ISIS Educational Module 5:

An Introduction to Structural Health Monitoring

Produced by ISIS Canada

Intro to SHM

Module Objectives

- To provide students with a general awareness of Structural Health Monitoring (SHM) and its potential applications
- To introduce students to the general apparatus and testing used for monitoring typical engineering structures

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Intro to SHM

Overview

- Introduction and Overview
- What is SHM?
- Methodology
- Sensor Technology
- SHM Testing Categories
- SHM System Design
- Case Studies
- Civionics Specs
- The Future of SHM
- Summary & Conclusion
- The Golden Boy

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Intro to SHM

Section 1: Intro and Overview

Section: 1

- The world's population depends on an extensive infrastructure system
  - Roads, sewers, highways, buildings
- The infrastructure system has suffered in past years
  - Neglect, deterioration, lack of funding

Global Infrastructure Crisis

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Intro to SHM

Introduction and Overview

Section: 1

- Factors leading to the extensive degradation…

Factor #1 → Unsatisfactory inspection and monitoring of existing infrastructure

Consequences → Problems become apparent only when structures are in dire need of repair

Result → **Repair costs become comparable to replacement costs**

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Intro to SHM

Introduction and Overview

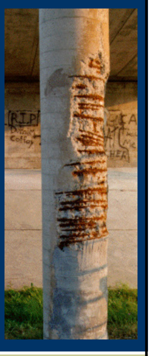
Section: 1

Factors Leading to Degradation

Factor #2 → Corrosion of conventional steel reinforcement within concrete

Consequences → Expansion of steel leads to cracking and spalling, further deterioration

Result → **Reductions in strength and serviceability resulting in need for repair and/or replacement**



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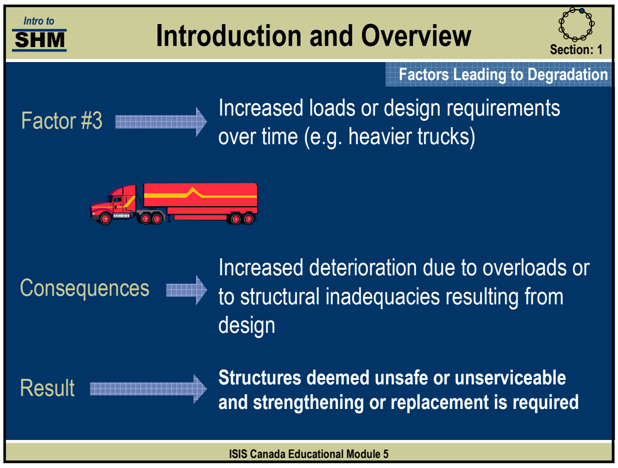
Intro to SHM
Introduction and Overview
Section: 1
Factors Leading to Degradation
Factor #3
Increased loads or design requirements over time (e.g. heavier trucks)
Consequences
Increased deterioration due to overloads or to structural inadequacies resulting from design
Result
Structures deemed unsafe or unserviceable and strengthening or replacement is required
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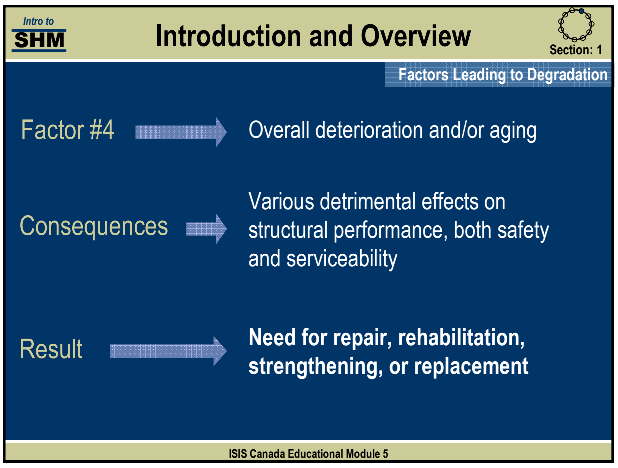
Intro to SHM
Introduction and Overview
Section: 1
Factors Leading to Degradation
Factor #4
Overall deterioration and/or aging
Consequences
Various detrimental effects on structural performance, both safety and serviceability
Result
Need for repair, rehabilitation, strengthening, or replacement
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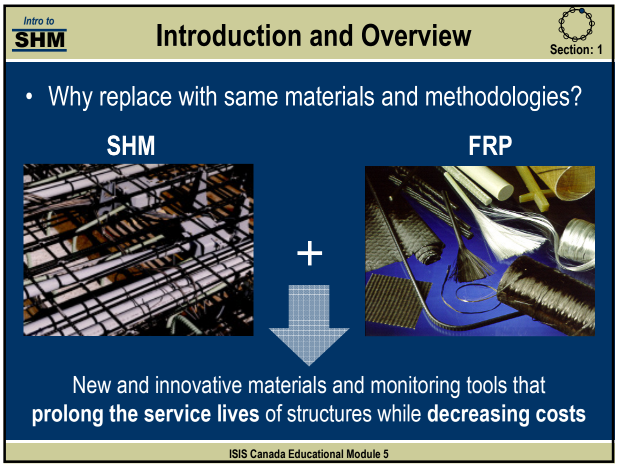
Intro to SHM
Introduction and Overview
Section: 1
Why replace with same materials and methodologies?
SHM
FRP
+
New and innovative materials and monitoring tools that prolong the service lives of structures while decreasing costs
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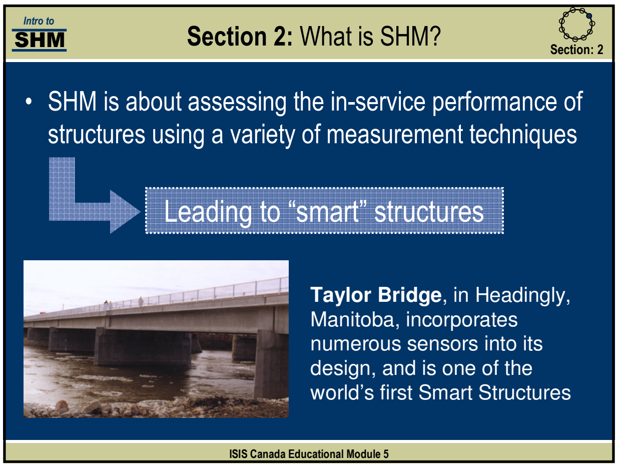
Intro to SHM
Section 2: What is SHM?
Section: 2
SHM is about assessing the in-service performance of structures using a variety of measurement techniques
Leading to “smart” structures
Taylor Bridge, in Headingly, Manitoba, incorporates numerous sensors into its design, and is one of the world’s first Smart Structures
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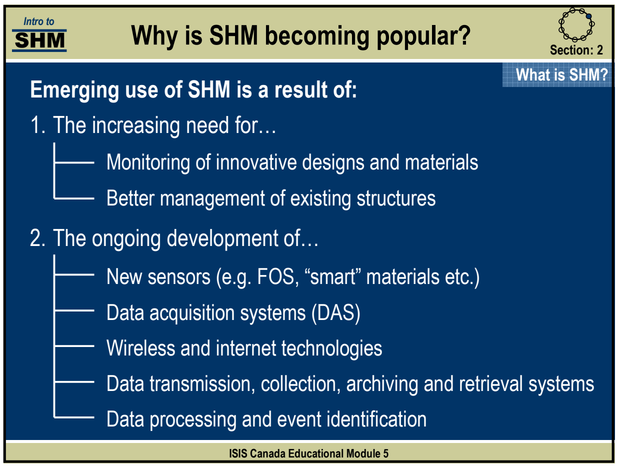
Intro to SHM
Why is SHM becoming popular?
Section: 2
What is SHM?
Emerging use of SHM is a result of:
1. The increasing need for…
Monitoring of innovative designs and materials
Better management of existing structures
2. The ongoing development of…
New sensors (e.g. FOS, “smart” materials etc.)
Data acquisition systems (DAS)
Wireless and internet technologies
Data transmission, collection, archiving and retrieval systems
Data processing and event identification
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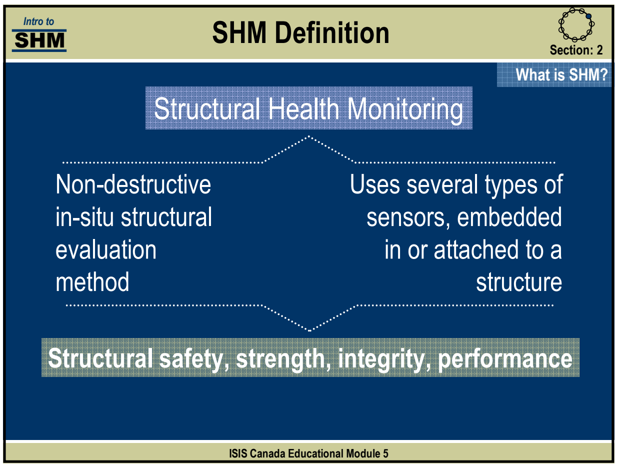
Intro to SHM
SHM Definition
Section: 2
What is SHM?
Structural Health Monitoring
Non-destructive in-situ structural evaluation method
Uses several types of sensors, embedded in or attached to a structure
Structural safety, strength, integrity, performance
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The SHM / Body Analogy

Intro to SHM — Section: 2 — What is SHM?

Medical Doctor

- Monitor patient's health
- Uses medical equipment to check overall health
- Prescribes corrective medicine if required

SHM Engineer

- Monitor condition of structures
- Uses sensors to check overall structural health
- If excessive stress or deformation, correct situation

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SHM System Components

Intro to SHM — Section: 2 — What is SHM?

- Acquisition of Data
- Communication of Data
- Intelligent Processing
- Storage of Processed Data → Retrieval of Data
- Diagnostics

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SHM Categories

Intro to SHM — Section: 2 — What is SHM?

Static Field Testing:
Behaviour tests
Diagnostic tests
Proof tests

Dynamic Field Testing:
Stress history tests
Ambient vibration tests
DLA tests
Pullback tests

Periodic Monitoring:
Includes field testing
Tests to determine changes in structure

Continuous Monitoring:
Active monitoring
Passive monitoring

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Classification of SHM Systems

Intro to SHM — Section: 2 — What is SHM?

Level IV
Detect presence, location, severity and consequences of damage

Level III
Detect presence, location and severity of damage

Level II
Detect presence and location of damage

Level I
Detect presence of damage

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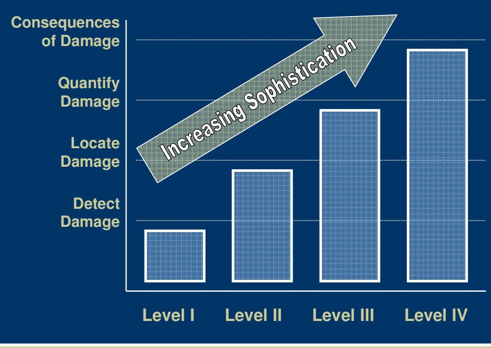
Classification of SHM Systems

Intro to SHM — Section: 2 — What is SHM?



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Advantages of SHM

Intro to SHM — Section: 2 — What is SHM?

Advantages of SHM include...

- Increased understanding of in-situ structural behaviour
- Early damage detection
- Assurances of structural strength and serviceability
- Decreased down time for inspection and repair
- Development of rational maintenance / management strategies
- Increased effectiveness in allocation of scarce resources
- Enables and encourages use of new and innovative materials

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Section 3: Methodology

Intro to SHM — Section: 3

- **Ideal SHM system**:
  - ❶ Information on demand about a structure's health
  - ❷ Warnings regarding any damage detected
- Development of a SHM system involves utilizing information from many different engineering disciplines including…

Computers, Materials, Communication, Structures, Intelligent Processing, Data Collection, Damage Detection, Sensors

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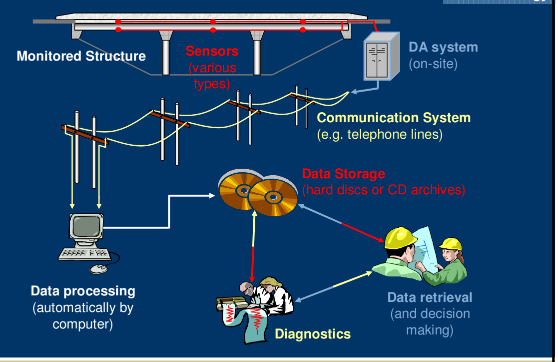
System Components Schematic

Intro to SHM — Section: 3 — Methodology



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1 – Acquisition of Data

Intro to SHM — Section: 3 — Methodology

The collection of raw data such as strains, deformations, accelerations, temperatures, moisture levels, acoustic emissions, and loads

(a) Selection of Sensors

- Appropriate and robust sensors
- Long-term versus short-term monitoring
- What aspects of the structure will be monitored?
- Sensors must serve **intended function** for **required duration**

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1 – Acquisition of Data

Intro to SHM — Section: 3 — Methodology

(b) Sensor Installation and Placement

- Must be able to install sensors without altering the behaviour of the structure
- Features such as sensor wiring, conduit, junction boxes and other accessories must be accounted for in the initial structural design
- **Civionics Specifications** – Available from ISIS Canada

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1 – Acquisition of Data

Intro to SHM — Section: 3 — Methodology

(c) Transfer to Data Acquisition System (DAS)

- Method ❶ - Lead wire
  - Direct physical link between sensor and DAS
  - least expensive and most common
  - Not practical for some large structures
  - Long lead wires increase signal "noise"
- Method ❷ - Wireless transmission
  - More expensive
  - Signals are transferred more slowly and are less secure
  - Use is expected to increase in the future

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1 – Acquisition of Data

Intro to SHM — Section: 3 — Methodology

(d) Data Sampling and Collection

General Rule: The amount of data should not be so scanty as to jeopardize its usefulness, nor should it be so voluminous as to overwhelm interpretation

- **Issues:**
  - Number of sensors and data sampling rates
  - Data sorting for onsite storage
  - In some cases, **large volumes of data**
- **Result:**
  - Efficient strategies needed for data sampling and storing

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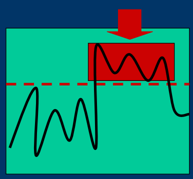
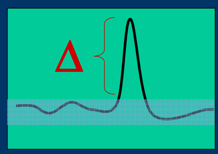
Intro to SHM — 1 – Acquisition of Data — Section: 3 — Methodology

Example Data Acquisition Algorithms



Record only values greater than a threshold value

(and times that readings occur)



Record only significant changes in readings

(and times that changes occur)

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Intro to SHM — 1 – Acquisition of Data — Section: 3 — Methodology

What is monitored, how and why?

Load
- Magnitude and configuration of forces applied to a structure
  - Are they as expected?
  - How are they distributed?
- Measured using load cells or inferred using strain data

Deformation
- Excessive or unexpected deformation, may result in a need for rehabilitation or upgrade
  - Are they as expected?
- Measured using various transducers

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Intro to SHM — 1 – Acquisition of Data — Section: 3 — What is monitored, how, and why?

Strain
- Strain: Intensity of deformation
- Magnitude and variation of strains can be examined to evaluate safety and integrity
- Measured using strain gauges
  - FOS, electrical, vibrating wire, etc.

Temperature
- Changes in temp. cause deformation
  - Thermal Expansion
  - Repeated cycles can cause damage
- Temperature affects strain readings
  - Temp must be "removed" from strain data
- Measured using TCs, TICs, thermistors

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Intro to SHM — 1 – Acquisition of Data — Section: 3 — What is monitored, how, and why?

Acceleration
- Loads cause accelerations of structural components and vice versa
  - How is the structure resisting accelerations and the resulting loads?
- Widespread use in highly seismic regions
- Measured using accelerometers

Wind Speed and Pressure
- Wind loads can govern the design of long-span bridges and tall buildings
  - Record speed and pressure at various locations
- Measured using anemometers

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Intro to SHM — 1 – Acquisition of Data — Section: 3 — What is monitored, how, and why?

Acoustic Emissions
- When certain structural elements break, they emit noise
  - AE listens for the noises, and pinpoints locations using triangulation
- Used in post-tensioned concrete and cable-stayed structures
- Measured using microphones

Video Monitoring
- Time-stamped videos and pictures can be used to witness extreme loads or events
  - Data can be correlated with images
  - Permits fining of overloaded trucks
- Emerging internet camera technology is used

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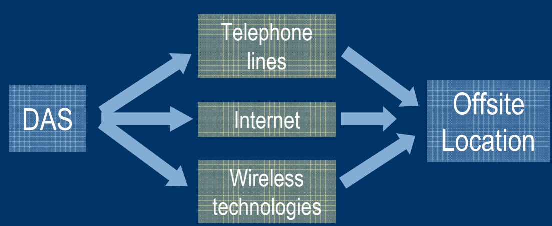
Intro to SHM — 2 – Communication of Data — Section: 3 — Methodology

- Refers to data transfer from the DAS to an offsite location
- Allows for remote monitoring, elimination of site visits



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3 – Intelligent Processing of Data

Intro to SHM — Section: 3 — Methodology

- Required before data can be stored for later interpretation and analysis
- The goal is to remove mundane data, noise, thermal, or other unwanted effects and to make data interpretation:
  - **Easier**
  - **Faster**
  - **More accurate**

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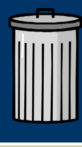
4 – Storage of Processed Data

Intro to SHM — Section: 3 — Methodology

- Data may be stored for very long periods of time
  - Retrieved data must be understandable
  - Data must not be corrupted
  - Sufficient memory must be available

- Data files must be well documented for future interpretation
- It is common to disregard raw data and store only processed or analyzed data
  - This does not allow for re-interpretation



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5 – Diagnostics

Intro to SHM — Section: 3 — Methodology

- **Extremely important** component
  - Converts abstract data signals into useful information about structural response and condition
- No "standard" rules exist for diagnostics
- Methodology used depends on…
  - Type of structure
  - Type and location of sensors used
  - Motivation for monitoring
  - Structural responses under consideration

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6 – Data Retrieval

Intro to SHM — Section: 3 — Methodology

When storing data for retrieval, consider…

- ❶ Significance of data
- ❷ Confidence in analysis

Remember:

The goal of SHM is to provide detailed physical data which can be used to enable rational, **knowledge-based engineering decisions**.

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Section 4: Sensor Technology

Intro to SHM — Section: 4

- Many sensor types are currently available
  - Choice for SHM depends on various factors
- **Fibre optic sensors** (FOSs)
  - Newer class of sensors
  - Emerging for infrastructure applications
  - Recent and ongoing developments (ISIS)

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Fibre Optic Sensors

Intro to SHM — Section: 4 — Sensor Technology

Sensor development is driving advances in SHM

Beddington Trail Bridge, Calgary, Alberta
- FOS sensors installed during construction in 1993
- Sensors were still performing well in 1999

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Intro to SHM — Section: 4

FOS Advantages

Sensor Technology

Innovative Sensing Capabilities

Stability
Increased long-term stability and decreased noise

Non-conductive
Immune to electromagnetic and radio frequency interference

Flexibility
Multiplexing and Distributed sensing

Convenience
Light, small diameters, non-corrosive, embeddable, easily bondable

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Intro to SHM — Section: 4

How do FOSs work?

Sensor Technology

Sensing using optical fibres and techniques

- Light beam (laser) is sent down an optical fibre toward a gauged length
- Light waves measure changes in state (i.e. elongation or contraction)
- Change in reflected light waves is correlated to strain reading
- Demodulation unit calculates strain from light signals and gives voltage
- DAS converts voltage to strain data for processing

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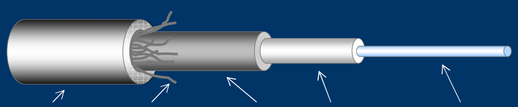
Intro to SHM — Section: 4

Sensor Technology

Fibre Optic Sensors

Typical Optical Fibre



Assorted fibre coatings are required to protect the fibre from…

Abrasion
Protection during handling and installation

Concrete
Alkaline environment is harmful to glass fibres

Moisture
Weakens the fibres and controls growth of microcracks

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Intro to SHM — Section: 4

Types of FOS

Fibre Optic Sensors

Bondable

Hand Installation

Care required during installation

Protection against humidity and environment required

Weldable

Embeddable

Premanufactured, easy to install

Sensor encapsulated in stainless steel container

Do not require protection against humidity or the chemical environment of concrete (embeddable sensors)

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Intro to SHM — Section: 4

Classes of FOS

Fibre Optic Sensors

Various classes of FOS gauges are available:

1. **Fibre Bragg Gratings (FBGs)**
2. **Long Gauge Sensors**
3. **Fabry-Perot Gauges**
4. **Brillouin Scattering Sensors**

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Intro to SHM — Section: 4

1 – Fibre Bragg Gratings

Fibre Optic Sensors

- **Optical "grating" is placed on the fibre**
  - Shift in grating spacing causes a shift in the wavelength of reflected light when a light pulse is sent down the fibre
  - Optical techniques are used to determine strain from wavelength shift
- **Characteristics:**
  - Measure only local "point" strains
  - Use for static and dynamic monitoring
  - Can be serially multiplexed
  - Embeddable, bondable and weldable
  - Requires thermal compensation

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2 – Long Gauge Sensors

Intro to SHM — Section: 4 — Fibre Optic Sensors

- Two tiny "mirrors" are placed in the fibre
  - Distance between mirrors is the gauge length
  - Sensor measures path displacement between the mirrors
  - Uses an optical technique called low coherence interferometry
- Characteristics:
  - Highly versatile
  - Gauge lengths from 5 cm up to 100 m
  - Static testing only at present
  - Thermal compensation is required

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3 – Fabry-Perot Gauges

Intro to SHM — Section: 4 — Fibre Optic Sensors

- Optical fibre is cut and a "gap" is inserted
  - An optical technique is used to determine the change in gap width
  - Strain can be obtained if the original gap width is known
- Characteristics:
  - Measure only local "point" strains
  - Use for static and dynamic monitoring
  - Cannot be serially multiplexed
  - Embeddable, bondable and weldable

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4 – Brillouin Scattering Sensors

Intro to SHM — Section: 4 — Fibre Optic Sensors

- These gauges in the developmental stage
  - Sophisticated optical techniques are used
  - Capable of measuring **static strain profiles** using a single optical fibre
- Characteristics:
  - Gauge length can vary from 15 cm to more than 1 km
  - Use for static monitoring only
  - Thermal and mechanical strains can be separated
  - Extensive signal processing and analysis is required
  - Currently very expensive

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Distributed Sensing

Intro to SHM — Section: 4 — Specialized Sensing

Distributed sensing is a technique that is possible with FBG and Brillouin scattering sensors:

- Allows continuous strain vs. position measurement over length of grating
- Useful to measure:
  - Width of cracks
  - Strain transfer in bonded joints
  - Stress concentrations
- A gauge bonded in the presence of strain distribution is a series of subgratings
- Spatial distribution of strains is obtained from individual measurements

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Multiplexed Sensing

Intro to SHM — Section: 4 — Specialized Sensing

In this technique a **large network** of sensors is interrogated by a **single sensor reading device** (demodulation unit)

1. **Serial Multiplexed:**
   - Several sensors distributed along a single optical fibre
2. **Parallel Multiplexed:**
   - Sensors on separate fibres

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Other Types of Sensors

Intro to SHM — Section: 4

LOAD	Load cells
DISPLACEMENT	Linear Variable Differential Transformer
	Linear Potentiometer
ACCELERATION	Accelerometers
TEMPERATURE	Thermocouples
	Integrated Temperature Circuits
STRAIN	Vibrating wire strain gauges
	Electrical resistance gauges

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Section 5: SHM Testing Categories

Intro to SHM — Section: 5

Overall SHM categories can be distinguished based on:

1. Timescale of the monitoring

Continuous ⟺ Periodic

2. Manner in which response is invoked in structure

Static load ⟺ Dynamic load ⟺ Ambient vibrations

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Static Field Testing

Intro to SHM — Section: 5 — Testing Categories

- This is the most common type of Field testing
- Loads are **slowly placed and sustained** on the structure
  - → **No dynamic effects** (loads move on real structures)
- There are essentially **three types of static field tests**:

1. Behaviour Tests
2. Diagnostic Tests
3. Proof Tests

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Static Field Testing

Intro to SHM — Section: 5 — Testing Categories

1. Behaviour Tests

Goal ⇒ Study mechanics of structure and/or verify methods of analysis

∴ Testing loads ≤ Maximum service loads

Results ⇒ How loads are distributed in structure
No information on ability of structure to sustain loads

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Static Field Testing

Intro to SHM — Section: 5 — Testing Categories

2. Diagnostic Tests

Goal ⇒ Determine interaction between various components in structure (how they help or hinder each other)

Essentially same method as Behaviour Tests

Results ⇒ Beneficial Interaction → Use to advantage
Detrimental Interaction → Repair

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Static Field Testing

Intro to SHM — Section: 5 — Testing Categories

3. Proof Tests

Goal ⇒ Induce **"proof loads"** to test the load carrying **capacity** of the structure

Increase load until linear elastic limit reached

Results ⇒ Proof load is maximum load the structure has withstood without suffering damage

CAUTION: Extreme care should be taken during proof testing
Monitoring should be continuous during testing
Supporting analysis is required

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Dynamic Field Testing

Intro to SHM — Section: 5 — Testing Categories

- For testing behaviour of structures subject to **moving loads**
- In a typical dynamic field test (for a bridge):
  - → A test vehicle travels across a "bump" on the bridge
  - → Dynamic response of the bridge is excited, measured and analyzed
- Essentially four types of dynamic test:

1. Stress History Tests
2. Dynamic Amplification Tests
3. Ambient Tests
4. Pull-back Tests

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Dynamic Field Testing

Intro to SHM — Section: 5 — Testing Categories

1. Stress History Tests

- Used for bridges that are **susceptible to fatigue** loading
- Determines the **range of stresses** that the bridge undergoes
- Requires a modern DAS with a **rapid sampling rate**
- Strain profiles are recorded and analyzed to **determine the fatigue life** of the structure (the time until failure by fatigue)

NOTE: Fatigue failure is a potentially disastrous type of failure which is caused by repeated cycles of loading and unloading

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Dynamic Field Testing

Intro to SHM — Section: 5 — Testing Categories

2. DLA Tests

- Structural design generally assumes loads are static – this is not always the case, particularly for bridges
- For dynamic loads, static loads are multiplied by a *dynamic amplification factor (DAF)*
- Various different dynamic test methods are used to calculate the DAF for bridges (no standard method exists)

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Dynamic Field Testing

Intro to SHM — Section: 5 — Testing Categories

3. Ambient Vibration Tests

- Vibration characteristics of structure are examined **based on vibrations** due to wind, human activity, and traffic
- **Changes in vibration characteristics** of bridge may indicate damage (vibration based damage identification)
- Strategically-placed **accelerometers** measure vibration response of bridge, and resulting data is analyzed using complex algorithms

Problems:
Global properties (vibration frequencies) have low sensitivity to local damage
Vibration characteristics affected by environment, temp. and boundaries

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Dynamic Field Testing

Intro to SHM — Section: 5 — Testing Categories

4. Pull-back Tests

- Usually conducted on bridges to determine response to lateral dynamic excitation
- Use cables to pull structure laterally and suddenly release
- Accelerometers used to monitor structure's response
- Data analysis is similar to that required for an ambient vibration test

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Periodic Monitoring

Intro to SHM — Section: 5 — Testing Categories

- Periodic SHM conducted to **investigate detrimental changes** that might occur in a structure
- Behaviour of structure is **monitored at specified time intervals** (days, weeks, months, years…)
- Examples include periodic monitoring:
  - through ambient vibration;
  - through testing under moving traffic;
  - through static field testing;
  - of crack growth; and
  - of repairs

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Continuous Monitoring

Intro to SHM — Section: 5 — Testing Categories

- Monitoring is **ongoing** for an extended period of time
- Only recently used in field applications because of high **costs** and relative **complexity**
- **Real-time** monitoring and data collection
  1. Stored on site for analysis later
  2. Communicated to remote location for real-time analysis
- Usually only applied to **important structures** or when there is **doubt about the structural integrity**

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Section 6: SHM System Design

Intro to SHM — Section: 6

1. Design Issues…

Definition of SHM objectives → Types of monitoring → Sensor placement → Durability and lifespan of SHM

Sensors installed on FRP reinforcing grid prior to installation in a concrete bridge deck

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SHM System Design

Intro to SHM — Section: 6

2. Installation Issues…

Contractor education → Sensor identification → Sensor damage during construction → Structural changes induced by presence of SHM system → Protection against deterioration and vandalism

Contractor education and careful sensor identification are critical in SHM projects

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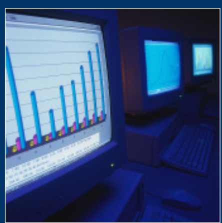
SHM System Design

Intro to SHM — Section: 6

3. Use Issues…

Dissemination of performance results → Continuity of knowledge → Data collection and management → Public awareness



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SHM System Design: Methodology

Intro to SHM — Section: 6

1. Identify the damage or deterioration mechanisms
2. Categorize influence of deterioration on the mechanical response
   – Theoretical and numerical models of structure
3. Establish characteristic response of key parameters
   – Establish sensitivity of each to an appropriate level of deterioration
4. Select the parameters and define performance index
   – Relates changes in response to level of deterioration
5. Design system
   – Selection of sensors, data acquisition and management
   – Data interpretation
6. Install and calibrate SHM system (baseline readings)
7. Assess field data and adapt system as necessary

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Section 7: Case Studies

Intro to SHM — Section: 7

Beddington Trail Bridge

- Calgary, AB, opened 1993
- 1st bridge in Canada with prestressed CFRP tendons and integrated FOS sensors
- SHM system was required due to innovative design
- FOS still performing well

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Case Studies

Intro to SHM — Section: 7

Beddington Trail Bridge

Bridge Specifics

- Two-span continuous bridge with 20 m spans
- Each span consists of 13 prestressed T-shaped girders
- Bridge is prestressed with two types of CFRP tendons

SHM System

- 20 FBG sensors to monitor during construction and service
- DAS consisting of a 4-channel FBG laser sensor system
- Network of FBG sensors in bridge is connected to a junction box for periodic on-site monitoring

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Case Studies

Intro to SHM — Section: 7 — Beddington Trail Bridge

System Performance and Results

- In 1999 the integrity of carbon FRP tendons was verified and no significant changes in structural behaviour were observed
- 18 of the original 20 FBG sensors were still functional
- Plans exist to conduct further testing after 10 years of service

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Case Studies

Intro to SHM — Section: 7

The Confederation Bridge

- Northumberland Strait, Canada
- Opened to traffic in 1997
- World's largest pre-stressed concrete box girder bridge over salt water
- Extensively instrumented for SHM

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Case Studies

Intro to SHM — Section: 7 — Confederation Bridge

Bridge Specifics

- Joins Borden, PEI to Cape Tormentine, New Brunswick
- 13.1 km long prestressed concrete box-girder
- 44 main spans, each 250 m long
- Each main span consists of main girders 190 m in length completed with drop-in girders 60 m in length
- Construction involved the development and use of several innovative technologies
- 100 year design life

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Case Studies

Intro to SHM — Section: 7 — Confederation Bridge

Confederation Bridge in an excellent Candidate for SHM:

1. It is subjected to extremely harsh environmental conditions
2. SHM data can be used to develop industry standards for future long-span bridges
3. It was designed with double the life span of similar bridges
4. It was important to verify design assumptions to ensure safety and serviceability (unique structure)
5. Develop new strategies for ongoing maintenance and repairs

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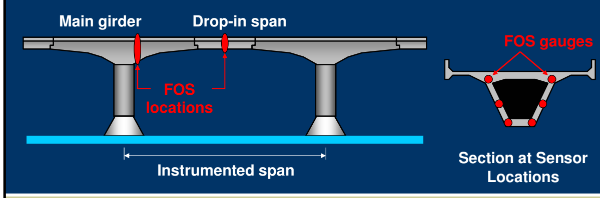
Case Studies

Intro to SHM — Section: 7 — Confederation Bridge

SHM System

- Both short and long-term behaviour are monitored
- Numerous sensors installed at various locations
- FBG sensor locations on the Confederation Bridge box girder:



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Case Studies

Intro to SHM — Section: 7 — Confederation Bridge

What is monitored?

- **Ice loads** ⇒ Tiltmeters, accelerometers, ice load panels, video monitoring, sonar
- **Traffic loads** ⇒ Strain gauges (conventional and FOS), video cameras
- **Bridge deformations** ⇒ mechanical, FOS, and vibrating wire strains gauges give short and long-term deformations
- **Thermal effects** ⇒ Thermocouples, vibrating wire strain gauges, pyranometers, cable tension linear transducers
- **Vibration/Dynamics** ⇒ 76 accelerometers, anemometers, dynamic displacement transducers
- **Rebar corrosion** ⇒ Corrosion probes in the splash zone

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Case Studies

Intro to SHM — Section: 7 — Confederation Bridge

Data Acquisition System

- Consists of a central computer system and two data loggers
- Data loggers collect data and convert to engineering units
- Data stored on-site for later transfer permanent retrieval site
- Data loggers operate at different speeds:
  - **High speed** → Dynamic response due to ice floes, wind, traffic loading
  - **Low speed** → Static response due to long term deflections, potential damage, thermal effects

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Case Studies

Intro to SHM — Section: 7 — Confederation Bridge

Data Acquisition System

Sensors → Loggers (Conversion to engineering units) → Central computer system on shore (Data Transfer) → Permanent retrieval site at Carlton University (Data Transfer)

Loggers operate in 2 modes:

1. Time-averaged mode
2. Event triggered burst mode

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Case Studies

Intro to SHM — Section: 7 — Confederation Bridge

System Performance and Results

- An important aspect of this SHM project was the **robustness** of sensors:
  - **During construction** → Some sensors damaged during the construction phase of the project (care is required)
  - **During service** → A comprehensive report on the performance of sensors is underway and should be available shortly

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Case Studies

Intro to SHM — Section: 7

Taylor Bridge

- Headingley, MB
- Opened 1998
- 165 metre length
- 2-lanes of traffic

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Case Studies

Intro to SHM — Section: 7 — Taylor Bridge

Bridge Specifics

- World's **largest span bridge** that uses:
  - **FRP bars for shear reinforcement** of concrete
  - **FRP bars for pre-stressing** of the main concrete girders
  - An **FOS system for remote SHM**
- 40 prestressed concrete I-girders
- 5 equal simple spans of 33m each
- 4 girders prestressed using 2 different types of carbon FRP prestressing cables
- 2 girders reinforced for shear using carbon FRP stirrups
- FRP bars in **deck slab** and **barrier walls**

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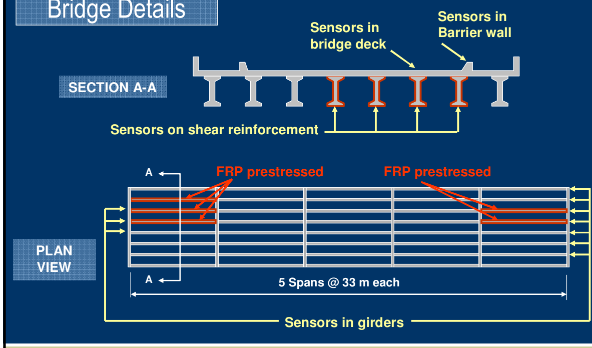
Case Studies

Intro to SHM — Section: 7 — Taylor Bridge

Bridge Details



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Intro to SHM

Case Studies

Section: 7

Taylor Bridge

System Performance and Results

- Various diagnostic tests have been performed on the bridge since it opened to traffic in 1997
- The response of the bridge to a slow moving vehicle was monitored soon after the bridge was completed
- Frequent load tests will be conducted in the future to evaluate the performance of the bridge girders, deck, and barrier wall

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Intro to SHM

Case Studies

Section: 7

Joffre Bridge

Sherbrooke, QC

Reconstructed 1997

Deck replaced

FRP rebars used

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Intro to SHM

Case Studies

Section: 7

Joffre Bridge

Bridge Specifics

- Originally build in 1950
- Reconstructed in 1997 following severe deterioration of the concrete deck slab and girders
- 2-lane, steel-concrete composite structure
- 5 spans of different lengths vary between 26 and 37 m
- Each span consists of 5 girders at a spacing of 3.7m
- During reconstruction it was decided that a portion of the deck slab would be reinforced with carbon FRP grid

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Intro to SHM

Case Studies

Section: 7

Joffre Bridge

SHM System

- A total of 180 sensors at various critical locations:
  - In deck slab
  - On steel girders
- Total of 44 FOS sensors :
  - 26 bonded Fabry-Perot FOSs on FRP grid
  - 6 Fabry-Perot sensors integrated into FRP grid
  - 2 Fabry-Perot sensors embedded in concrete
  - 3 Fabry-Perot strain fibre optic weldable sensors welded on girders
  - 3 FBG sensors bonded on the FRP grid
  - 1 Fabry-Perot and 1 FBG sensor bonded on an FRP bar for thermal strain monitoring
- Vibrating wire and electrical resistance strain gauges also used

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Intro to SHM

Case Studies

Section: 7

Joffre Bridge

System Performance and Results

- Since 1997 the static and dynamic responses of the bridge have been recorded regularly
- sensors in this structure have provided a wealth of information on the thermal and mechanical stresses occurring in the reconstructed bridge
- **Conclusions:**
  - It is possible to obtain meaningful and consistent results from FOSs used in SHM applications
  - Temperature is a dominant factor influencing the strain variation in the bridge

Load testing of the Joffre Bridge

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Intro to SHM

Section 8: Civionics Specifications

Section: 8

What is Civionics?

CIVIL ENGINEERING + ELECTRONICS

= CIVIONICS

Cooperation between engineers from various specific disciplines to form a new discipline within the field of civil engineering that refers to the applications of electronic systems in civil engineering applications

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Civionics Specifications

Intro to SHM — Section: 8

ISIS Canada has recently published "Civionics Specifications" - a manual providing best-practice guidelines for applying SHM

Topics include:

Fibre optic sensors
- Fibre Bragg grating sensors and readout units
- Long gauge FOSs and readout units
- Fabry-Perot FOSs and readout units

Wiring procedures and connections
- Sensor cables
- Conduits
- Junction boxes
- Cable termination
- On-site control rooms

FOS installation procedures

SHM system and FOS suppliers

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Section 9: The Future of SHM

Intro to SHM — Section: 9

- **SHM** is increasingly seen as an important tool in the maintenance of **sustainable infrastructure systems**
- Ongoing advancements are expected, emerging technologies include:
  → **Smart Composites**
  → **Live Structures**

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The Future of SHM

Intro to SHM — Section: 9

Smart Composites

Composites (e.g. FRP) with sensors embedded inside that provide information about the condition of the structural component

Muscle/Member Analogy:

Muscles have nerve cells embedded in them that provide information to the brain about the conditions of the muscles ⇔ Smart composites have sensors inside that provide information about the structural members' condition

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The Future of SHM

Intro to SHM — Section: 9

Live Structures

- Represent the **cutting edge** of civil engineering design and analysis
- Live structures are capable of:
  - **Sensing** loads, deformations, and damage
  - **Correcting and countering** the load effects
- Presently structures are largely theoretical
- Accomplished using emerging **self-actuating** materials

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Section 10: Summary and Conclusion

Intro to SHM — Section: 10

Structural Health Monitoring

- Provides the civil engineering community with a **suite of options for monitoring, analysing, and understanding** the **health of our infrastructure systems**
- Provide **essential tools** to engineers who must take steps to **improve the sustainability** of infrastructure systems

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Section 11: The Golden Boy

Intro to SHM — Section: 11

- The Golden Boy is a Statue mounted on top of the dome of the Manitoba Legislature
- It is one of Manitoba's best recognized symbols
- Designed and built in Paris, France in 1918
- Originally mounted on the dome in 1919

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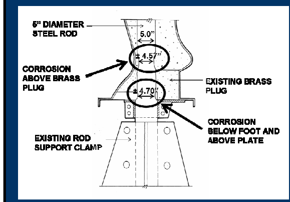
Intro to SHM — Detailed Example: Golden Boy (Section: 11)

The Problem



Magnitude of the corrosion of the steel support shaft observed in the Golden Boy's left foot

- In 2000, examination of the statue showed that the central support structure was severely corroded
- Inspectors noted that corrosion had reduced the steel support shaft's diameter by about 10%
- Wind tunnel testing and finite element modelling indicated that the shaft would be stressed to 93% of its ultimate strength under expected wind velocities
- **The shaft had to be replaced**

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Intro to SHM — Detailed Example: Golden Boy (Section: 11)

The decision to replace the shaft…

- Based on combined stress condition for 100-yr wind forces
- Statue treated as a simple cantilever
- From wind-tunnel testing:

Wind-induced moment at base = $16.9\,\text{kN}\cdot\text{m}$

Wind-induced shear at base = $6.2\,\text{kN}$

Wind-load moment arm = $\dfrac{16.9}{6.2} = 2.726\,\text{m}$

The dead-load of the statue is taken as: $DL = 3.0\,\text{tons} = 27.0\,\text{kN}$

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Intro to SHM — Detailed Example: Golden Boy (Section: 11)

The torque on the shaft can be calculated as the product of the shear due to wind and the lever arm about the vertical axis, hence:

Torque due to wind = $12.34 \times 0.15 = 1.85\,\text{kN}\cdot\text{m}$

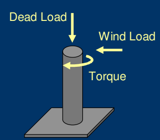
Thus, the design loads on the shaft at its base can be approximated as:

Moment, M_f = 34.68 kN.m

Axial, P_f = 33.75 kN

Shear, V_f = 12.34 kN

Torque, T_f = 1.85 kN.m



The stresses in the shaft can now be calculated using simple mechanics of materials

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Intro to SHM — Detailed Example: Golden Boy (Section: 11)

The mechanical properties of the shaft, in the deteriorated (corroded) condition were as follows:

Yield strength of steel, f_y = 275 MPa

Diameter at base, d = 116.1 mm

Moment of inertia, $I = \dfrac{\pi d^4}{64} = 8.91 \times 10^6\ \text{mm}^4$

Polar moment of inertia, $J = \dfrac{\pi d^4}{32} = 17.82 \times 10^6\ \text{mm}^4$

Cross-sectional area, $A = \dfrac{\pi d^2}{4} = 10.6 \times 10^3\ \text{mm}^2$

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Intro to SHM — Detailed Example: Golden Boy (Section: 11)

Thus, the stresses in the shaft at its base can be calculated as follows:

Bending Stress $\sigma_b = \dfrac{Mc}{\phi_s I} = \dfrac{34.68\times10^6 \times 58.04}{0.9\times8.91\times10^6} = 251.01\,\text{MPa}$

Axial Stress $\sigma_a = \dfrac{P_f}{\phi_s A} = \dfrac{33.75\times10^3}{0.9\times10600} = 3.53\,\text{MPa}$

Shear Stress $\tau_v = \dfrac{4V_f}{3\phi_s A} = \dfrac{4\times12.34\times10^3}{3\times0.9\times10600} = 1.72\,\text{MPa}$

Torsional Shear Stress $\tau_t = \dfrac{Tc}{\phi_s J} = \dfrac{1.85\times10^6 \times 58.04}{0.9\times17.82\times10^6} = 6.69\,\text{MPa}$

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Intro to SHM — Detailed Example: Golden Boy (Section: 11)

Mohr's circle can then be used to determine the maximum principal stress due to the combined loading condition in the shaft:

$$\sigma_{\max} = 254.72\,\text{MPa}$$

The yield stress of the steel in the shaft is approximately 275 MPa.

∴ the factored maximum principal stress in the shaft under a 100-year wind load is about 93% of the yield load

∴ upgrading of the shaft was required

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Intro to SHM

Detailed Example: Golden Boy

Section: 11

SHM System Specifics

- This system was designed to:
  - Monitor the statues performance on an ongoing basis
  - Provide information to engineers and government about long-term effectiveness of the restoration
- Consisting of three types of gauges:
  - Accelerometers
  - Strain gauges (both electric resistance and fibre optic)
  - Temperature sensors

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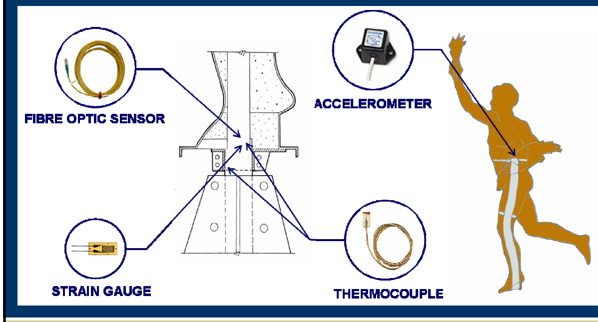
Intro to SHM

Detailed Example: Golden Boy

Section: 11

The SHM System



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Intro to SHM

Detailed Example: Golden Boy

Section: 11

The SHM System

- 2 accelerometers placed at the top of the new support shaft:
  - If accelerometers give frequency readings outside the normal range, further examination is made into the health of the structure
- 2 types of strain gauges installed on steel support shaft:
  - Electrical resistance strain gauges and FBG strain sensors
  - If strain readings fall outside the normal range, an alert is provided to potential structural health issues before a major problem develops
- Thermocouples installed in proximity to the strain gauges:
  - Temperature has a direct effect on the material properties of the column and the strains measured by both types of strain sensors

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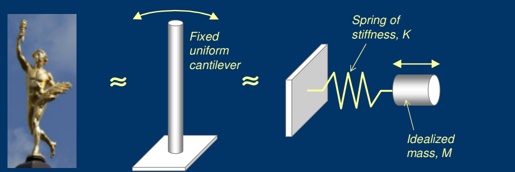
Intro to SHM

Detailed Example: Golden Boy

Section: 11

Monitoring Principles

- Golden Boy's steel support shaft is a simple structural element that can be approximated as a single vertical cantilever
- Cantilevers can be modelled as single degree of freedom systems using straightforward structural dynamics principles



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Intro to SHM

Detailed Example: Golden Boy

Section: 11

Monitoring Principles

Natural frequency can be determined as follows:

1. The moment of inertia, *I*, of a cylindrical solid rod of diameter, *d*, is:

$$I = \frac{\pi d^4}{64} = \frac{\pi (127)^4}{64} = 12769820 \text{ mm}^4$$

2. The cantilever is treated as a 2750 mm long steel (elastic modulus, *E* = 200 GPa) spring of stiffness, *K*, where *K* is calculated as:

$$K = \frac{3EI}{L^3} = \frac{3(200000)(12769820)}{2750^3}$$
$$= 368.4 \text{ N/mm} = 368400 \text{ kg/s}^2$$

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Intro to SHM

Detailed Example: Golden Boy

Section: 11

Monitoring Principles

3. The mass, *M*, of the idealized single degree of freedom system can be roughly approximated as the mass of the statue:

$$M = 1.52 \text{ Tons} = 1520 \text{ kg}$$

4. The theoretical first *natural frequency* of the idealized system is given by the following:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} = \frac{1}{2\pi}\sqrt{\frac{368400}{1520}} = 2.48 \text{ Hz}$$

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Intro to SHM

Detailed Example: Golden Boy

Section: 11

Golden Boy's DAS

- Sensors wired to on-site data logger and personal computer
- SHM data can be accessed on an ongoing basis through the ISIS Canada Active Structural Health Monitoring Website
  - Go to www.isiscanada.com and click on "Remote Monitoring"
- Web access allows for instantaneous examination of accelerations, strains, temperatures, and wind speeds

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Intro to SHM

Detailed Example: Golden Boy

Section: 11

Screen capture from ISIS Canada website (www.isiscanada.com)

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Intro to SHM

Section 12: Additional Information

Section: 12

Available from www.isiscanada.com

- ISIS Design Manual No. 1: Installation, Use and Repair of FOS
- ISIS Design Manual No. 2: Guidelines for Structural Health Monitoring
- ISIS EC Module 1: Mechanics Examples Incorporating FRP Materials
- ISIS EC Module 2: An Introduction to FRP Composites for Construction
- ISIS EC Module 3: An introduction to FRP-Reinforced Concrete Structures
- ISIS EC Module 4: An Introduction to FRP-Strengthening of Reinforced Concrete Structures

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