The Use Of Fiber Bragg Grating In Structural Health Monitoring Applications

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Introduction to structural health monitoring (SHM).
Optical Fiber Bragg Grating (FBG) sensors.
Monitoring of existing structural members.
Experimental Creep Investigation.
NS, HS, UHPC.
Summary and Conclusions.
Definition of SHM

Structural health monitoring (SHM) is defined as the process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure. It consists of permanent continuous, periodic or periodically continuous recording of representative parameters, over short or long terms.

Advantages/Benefits of SHM

1. Improved understanding of in-situ structural behaviour
2. Early damage detection
3. Assurances of a structure’s strength and serviceability
4. Reduction in down time
5. Improved maintenance and management strategies for better allocation of resources
6. Enables and encourages use of innovative materials
In the most general terms, damage can be defined as changes introduced into a system that adversely affects its current or future performance.

**Damage levels:**
1. Identification that are detection of the damage,
2. Localization of the damage,
3. Quantification of damage, and
4. Decision-making.

Different types of damage:
- Longitudinal Flexure cracks
- Punching shear cracks
- One-way shear cracks
SYSTEM COMPONENTS

1. Selection of Sensors
2. Sensor Installation and Placement
3. Transfer to Data Acquisition System
4. Data Sampling and Collection
5. Intelligent processing and management of DATA
6. Storage of processed DATA
7. Diagnostics
FIBRE OPTIC SENSORS

Advantages of Fibre Optic Sensors
1. Non-conductive
2. Stable
3. Convenience
4. Flexibility

Types of Fibre Optic Sensors
1. Fibre Bragg Grating (FBG)
2. Long Gauge Sensors
3. Fabry-Perot
4. Brillouin Scattering
FBG Array
Operating Principle

Bragg wavelength

\[ \lambda_o = 2n\Lambda \]

\( \Lambda \): modal index or grating pitch

Transmission and reflection spectra of a fiber Bragg grating FBG
Advantages of Optical Fiber Sensing

• High Sensitivity;
• Electrical Passiveness;
• Wide Dynamic Range;
• Multiplexing Capability.

Physical phenomenon to be measured
Wavelength Shift for Fiber Bragg Grating
Types of Optical Fiber Sensors

1) Temperature sensor
2) Strain Sensor
3) Pressure sensor
4) Chemical sensor
5) Biomedical sensor (oxygen sensor)
6) Fiber-optic gyroscope
7) Electrical and magnetic sensors
8) Displacement and position sensors
Reflection spectrum of a fiber Bragg Grating
Calibration of FBG
DATA ANALYSIS – STATIC LOAD TEST

\[
\text{Strain (microstrain)} = \frac{\lambda_2 - \lambda_1}{1.2} \times 1000
\]

Fig. 1 Time-Strain Relationship of the Concrete and Steel FBG Sensors
Electric Strain Gauge (ESG) Versus Fiber Bragg Grating (FBG)

Fig. 3 Comparison for average steel strain Using ESG and FBG
Fiber Bragg grating wavelength sensing system
Placing of FBG In Concrete Slab
Structural Health Monitoring Using Fiber Optics

Experimental Program
Structural health monitoring of slab-column connections using FBG sensors

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Health Monitoring of Flexural Cracks

**Long-gauge sensors** allow the measurement of deformations over measurement bases that can reach tens of metres with resolutions in the micrometre range.

FBG and ESG sensors glued to tensile rebars

Long FBG sensor embedded in the concrete slab (300 mm)

FBG and ESG sensors to monitor Flexural cracks
Health Monitoring of New Structures

SHM for a reinforced concrete beam

Dimensions and reinforcement of test beam

Test setup and instrumentation
Test Results

Crack pattern for test beam

Long FBG sensor
Cyclic Load Test (ACI 437R-03)

The loading process involved a serviceability limit state cycle test and a failure cycle test. In the serviceability test, a relatively small force was imposed on the slab of approximately $0.5P_u$ and then it was released after finishing the test. When using the cyclic load test method (ACI 437R-03), load is typically applied by hydraulic actuators in a stepped loading pattern that is made up of:

1. At least three (3) load-sets.
2. Each load-set is made up of two (2) or more identical load cycles.

Load Control (Slab)  Displacement Control (Beam)

Loading profile for service loading test
Test Results

Flexural Cracks Detection (Slab)

Concrete tensile strains

The long FBG sensor was able to capture the initiation of the first and second transverse cracks; this is indicated by a sudden increase (shift) in the concrete tensile strain value. The first crack width could be calculated by multiplying the difference in the concrete tensile strain (340 µε) by the gauge length value (300 mm), and it is equal to 0.102 mm.
Steel strains

Based on a calibration test, the wavelength-strain coefficient for the FBG sensor was estimated to be approximately \(0.95 \text{ pm/με}\).

Strain response of cracked slab under cyclic loading

Typical behaviour

Load-steel strain
Long FBG sensor was able to measure the shear strain and to capture the initiation of two Flexural cracks. The first shear crack occurred at a shear strain of 214 micro strain and a load 145 kN. The max. recorded shear strain Of 1186 micro strain at a failure load of 226 kN.
Test Results

One-Way Shear (Beam)

Loading Profile

The test was carried out using a closed-loop (MTS) testing machine with a maximum capacity of 670 kN. The load was applied by means of a hydraulic actuator in displacement control mode.
Test Results

One-Way Shear (Beam)

Steel strains

Electrical strain gauges (ESG) sensors were able to capture the initiation of two Flexural cracks as well as m.
Fiber Bragg Grating sensors (FBG)

(FBG) sensors are the most common types of fiber optic sensors used for structural applications.

FBG system includes:

- Optical fiber with prewritten grating sensors
- A broadband source (light emission device)
- Coupler
- Optical spectrum analyzers (OSA)
Fiber Bragg Grating
ASSMEBLEING
Fiber Bragg Grating Packaging
I-MON 512-USB2
Evaluation software
FBG installation for Beam
**Use of FBG Sensor to Determine the Fracture Energy Properties of UHPFC**

**Definition of SHM**
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**Advantages/Benefits of SHM**
1. Improved understanding of in-situ structural behaviour
2. Early damage detection
3. Assessments of a structure’s serviceability
4. Reduction in down time
5. Improved maintenance and management strategies for better allocation of resources
6. Enables and encourages use of innovative materials and Extended bridge service life

**Advantages of Fibre Optic Sensors**
1. Non-conductive, Stable, Convenience and Flexibility
2. High Sensitivity and Electrical Passiveness
3. Wide Dynamic Range and Multiplexing Capability.

**Types of Fiber Optic Sensors**
1. Fibre Bragg Grating (FBG)
2. Long Gauge Sensors
3. Fabry-Perot
4. Brillouin Scattering

**Analytical Model For Crack Spacing**

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**RESEARCH FINDINGS**

UHPFRC, exhibits superior qualities compared to normal and high strength concrete. The introduction of fiber reinforcement proves to increase, significantly, the ductility of the mix; resulting in a concrete material that behaves rather different than conventional concrete. High strength concrete has a more brittle behavior to that of normal strength concrete, demonstrated by the sharp descends in the stress-strain curve. UHPFRC exhibits a far more ductile behavior when compared to normal and high strength concrete. This ductile behavior and the increased strength ultimately result in concrete with significantly higher fracture energy, consequently a higher characteristic length.
TEST SET UP FOR CONCRETE BEAMS

- Beam (200x300x1000 mm)
- Two point load
- 150mm gage length of FBG
- Normal strength concrete: 35 Mpa
- Specimens were loaded at a displacement rate
  - 0.003 mm/s
  - 0.002 mm/s
  - 0.0002 mm/s
# Mix Properties of three graded concrete

<table>
<thead>
<tr>
<th>Mix Properties</th>
<th>Normal-Strength</th>
<th>High-Strength*</th>
<th>Ultra-High Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>fcm28, MPa</td>
<td>30</td>
<td>70</td>
<td>140</td>
</tr>
<tr>
<td>Water Content</td>
<td>0.40-0.45</td>
<td>0.27-0.3</td>
<td>0.17-0.20</td>
</tr>
<tr>
<td>Cement Content kg/m3 (silica fume)</td>
<td>350</td>
<td>440</td>
<td>SF(5% of cement content) 883 SF(24% of cement content)</td>
</tr>
<tr>
<td>Coarse aggregate kg/m3</td>
<td>1200</td>
<td>1100</td>
<td>-</td>
</tr>
<tr>
<td>Air entrainment agent (ml/m³)</td>
<td>300</td>
<td>325</td>
<td>-</td>
</tr>
<tr>
<td>Water reducing agent (ml/m³)</td>
<td>1400</td>
<td>825</td>
<td>4% of cement content</td>
</tr>
<tr>
<td>Superplasticizers (ml/m³)</td>
<td>1500</td>
<td>7500</td>
<td>Na</td>
</tr>
<tr>
<td>Relative Humidity, %</td>
<td>95</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Type of Cement</td>
<td>ASTM (I)</td>
<td>ASTM (I)</td>
<td>ASTM (I)</td>
</tr>
<tr>
<td>t₀ (time of curing, days)</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>t (time of loading, days)</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Type of curing</td>
<td>Moist</td>
<td>Moist</td>
<td>Moist</td>
</tr>
</tbody>
</table>
SPECIMENS PREPARATION FOR CREEP AND SHRINKAGE MEASUREMENT
Creep testing

Experimental set up for creep test
Testing procedure

- Civil Lab, Ryerson university
Creep testing

cylinders under constant load with
a) FBG embedded          b) ESG on surface
Compressive Strength

![Graph showing the compressive strength comparison between different materials: HSC, HPFC1, HPFC2, and UHP-FRC. The x-axis represents axial strain, and the y-axis represents axial compressive stress. The graph illustrates the stress-strain behavior of these materials under axial loading.]
Modulus of Elasticity test with embedded FBG sensor
Creep and shrinkage strain from FBG sensors

Days of loading

Creep and shrinkage strain (µε)

UHPC
HPC
NC
Shrinkage from FBG sensors

![Graph showing shrinkage strain over days after casting for UHPC, HPC, and NC](image)
Long-Term creep prediction base on experimental result

\[
y = 1.5642 \ln(x) + 1.1233
\]

\[
y = 3.783 \ln(x) + 2.5453
\]

\[
y = 19.172 \ln(x) + 5.2603
\]
SHM Methodology

Structure Health Monitoring

Data Collection
- RD Signature
- Visual Inspection
  - Inspection Reports
- Field Measurements
  - Fiber Optic Sensors
  - Data Acquisition
  - Database Station
- System Integration
  - F.E Model

Lifecycle Management and Assessment
- Lifecycle Algorithm
- Detoriation Model
- Risk and Reliability Assessment
  - Reliability Index

Decision Making
Management Strategy

- **Assessment Results**
  - Assumption of a generic degradation model.
  - Stiffness, crack width, settlement, deflection.
  - Visual inspection, damage detection methodologies.
  - Dynamic monitoring methodologies.

- **Life cycle analysis**, durability, the real degradation process and residual lifetime considerations
  - Estimation of the design life of the existing structure.
  - Assessment criteria in order to take corrective measure;
    - Dynamic bridge monitoring
    - Visual inspections
    - Material tests.
  - Maintenance instructions to preserve the original design life.
SHM Performance Indicator

- Random Decrement
- Mode Shapes
- Half cell Potential
- MultiChannel Random Decrement
- Trend (Time)
- Crack Width (piezo-ceramic sensors)

- Integrity
- Operability
- Corrosion
- Damage Localization
- Life-Cycle-Curve
- Stiffness Mapping

KPIs (Key Performance Indicators) according to BRIMOS®

- Frequency Analysis
- Mode Shapes
- Vibration Intensity
- Dissipation Path
- Trend (Time)
- Trend (Positioning)

- Integrity
- Operability
- Fatigue Assessment
- Damage Localization
- Life-Cycle-Curve
- Stiffness Mapping

Trend (Time)
Life-Cycle-Curve
Stiffness Mapping

CRACK WIDTH
(piezo-ceramic sensors)
Design life using probability density functions
# Bridge Condition Index (BCI)

## BCI Ratings Used by MTO

<table>
<thead>
<tr>
<th>BCI Range</th>
<th>Condition</th>
<th>Recommended Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 – 100</td>
<td>Good</td>
<td>Maintenance work is usually not required within the next five years.</td>
</tr>
<tr>
<td>60 – 70</td>
<td>Fair</td>
<td>Maintenance work is usually scheduled within the next five years. This is the ideal time to schedule major bridge repairs from an economic perspective.</td>
</tr>
<tr>
<td>Less than 60</td>
<td>Poor</td>
<td>Maintenance work is usually scheduled within one year from inspection date.</td>
</tr>
</tbody>
</table>
## Bridge Condition Index (BCI)

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Weight Factor</th>
<th>Deterioration Type</th>
<th>Weight Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>0.25</td>
<td>Delamination</td>
<td>0.42</td>
</tr>
<tr>
<td>Precision</td>
<td>0.30</td>
<td>Corrosion</td>
<td>0.35</td>
</tr>
<tr>
<td>Speed</td>
<td>0.25</td>
<td>Cracking</td>
<td>0.10</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>0.10</td>
<td>Concrete Degradation</td>
<td>0.13</td>
</tr>
<tr>
<td>Cost</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.4.3.1 – Performance Measure and Deterioration Type Vs. Weight Factor (Gucunski et al, 2010)

<table>
<thead>
<tr>
<th>Deterioration Type</th>
<th>Delamination</th>
<th>Corrosion</th>
<th>Cracking</th>
<th>Concrete Deterioration</th>
<th>Overall Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Echo</td>
<td>4.7</td>
<td>1.0</td>
<td>2.5</td>
<td>3.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Ultrasonic Pulse Echo</td>
<td>3.6</td>
<td>1.0</td>
<td>2.6</td>
<td>3.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Half-Cell Potential</td>
<td>1.0</td>
<td>4.9</td>
<td>0.0</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>Impulse Response</td>
<td>3.6</td>
<td>1.0</td>
<td>0.0</td>
<td>2.6</td>
<td>2.2</td>
</tr>
<tr>
<td>Ultrasonic Surface Waves</td>
<td>2.5</td>
<td>1.0</td>
<td>3.0</td>
<td>3.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Ground Penetrating Radar</td>
<td>3.0</td>
<td>1.0</td>
<td>1.0</td>
<td>3.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Chain Drag/ Hammer Sounding</td>
<td>3.7</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>1.0</td>
<td>3.9</td>
<td>0.0</td>
<td>1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Infrared Thermography</td>
<td>3.2</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Galvanostatic Pulse Measurement</td>
<td>1.0</td>
<td>3.0</td>
<td>0.0</td>
<td>1.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Experimental investigation

- **Equipment:**
  - Impact hammer (type Kistler 9728A)
  - 10g accelerometer (type Kistler 8704B500)
  - Data acquisition system (NI cDAQ-9184 (NI) compact DAQ)
Experimental investigation

- The initiation of the flexural crack was achieved where the beam was loaded using concentrated three point load setup.
Theoretical investigation

\[ X_{R_i}(\tau) = \frac{1}{N} \sum_{i=1}^{N} x_i (t_i + \tau) \]

- \( X_{R_i}(\tau) \) is the estimate of the RD interpreted in terms of correlation function
- \( t_i \) is the time past the triggering
- \( N \) is the number of triggering points
- \( \tau \) is time lag

Brincker, R. 2005
Theoretical investigation

- Locating damage using differences of the normalized mode shape

\[ x_i(t) = A_i e^{-2 \varepsilon \omega t} \cos (\omega_i t - \varphi_i), \ i = 1, 2, 3, \ldots, N \]

\[ \lambda_i = \{A_1, A_2, \ldots, A_m\}^T \]

\[ \lambda_i^* = \{A_1^*, A_2^*, \ldots, A_m^*\}^T \]

\[ \Delta \lambda_i = \{A_1^n - A_1^{*n}, A_2^n - A_2^{*n}, \ldots, A_m^n - A_m^{*n}\}^T \]

- \( x_i(t) \) is the random decrement for certain channel
- \( \varepsilon \) is the damping coefficient
- \( \omega_i \) is the natural frequency and \( \varphi_i \) is the phase angle
- \( A_i \) is the displacement amplitude
- \( n \) is superscript indicates the normalized value
- \( \lambda_i \) is the mode shape
- \( \Delta \lambda_i \) is the modal vector difference
Data analysis

- Logarithmic Decrement

\[
f_r = \frac{1}{T}
\]

\[
\delta = \frac{1}{n} \ln \left| \frac{A_i}{A_{i+n}} \right|
\]

\[
\zeta = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}}
\]
Methodology

- Theoretical investigation
  
  - It reduces the response to equivalent free decay of the structure.
    \[ \ddot{\mu}_1 + 2\xi \omega_o \mu_1 + \omega_o^2 \mu_1 = 0 \]
    
    \( \omega_o \) is the natural frequency
    \( \xi \) is the damping ratio
  
  - It is an approach to identify the dynamic parameters using logarithmic decrement from the free decay curve.
Theoretical investigation

\[ [M] \{\ddot{x}(t)\} + [C] \{\dot{x}(t)\} + [K] \{x(t)\} = \{f(t)\} \]
\[ \ddot{x}(t) + 2\omega_0 \xi \dot{x}(t) + \omega_0^2 x(t) = f(t) \]

Let \( y_1 = x \) and \( y_2 = \dot{x} \)

\[ \dot{y}_1 = y_2 \]
\[ \dot{y}_2 = -2\omega_0 \xi y_2 - \omega_0 y_1 + f(t) \]

\[ \frac{\partial P}{\partial t} = \frac{\partial}{\partial y_1} (y_2 P) + \frac{\partial}{\partial y_2} (-2\omega_0 \xi y_2 - \omega_0^2 y_1)P + \frac{\psi_o}{2} \frac{\partial^2}{\partial y_2^2} \]

\[ P(Y, t + dt|Y_0) - P(Y, t|Y_0) \]

\[ = \frac{\partial}{\partial y_1} (y_2 P) + \frac{\partial}{\partial y_2} (-2\omega_0 \xi y_2 - \omega_0^2 y_1)P + \frac{\psi_o}{2} \frac{\partial^2}{\partial y_2^2} \]
Theoretical investigation

\[ \int_{-\infty}^{\infty} y_2 \left( \frac{\partial}{\partial y_2} (2\omega_0 \xi y_2 - \omega_0^2 y_1)P \right) dy_1 dy_2 = -(2\omega_0 \xi y_2 + \omega_0^2 y_1) \]

\[ \dot{\mu}_1 = \dot{\mu}_2 = -(2\omega_0 \xi y_2 + \omega_0^2 y_1) \]

\[ \int_{-\infty}^{\infty} y_1 (Y, t + dt|Y_0) dy_1 dy_2 = \mu_1(t + dt) \]

\[ \int_{-\infty}^{\infty} y_2 \left( \frac{\partial}{\partial y_2} (2\omega_0 \xi y_2 - \omega_0^2 y_1)P \right) dy_1 dy_2 = -(2\omega_0 \xi y_2 + \omega_0^2 y_1) \]

\[ \ddot{\mu}_1 + 2\xi \omega_0 \dot{\mu} + \omega_0^2 \mu_1 = 0 \]
Results

- Figures show the RD signatures at different damage.
Results

• Concrete Beam

<table>
<thead>
<tr>
<th>Load</th>
<th>Natural frequency (Hz)</th>
<th>Damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact</td>
<td>63.83</td>
<td>0.70</td>
</tr>
<tr>
<td>Cracking</td>
<td>62.50</td>
<td>1.18</td>
</tr>
<tr>
<td>Yeild</td>
<td>61.22</td>
<td>2.28</td>
</tr>
<tr>
<td>Ultimate</td>
<td>60.00</td>
<td>5.33</td>
</tr>
</tbody>
</table>
**Results**

- Normalizing the difference between the mode shapes of intact and damaged cases

**Mode (2)**

![Graph showing normalized deflection against node number for intact and damaged cases.](image)
Conclusion

- RD technique showed a similarity in detecting the damage in concrete, as the technique showed significant results for detecting the damage applied on steel structures.

- RD technique can be used for structural health monitoring of important mega structures, especially the structures subjected to ambient vibration loads.

- Damage location was determined by the normalized difference between the intact and damaged mode shape, which was shown that it is an effective to locate the damage.
Thanks
Questions & Comments
Creep strain from FBG sensors

![Graph showing creep strain over days with different materials: UHPC, HPC, NC.](graph)
Result for UHPC cylinders

<table>
<thead>
<tr>
<th>Compressive strength (MPa)</th>
<th>Modulus of elasticity</th>
<th>Strain at Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>49.9</td>
<td>0.00315</td>
</tr>
</tbody>
</table>