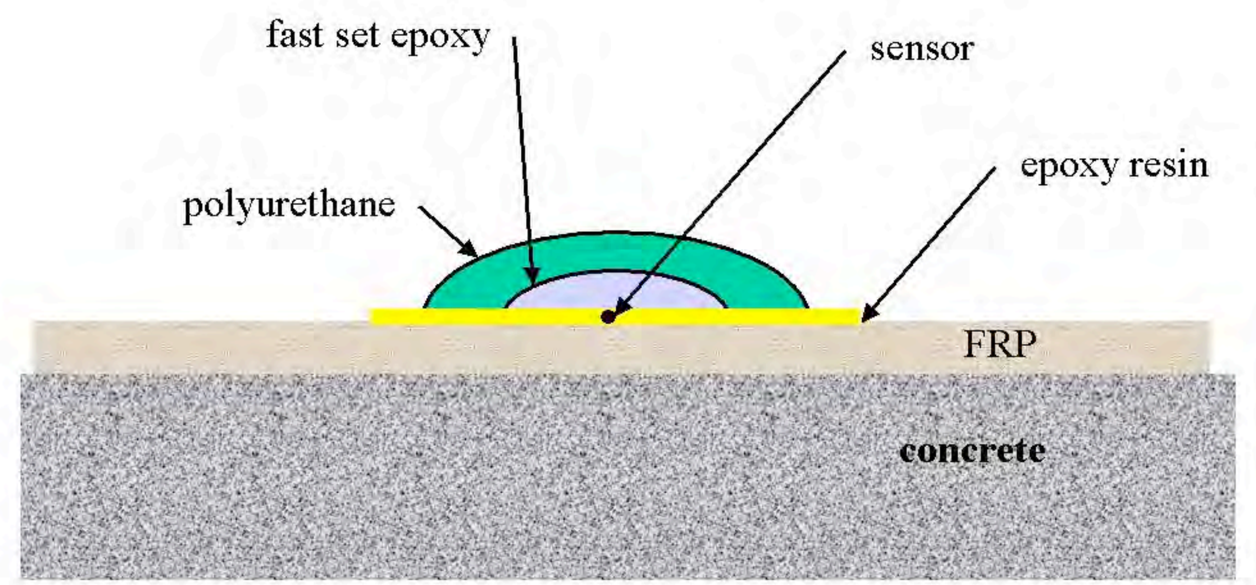

Figure 6 Protection of Fibre Optic Sensors

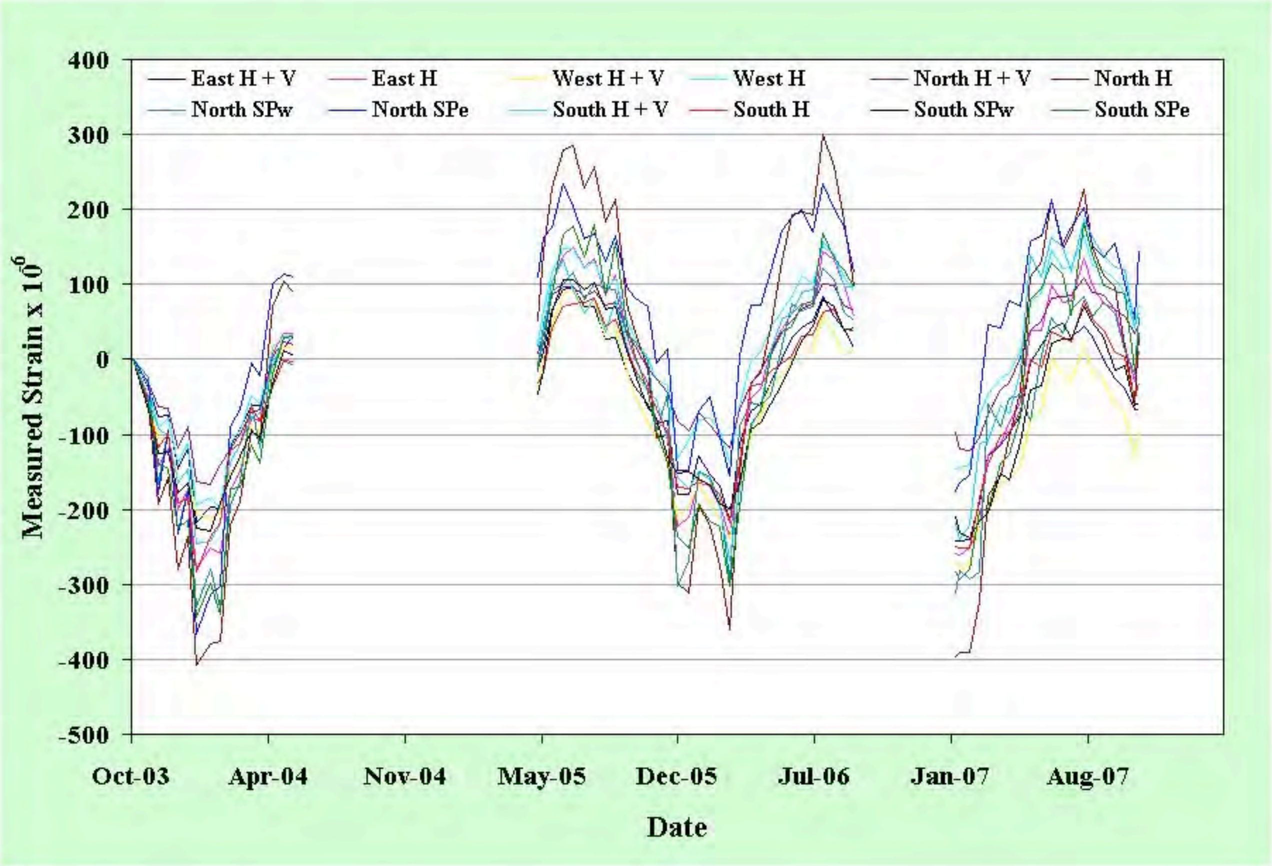

Figure 7 FOS – Measured Strain

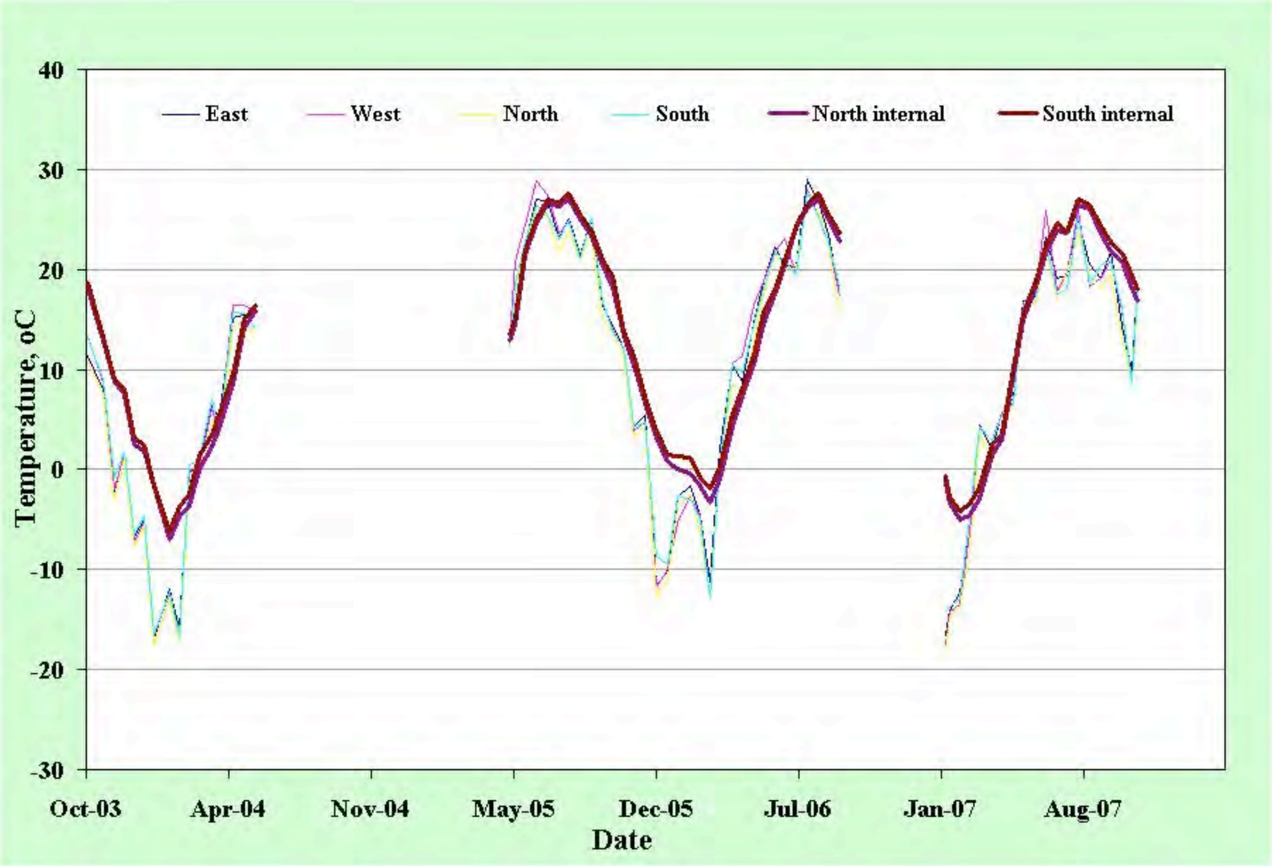

Figure 8 FOS – Measured Temperature using Thermocouples

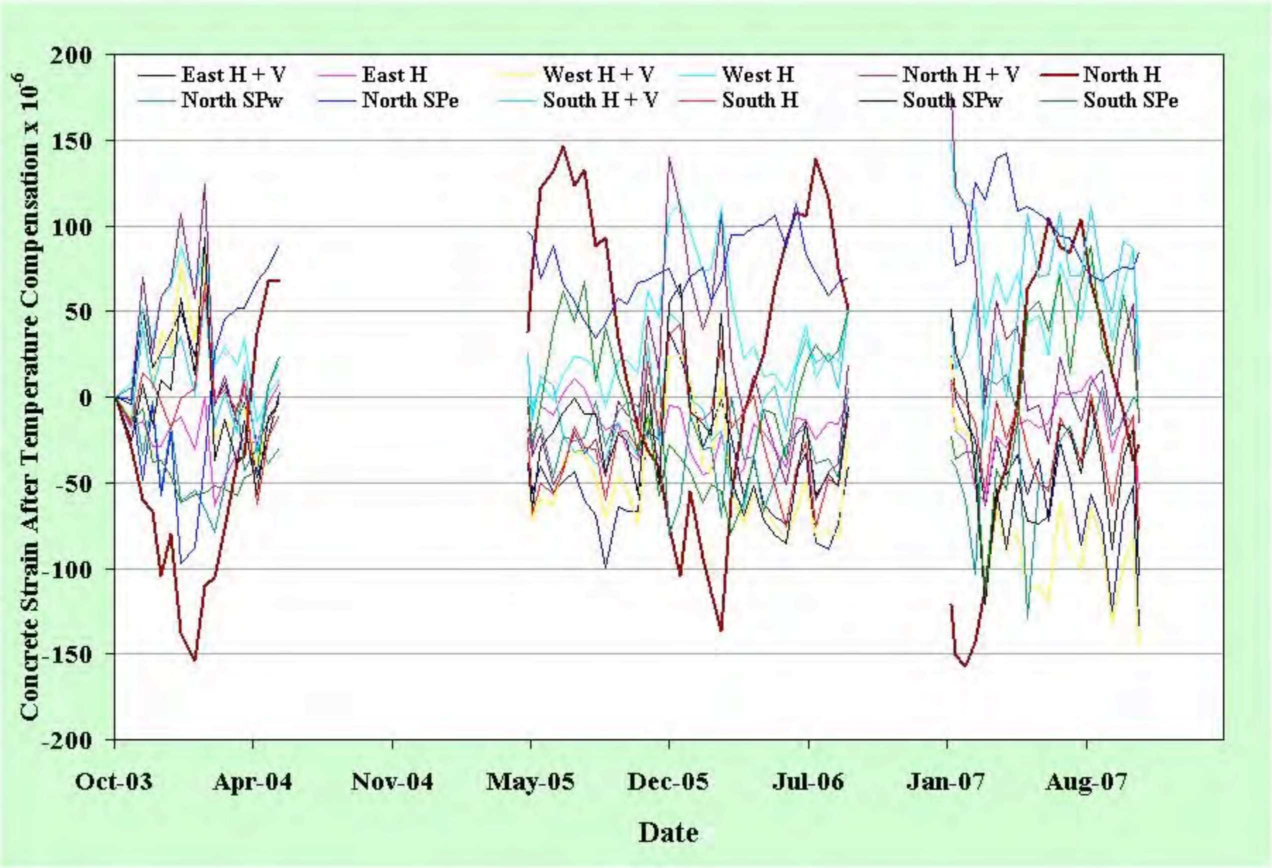

Figure 9 FOS – Concrete Strain after Temperature Compensation