Structural Health Monitoring Systems
SHMS – Technologies and Practices

Virginia DOT
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Introductions
Overview (what why how)
Sensor Technology
System Design Economics
System / Software Automation
Data Management
Case Studies
Use of Innovative Technology
Introductions

- Tom Weinmann, Practice Area Leader – Structural Health Monitoring
  - Over 35 Years of Experience with Design, Development and Implementation of SHM Systems on Various Structures throughout the US and Abroad Derived from Large Scale Building and Bridge Component Testing
Who is Geocomp?

Continually developing and integrating technologies to manage risk for infrastructure. More than 15,000 projects for A/E/Consulting firms, Contractors, Agencies and Owners

- GeoStructural Engineering and Design
- Active Risk Management
- Materials Testing
- Products Group
- Instrumentation & Monitoring
  - Geotechnical
  - Structural
GTX Experience in Virginia

Since the start of 2017, GTX has performed work on over 80 projects in the State of Virginia for 15 different clients.

- Some of these clients include:
  - ECS Limited
  - Froehling & Robertson, Inc.
  - Geoconcepts
  - Geosyntec
  - GET Solutions
  - Haley & Aldrich
  - HDR Engineering, Inc.
  - Schnabel Engineering, LLC
  - Underhill Engineering

- Some of the projects include:
  - Dulles Corridor Phase 2
  - S. James Madison Highway (VDOT)
  - Lynch Mill Road (VDOT)
  - I-81 Exit 114 over Rt 8
  - Route 360 Widening
  - Route 720 Bridge over I-81
  - Route 7 and Route 690 Interchange
  - Dulles Corridor Metrorail
  - I-64 Hampton Roads Bridge - Tunnel Expansion
  - I-95 South Bound Lanes
  - Clifton Lake Dam
  - I-64 High Rise Bridge
GTX Experience in Virginia

- GTX performed the following testing on soils, rock, and geosynthetic materials in support of these projects:
  - Grain Size and Atterberg Limits for Soil Classification
  - Permeability testing on coarse and fine grained soils
  - Incremental Consolidation tests
  - CU Triaxial tests
  - Slake Durability and LA Abrasion tests on Aggregate
  - Unconfined Compressive Strength of Rock Core with Young’s Modulus and Poisson’s Ratio.
  - Soil Abrasion Testing
  - Interface Shear testing on soil and geosynthetic materials
I&M Experience in Virginia
Parallel Thimble Shoal Tunnel
I&M Experience in Virginia
Parallel Thimble Shoal Tunnel
I&M Experience in Virginia
Craney Island Land Reclamation
I&M Experience in Virginia
Craney Island Land Reclamation
I&M Experience in Virginia
Midtown Tunnel
Types of Structures

- Bridges
- Buildings
- Stadiums
- Dams
- Wind Towers
- Industrial Facilities
- Pavements
- Tunnels
Reasons for Monitoring

- Risk Management
- Construction Monitoring
- Performance Evaluation
- Model Validation
- Prototype Testing
- Predictive Maintenance (Asset Management)

- COST MUST BE JUSTIFIED
Sensor Technology

- **Static Sensors**
  - Lowest cost / low channel count, Long cable runs
  - No dynamic response, Susceptible to EMI/RFI/Lightning

- **Dynamic Sensors**
  - Dynamic response
  - Short cable runs/signal loss, Susceptible to EMI/RFI/Lightning

- **Fiber Optics**
  - EMI/RFI/Lightning immunity, Intrinsically safe, Ease of installation, Longest cables runs
  - Temperature sensitive
  - FBG: Static or Dynamic, Higher cost for low channel count
  - DS/T: Lowest cost / high channel count, Highest cost for low channel count
Fiber Sensor Configurations

Single-point sensor (FBG)

Single-point sensors in series (FBG < 40)

Distributed sensor in series up to 10,000 pts

Continuous sensing element
System Design Economics

50 Sensor System

- VWSG System
- ERSG System
- FBG FO System
- DST FO System

$0 - $250,000

50 Sensor System Cost Breakdown:
- Lightening Protection
- System Design/Programming
- System Hardware
- Installation Travel
- Wire Routing/Termination
- Sensor Installation
- Sensor Cost

Geocomp
System Design Economics

100 Sensor System

- VWG System
- ERSG System
- FBG FO System
- DST FO System

Cost Breakdown:
- Lightening Protection
- System Design/Programming
- System Hardware
- Installation Travel
- Wire Routing/Termination
- Sensor Installation
- Sensor Cost

Costs:
- $0
- $50,000
- $100,000
- $150,000
- $200,000
- $250,000
- $200,000
- $250,000
- $300,000
- $350,000
- $400,000
- $450,000
- $500,000
- $550,000
- $600,000

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System Design Economics

500 Sensor System

- VWSG System
- ERSG System
- FBG FO System
- DST FO System

- Lightening Protection
- System Design/Programming
- System Hardware
- Installation Travel
- Wire Routing/Termination
- Sensor Installation
- Sensor Cost

System Design Economics
System Design Economics

1000 Sensor System

- VWSG System
- ERSG System
- FBG FO System
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- Lightening Protection
- System Design/Programming
- System Hardware
- Installation Travel
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- Sensor Installation
- Sensor Cost

Example for strain and temperature sensors only

$0, $200,000, $400,000, $600,000, $800,000, $1,000,000, $1,200,000, $1,400,000, $1,600,000
System Automation

- Manual Readings and Processing = $1,000/week
- Automated = System cost ($32k) + $400/month

Manual vs Automated for 30 Existing Sensors

<table>
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<th>Time 0</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<td>$200,000</td>
<td>$220,000</td>
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Cumulative Cost

- Red: Manual Weekly Readings
- Green: Automated Hourly Readings w/Alarms
System Integration

Universal Data Management System

Management System

- Available 24/7
- Secure Access
- Multiple Users
- Daily Backup
- Dual-System Synchronization
  Ensuring 99.99% Uptime
- 3rd Party Monitoring

Users

Regulators, Contractors, 3rd Parties, Operators, and Owners

Anytime Access

Auto-generated PDF Reports

Web-based Charts & Graphs

Alarms

Sensors
- Environmental
- Load
- Tilt
- Stress
- Piezo
- Geomatics
- Vibration

Equipment Information
- TBM
- AMTS
- Acoustic Emission

Site Information
- Construction Activities
- Field Observations
- Laboratory Tests
- Reports
- Photos
Software / Database Management

KY Lock Addition

iSiteCentral GIS - Kentucky Lock

username
password

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Landslide is active

Software / Database Management
Penitencia Seismic Retrofit
iSite Central GIS for Asset Management
MassDOT MHS Structure Example
iSite Central GIS for Asset Management

MIDOT Multiple Bridges (5 and counting) Example

- Bridge Street Bridge Project
  - CFRP Pre-stressing
  - CFRP Reinforcement
  - CFRP Post-tensioning

- Pembroke/M39
  - CFRP Deck Mat
  - CFRP Post-tensioning

- M50/US127
  - CFRP Post-tensioning

- M120/8 Mile
  - CFRP Pre-stressing

- I-75
  - CFRP Pre-stressing
Structural Health Monitoring Case Studies

How can this technology be used?
Case Study - Bridges
Construction Verification / Model Verification

• **Sunshine Skyway Bridge**
  • Unique structure in 1983
  • Long-term creep/shrinkage
  • 1st Automated system in US

• **H3 Viaduct**
  • Light weight concrete
  • Long-term creep/shrinkage
  • Data used to verify modeling
Case Study - Bridges
Reducing Risk / Verify Construction Procedures

- Bayonne Bridge, NY - Monitoring During Construction

- Monitoring of existing structure and foundation
- iSite Central GIS real-time reporting
- Automated reporting
- Alarm Notification
Case Study - Bridges
Extend Service Life – Assess Remaining Fatigue Life

- I-91 Viaduct Springfield, MA
  - Measure fatigue stress range in select non-redundant members
  - Determine Stress Life (S-N curves)
  - Predict remaining Service Life
  - Strengthening/repairs where necessary

- Walt Whitman Bridge
- GoldStar Bridge
- Charter Oak Bridge
Service Life Extension
Prioritize/Verify Need for Repairs

$5,000,000 \times 0.04 = $200,000 savings to extend the service life for one year

Cost of borrowed money for immediate repair or replacement

- Year 1: $200,000
- Year 2: $200,000
- Year 3: $200,000

$600,000

Cost for SHMS to extend service life

- Initial Cost: $100,000
- Year 2: $25,000
- Year 3: $25,000

$150,000

Or – Realize concern is overstated and save $500M
Case Study - Bridges
Performance Testing - Utilization of Innovative Materials

- Bridge Street Bridge Project
- M39/Pembroke
- M50/US127
- M120/8 Mile
- I-75

All with Carbon Fiber Composite components
- Deck Mat
- Prestressing
- Post-tensioning
- Reinforcement
Case Study - Bridges
Serviceability for Modification / Verification of Model

- Homer Hadley Floating Bridge
  - Modeling Verification
  - LRT Simulated Load Test
- Monitor
  - Dynamic response
  - Cross-sectional strains
  - Bridge list
  - Joint movements
    - Displacement
    - Rotation
Case Study – Bridge Widening
Owner RISK Mitigation

- **Huey P Long Bridge Widening Project**
  - Truss Monitoring Specification (S107)
    - Eye Bar Force Measurements
    - Static Strain Gage System
    - Live Load Strain Gage System
    - Baseline Measurements
    - Load Test
    - Construction Monitoring
Case Study – Bridge Lifts
Contractor RISK Mitigation / Improve Controlled Performance

- **Huey P Long Bridge**
  - 528-ft, 2700-ton Truss Lifts (3 pairs)

- Monitor
  - Truss tilt
  - Truss sweep
  - Continuous, wireless communication for control of lifting operation for MTI, HNTB
Case Study – Bridge Transport
Owner and Contractor RISK Mitigation

- I-84 ABC Deck Transport, CT
  - SPMT Transport
  - Measure Deck Strains
  - Measure Deck ‘twist’
  - Stresses minimized
  - Real-time results
  - Controlled Operations
  - No Delays
Case Study - Buildings
Protection from Adjacent Excavation (Big Dig)

Federal Reserve Bank of Boston and One Financial Center
- Deepest Part of Excavation
- Immediately Adjacent to SW
- Unplanned Dewatering

- Monitor
  - Beam/Column Strains
  - Settlement
  - Tilt
  - Foundation ‘spreading’
- No Disruption to 24/7 Operation
- No Construction Delays
Case Study - Buildings
Façade Restoration / Evaluation of Retrofit

Guggenheim Museum
• Façade Cracks
• Thermal Response
• Temperature/Humidity

• Monitor
  • Cracks
  • Temperature
  • Humidity

• Input for Façade Re-design
• Re-design of Controlled Temperature/Humidity Environment
Case Study – Lock/Dam
Construction Monitoring (Risk Mitigation)

Kentucky Lock Addition

- Monitor
  - Lock wall Joints
  - Lock wall Tilt
  - Cofferdam Stability
  - Pore Water Pressure
  - Automated System
  - Alarm Notification

- Control Construction Procedures
- Barge Impact
Case Study – Wind Towers
Performance Assessment / Retrofit Verification

Trent Mesa
• Foundation Retrofit

Buffalo Gap
• Performance Assessment

Palm Springs
• Fatigue Issues
• Retrofit Operations
Case Study - Pavements
Accelerated Test Pavement Facilities / Test Roads

- 20 Years in 3 Months
- Variable Test Sections
- Measure Load Response
  - Pavement Strains/Temp
  - Pavement Deflection
  - Subsurface Deformation
  - Load Distribution
  - Layer Shear
  - Slab Curling
Case Study - Stadium
Asset Management

SAFECO Field

- Assess Roof Damper Performance
- Assess Roof Performance

- Monitor
  - Damper Force/Displacement
  - Roof/Ground Accelerations

- Predict Damper Displacement
- Bonus –
  - 2001 Nisqually Earthquake Response
  - Wheel Bogie Bearing Maintenance
Case Study - Pipelines
Asset Management – Seismic Retrofit
Tappan Zee Bridge (Asset Management)
Fluor, American Bridge, Traylor Bros., Granite, HDR, B&T

- Completed in late 2018
- New clearance 212 ft.
- Built for 100 year design life
- Will have the most comprehensive SHMS for a Bridge in the US
- A ‘closed loop’ type system
SHM System
Component Performance Interaction

Cable Forces
- Deck stresses
- Girder strains
- Tower moments
- Deck deflections

Superstructure Strain
Bearing/ Expansion Joint
Cable Forces

Bearing Movement
- Deck stresses
- Girder Strains
- Expansion joints

Expansion Joint Movement
- Deck stresses
- Girder strains
- Cable forces
- Pier moments

Photo Credit: New York State Thruway Authority
SHM System
Component Interaction during an Event

- Expansion Joint ceased to function
- Deck Strain increases
- Pier Tilt increases
New Tappan Zee Bridge SHMS
Sensors (430) and their Measurements (780)

- Sensors
  - Accelerometers (cables, towers, deck)
  - Displacement (bearings, joints)
  - Inclinometers (towers, deck, piers)
  - Strain gages (cables)
  - Temperature (towers, road surface/deck, girders)
  - Environmental (WS/WD, temp, pressure, rain, fog, solar)
  - Corrosion (towers, piers, deck)
  - GPS (towers, mid-span, abutment)
SHMS
Software Demo Video

Structural Health Monitoring System
Innovative Technology
Case Studies
Fiber Bragg Gratings
Strain or Temperature Change

Input spectrum

reflected wavelength $\lambda_0$

reflected wavelength $\lambda_{\varepsilon/T}$

with no effect

change in $\varepsilon$ or $T$

returned signal: Shift in wavelength of signal is proportional strain/temp change
Case Study – FBG Fiber Optics
SPCC Smart Cable Technology

- **Shanghai Pujiang Cable Co.**
  - Force Measurement in stay cables using fiber optics
- Monitor
  - Cable force
  - Cable temperature
  - Moisture/humidity
- Assess Performance
- Predict Maintenance
Case Study – FBG Fiber Optics
FAA Airport Runway Pavement Research

- Fiber Bragg Grating (FBG) String Array
  Embedded in Asphalt Layers
  Retrofitted in Concrete Surface
Case Study – FBG Fiber Optics
MSE Walls using GeoDetect Geosynthetic

- Fiber Bragg Grating (FBG) String Array
  Embedded in Geosynthetic Material in Multiple Layers
  Measures Geosynthetic Strain/Soil Pressures
Case Study - SMART Bearings
EXXON Mobil Building, Houston, TX

- Measure Force Distribution from Thermal or Event Driven Conditions
- 1000 & 3900 Kip Fixed Bearings
- 1000 & 3900 Kip Guided Bearings
- Monitor
  - Load / Rotation / Displacement
Case Study – Corrosion Protection
Inert Gas Monitoring System

• **Penobscot Bridge**
  • Corrosion protection- Inert (Nitrogen) gas
  • Cable replacement – CFRP
  • Monitor
    • Gas pressure
    • Gas flow
    • Strand forces
  • Predict Maintenance
QuickChek/CrackChek
Metal Fatigue Solutions

- **QuickChek- Single location**
  - Hand held check in minutes under load
  - Is Crack Active?
  - Red, Yellow, Green

- **CrackChek- Multiple locations**
  - Measures rate of Crack Growth
Introduction of Distributed Strain and Temperature Sensing (DST) Applications

APPROPRIATE FOR LONG LINEAR STRUCTURES AND VERY HIGH SENSOR COUNTS
Distributed Strain and Temperature
Physics Behind the Measurement

Brillouin-based sensing technique – BOTDA

30 km fiber optic cable

Residual Strain + 150 microstrain

Residual Strain + 50 microstrain

Measures backscatter of light from moving pulse down the fiber
Repeats process at different frequencies to build matrix
Shifts in frequencies are due to change in fiber geometry
Distributed Strain and Temperature
Accuracy and Limitations

Relationship between DITEST performance parameters

10 km run
10 min analysis
6-7 με resolution
System Design Economics

1000 Sensor System

- VWSG System
- ERSG System
- FBG FO System
- DST FO System

Cost Breakdown:
- Lightening Protection
- System Design/Programming
- System Hardware
- Installation Travel
- Wire Routing/Termination
- Sensor Installation
- Sensor Cost

Cost Ranges:
- $0 to $200,000
- $400,000
- $800,000
- $1,000,000
- $1,200,000
- $1,400,000
- $1,600,000

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DST Case Study
Williams Gas Pipeline

- 500m Pipeline (1500 pts)
- Monitor
  - Bending Strain
  - Temperature
  - Leaks
- Predict Maintenance
- Monitor ROW
DST Case Study
Levee/Floodwall Alignment, 17th Street Canal in New Orleans, LA

- 0.3 miles of DST along floodwall
- 0.6 miles of DST along levee crest and toe
- 300 ft. of leakage detection heated cable along levee toe

- Monitor
  - Long-term Deformation of Floodwall
  - Long-term Deformation of Levee

- Aid in early identification of sections requiring maintenance
DST Bridge Application
Qatar-Bahrain Causeway (Specified)

- 20km Causeway
- COWI Specification
- Monitor
  - Strain
  - Temperature
- Used for Active Modeling

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<th>1.5</th>
<th>Structural Monitoring System Cost to Cost</th>
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<td>Distributed Strain / Temp sensor</td>
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DST Bridge Application
One Meter Section Measurements

Simple communication fiber embedded (concrete) or fixed (steel) to corners of box section

Obtain strain measurements through cross-section

Determine Bending/Axial Stresses (plane sections remain plane)
DST Potential Pavement Application

Subsidence (karst)

Sinks and their relation to solution cavities beneath the surface.
DST Potential H-S Rail Application

Seismic
What Sets Us Apart in SHM?

- **Industry Leader** - Development of most complex SHMS for Bridges in the U.S.; New Tappan Zee.

- **Project Experience** - Development of SHMS for almost any type of structure.

- **Innovative Technologies** – Development of SMART Structural components, including fiber optic technology and sensors.

- **Product Development** – Development of SHM data collection hardware and software algorithms.
Summary / Discussion

- **What is the Payback??**
- Define Your Objectives (what are your needs)
- Define Your Reading Frequency (static/dynamic)
- Define Your Time Period (manual/automated)
- Define Data Processing (immediate or reported)
- Define Your Data Access (remote/web-based)
- Decision Making Process (alarm notification?)
- Maintain Your System (must be reliable)