MULTI-HAZARDS RISK MANAGEMENT IN METROPOLITAN USA

Partnership for Developing a Systemic Methodology and Related Technologies:
DRPA of PA&NJ, SANDIA NL, DREXEL

Emin Aktan
Director of Intelligent Infrastructure Institute
Drexel and MCP Hahnemann Universities
Infrastructure Systems and Multi-Hazards Risk Management

1. Introduction to DI3
2. Problem areas addressed
3. Fundamental principles guiding DI3 research
4. Technologies that DI3 has integrated
5. Technology application examples
6. Health, safety and security monitoring
7. Metro infrastructure security
Drexel Intelligent Infrastructure Institute (1997-2002)

**University Collaborators**
- Johns Hopkins
- Tufts
- Columbia
- Virginia Tech
- Carnegie-Mellon
- University of Pennsylvania
- Lehigh
- Notre Dame
- University of Delaware
- University of Maryland
- University of Pittsburgh
- Bauhaus, Germany
- Tokyo, Kyoto Universities, Japan

**Government:**
- DRPA of PA and NJ
- Pennsylvania DOT
- Federal Highway Administration
- National Institute for Standards and Technology
- National Science Foundation

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Earthquake Engineering

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- Dr. Meystel (EE-Intel Systems)
- Dr. Hsuan, (CE, Materials)
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- Dr. Wang (ME-Solid Mech.)
- Dr. Gombola (Finance)
- Dr. Regli (Computer Science)

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Electrical and Computer Engineering

**Graduate Students**
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**Industry**
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**Operations:**
TB A
Systems:
Onur Cinar CS
Problem Areas Addressed by DI3

• How can we define and objectively assess:
  – **Condition** of an infrastructure component ?
  – **Performance** of an infrastructure system ?
  – **Health** (inclusive of environmental, operational and structural) of meta-infrastructure-systems ?

• How can we capitalize on innovative paradigms and effectively leverage technology for improving infrastructure performance ?

• Multi-hazards risk management problem for metropolitan regions with emphasis on homeland security and safety ?
Drexel Intelligent Infrastructure Institute

- Academe-Government-Industry Partnership
- International Nexus
- Operating Infrastructure Test-Beds
- Systems-Based, Integrative:
  - Natural-Engineered-Social Systems
  - Organizational-Operational-Physical Systems
  - Experiment-Analysis-Information-Heuristics
  - Reality: Observable, Measurable, Systemic
  - Modular, Scalable, Interoperable Products for Health, Performance and Security Monitoring of Interconnected Infrastructure Systems
Berkeley Projects

Sander Tower

Seismic Vulnerability of Flat Slab-Core Buildings (1988-1991)
Clermont Bridge
Non Destructive And
Destructive Testing Of A
Concrete Slab Bridge and
Associated Analytical Studies
(1990-1992)

40-year Old RC Slab Bridge
Chem Deterioration of Concrete

D-Cracking and Alkali-Silica
Reaction

Servo-Controller
and Data
Acquisition
Hardware in
Field Office

Load-Displacement
Test Response

Loading System

Shear Failure Triggered By Deterioration
Analytical Modeling and Nonlinear FE Analysis Of The Clermont Bridge

Pratt Bridge

Camelback Bridge

Alkire Bridges

Chord Failure

Load Transfer System

Camelback Bridge
Simulation Of Nonlinear Responses of the Pratt Truss Bridge

- Span = 46.3 m
- Mid span Deflection History (cm)
- Total Actuator Load (kN)

Graph showing the relationship between Total Actuator Load (kN) and Mid span Deflection History (cm) for different load cases: 2T/B, 3T/B, and TEST.
Seymour Bridge

Bridge-Type Specific Management of Steel-Stringer Bridges in Ohio (1996-1998)

Transforming a bridge into a laboratory:

Damage Scenarios: Steel Superstructure

One-Sided Flange Cut

Two-Sided Flange Cut

Web Cut

Crossframe Cuts

Modal Flexibility Based Deflections (BGCI)

- Welding/Restoration of BC’s
- After X-Brace Cut at South Span

Deflection, in.

1 kip/point

Damage Location

Test (Baseline)
**Reading Road Bridge**


**Site Design for Bridge Monitor System**

**Two Year Continuous Monitoring Results (Nov 94-Nov 96)**

- Ambient Temp. (DEGF)
- Microstrain

- ΔT = 111.4 °F
- Δε = 359 µε

**Instrumentation of Steel Grid Superstructure**

**Data Acquisition Cabinet for Teleremote On-Line Monitoring of In-Service Responses**
ANALYTICAL MODELING FOR ACCURATE SIMULATION

Bridge Characterization through Grid Model

(a) 2-D Grid
(b) Slab, Girders, and Cross-Braces
(c) Equivalent Beams

Bridge Characterization through FE Model

(a) 3-D FEM
(b) Slab, Girders, and Cross-Braces
(c) Abutment
(d) Pier

Bridge Ham 42-0992

Abutment Detail
Bearing Pad Detail Over Pier
Hamilton Bridge


- Heat-Camber Instrumentation
- View Under the Deck
- Instrumentation of the Stringers
- RC deck Embedment Sensors
- Pile Instrumentation
- Deck Pouring Operation
- Deck Pouring Operation

Instrumentation of the Stringers
Instrumentation, Proof-Testing and Monitoring of Three Reinforced Concrete Deck-on-Steel Girder Bridges Prior to, During and After Superload (1996-1997)

Toledo Super-Load

Loaded Truck Crossing A Bridge

Close-Up of Superload

Correlations Between The Super-Load Measurements and Simulations Obtained From FE Analyses

Instrumenting bridges by strain, tilt and displacement sensors
Tindall Bridge

Nondestructive Condition Assessment of a Posted Bridge (1996-1997)

Tindall Bridge

Top Chord and Instrumentation Details

Floor Grate

Compression-Strut-to-Lower-Chord Joint Deterioration

FE Modeling for Sample Locations

Micro-Sampling Technique

Scanning Electron Microscope Photos:
Aged Steel With Corroded Layer
Contemporary Steel
Profile of T-Beam Bridges in Pennsylvania

1,651 Single Span T-beam Bridges in PA

- Total Number in USA > 32,000
- Total Number in PA > 2600
- Type Specific Design
  - Built Between ~1930 & 1950
  - Span ~20 ft - 40 ft
  - Width ~ 20 ft - 40 ft
  - Skew ~ 0 - 45 deg
  - Slab Thickness ~ 8-8.5 in
  - Beam Spacing ~ 5 ft on center
  - Beam Depth ~ 19 in - 40 in
Entire T-Beam Population & Statistically Representative 60 Distribution in Pennsylvania
Details of the Swan Road Bridge Finite Element Model

Statistics of The Model:
Number of DOF = 108243
Number of Solid Elements = 22940
Number of Frame Elements = 7636

Cross Section of the Model

Reinforcement

Structural Details & Boundary Condition

Typical Solid Element Dimensions

- 3.375"
- 3.375"
- 12"
- 3.375"

Parapet

End Diaphragm

T-Beams
Regional Calibration - Deflections of the Swan Road Bridge & Test Results

Section A-A

Section B-B

Transverse Centerline Deflection of the Superstructure (Test vs. Models)

Deflection (in)

-0.010
-0.020
-0.030
-0.040
-0.050
-0.060
-0.070

Deflection of the T-Beam "C" (Test vs. Models)

Deflection (in)

-0.010
-0.020
-0.030
-0.040
-0.050
-0.060
-0.070

Truck and Sensor Locations:

A
B
C
D
E
F

1
2
3
A-A
B-B

Displacement Sensor Location

Boundary Condition Idealization of Different Models:

- Model 1
- Model 2
- Model 3
- Model 4
- Model 5
- Model 6

K = 1000 kip/in

K

K

UNIVERSITY

Regional Calibration - Deflections of the Swan Road Bridge & Test Results
Comparison of Different Model Load Rating Results

H20 Truck

a) AASHTO based BAR7 Analysis
Rating Factor: RI=1.27, RO=2.11

b) Field-calibrated FE Model
Rating Factor: RI=3.18, RO=5.32

c) Field-calib FEM w/o Parapet and Sidewalks
Rating Factor: RI=3.10, RO=5.18

d) Field-calib. FEM w/o Concrete Deck
Rating Factor: RI=2.18, RO=3.63

e) Damage and Deterioration Case 1 (40% of concrete, only 80% of upper layer rebar)
Rating Factor: RI=1.16, RO=1.93

f) Damage and Deterioration Case 2 (Case e and only vertical restraints at the inner edge of the boundary)
Rating Factor: RI=1.05, RO=1.76
Views of the Principal Structural Systems of the Commodore Barry Bridge

- Steel Stringer Approach
- Deck Truss Approach
- Cantilever Truss
- Deck Truss Approach
- Steel Stringer Approach

Dimensions:
- 13,912’
- 822’
- 1644’

- Lower Chord of Main Truss
- Deck Truss Approach
- Steel Stringer Approach
Health Monitor Design Process for the Commodore Barry Bridge

1. Characterization of the Bridge
2. **Determine Typical Known/Unknown Phenomena Affecting Performance**
3. **Measurands, Sensors & Data Acquisition**
4. **Sensor & Measurement Calibration Studies**
5. **Data Acquisition Control, Synchronization & Integration**
6. **Data Quality Assurance, Processing & Archival**
7. **Data & Information Management In Real-Time**
Survey of The Bridge: Observe, Measure

CAD Drawings: Visualize, Conceptualize

Experiments

Conceptualization

Parameter Estimation

Calibrated Analytical Model for Reliable Simulations
FE Models of Commodore Barry Bridge

3D Model Statistics (Deck Truss)
Nodes: 1480
DOFs ~8870
Frame Elements: 867
Shell Element: 618

3D Model Statistics (Steel Stringer)
Nodes: 705
DOFs ~4590
Frame Elements: 246
Shell Element: 480

3D Model Statistics
Nodes: 7730
DOFs ~46400
Frame Elements: 5341
Shell Element: 2910
Free Body Diagrams of Critical Continuity Conditions
Ambient Vibration Monitoring
For Insight Into Behavior
Ambient Vibration Testing for FEM Calibration

Pier W1

822' Anchor Span
411' Cant. Arm
822' Suspended Span
411' Cant. Arm
822' Anchor Span

Vert. Accel.
Long. Accel.
Lat. Accel.

45 Accelerometers Utilized

Bottom Chord Level
Finite Element Model and Test Correlation

Nominal FEM

Mode 1
f=0.205 Hz

Mode 2
f=0.312 Hz

Mode 3
f=0.314 Hz

Ambient Vibration Test

Mode 1
f=0.25 Hz

Mode 2
f=0.360 Hz

Mode 3
f=0.65 Hz

Upper Bound FEM

Mode 1
f=0.223 Hz

Mode 2
f=0.329 Hz

Mode 3
f=0.519 Hz
Finite Element Model and Test Correlation

Nominal FEM

Mode 4
f=0.414 Hz

Mode 5
f=0.456 Hz

Mode 6
f=0.534 Hz

Ambient Vibration Test

Mode 4
f=0.83 Hz

Mode 5
f=0.880 Hz

Mode 6
f=1.05 Hz

Upper Bound FEM

Mode 4
f=0.542 Hz

Mode 5
f=0.582 Hz

Mode 6
f=0.591 Hz
Stringer Strains at Different Static Loading Configurations

Strain (microstrain)

Time (sec) and Position of Load

South Hanger Strains (L1)

South Hanger Strains During Crawling on Different Lanes

L.C. 1 (Crane A)
L.C. 4 (Crane A)
L.C. 7 (Crane A+B)

South Hanger Strains (L1)

Repeatability Check

L.C. 1 (Crane A)
L.C. 4 (Crane A)
L.C. 7 (Crane A+B)

Stringer 8

Single Crane During Crawl Speed Test

L1

Panel points

5-7 mph

South Hanger Strains (L1)

Stringer Strains at Different Static Loading Configurations

Time (sec) and Position of Load

Strain (microstrain)
Phenomena to be Identified & Measured

- **Environmental Effects: Changes in Wind, Ice, Radiation and Ambient Temperatures and their gradients impacting the bridge structure**

- **Soil, Water, Foundation & Structural Movements**

- **Dead Loads & Intrinsic Responses due to Env. Inputs & Movements**

- **Live Loads & Serviceability: WIM, critical strains & vibrations**

- **Retrofit Installation & Effectiveness**

- **Fatigue Environment**

- **Electro-Chemical & Other Phenomena Affecting Deterioration**

- **Local Sentry Functions: Fatigue Sensitive & Fracture Critical Details**

- **Operational & Maintenance Management Planning Data**
## Bridge Monitor Sensors & Their Characteristics

<table>
<thead>
<tr>
<th>Phenomena To Be Monitored</th>
<th>Sensor Designation</th>
<th>Sensor Photo</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic</td>
<td>Image Streams</td>
<td>Sony EVI Camera</td>
<td>Real-Time Video Image Streams</td>
</tr>
<tr>
<td></td>
<td>WIM</td>
<td>International Road Dynamics</td>
<td>Bending Plate Scale</td>
</tr>
<tr>
<td>Weather</td>
<td>Temperature</td>
<td>Vaisala Weather Station</td>
<td>Self-Contained Weather Station</td>
</tr>
<tr>
<td></td>
<td>Humidity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar Radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind Speed</td>
<td>Handar Wind Speed &amp; Direction Sensor</td>
<td>Ultrasonic Sensor</td>
</tr>
<tr>
<td>Bridge Response</td>
<td>Live Load Strain</td>
<td>Hitec Products Inc. Quarter Bridge (2&quot;)</td>
<td>350 Ohm Weldable</td>
</tr>
<tr>
<td></td>
<td>Live Load Strain</td>
<td>Hitec Products Inc. Quarter Bridge (4&quot;)</td>
<td>350 Ohm Weldable</td>
</tr>
<tr>
<td></td>
<td>Environmental Strain</td>
<td>Geokon VSM 4000 Strain Gage (6&quot;)</td>
<td>Vibrating Wire Sensor</td>
</tr>
<tr>
<td></td>
<td>Environmental Strain</td>
<td>Geokon VSM 4050 Strain Gage (12&quot;)</td>
<td>Vibrating Wire Sensor</td>
</tr>
<tr>
<td></td>
<td>Tilt</td>
<td>Geokon 6350 Tiltmeter</td>
<td>Vibrating Wire Sensor</td>
</tr>
<tr>
<td></td>
<td>Displacement</td>
<td>Geokon 4420 Crackmeter</td>
<td>Vibrating Wire Sensor</td>
</tr>
<tr>
<td></td>
<td>Acceleration</td>
<td>PCB 3701 Accelerometer</td>
<td>Capacitive Sensor</td>
</tr>
<tr>
<td></td>
<td>Acceleration</td>
<td>PCB 393C Accelerometer</td>
<td>Piezoelectric Sensor</td>
</tr>
<tr>
<td></td>
<td>Fiber Optic Strain</td>
<td>FOX-TEC Fiber Optic System</td>
<td>Bragg-Grating</td>
</tr>
</tbody>
</table>
Commodore Barry Bridge Instrumentation Map

<table>
<thead>
<tr>
<th>PHENOMENA</th>
<th>MEASURAND</th>
<th>SENSOR</th>
<th>QTY</th>
<th>LOCATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic</td>
<td>Image</td>
<td>Video Camera</td>
<td>4</td>
<td>D, E, J</td>
</tr>
<tr>
<td></td>
<td>Speed &amp; Weight</td>
<td>WIM System</td>
<td>2 Lanes</td>
<td>K</td>
</tr>
<tr>
<td>Weather</td>
<td>Air Temperature</td>
<td>Weather Station</td>
<td>1</td>
<td>G</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar Radiation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind Speed &amp; Dir.</td>
<td>Ultrasonic Wind</td>
<td>4</td>
<td>E, G</td>
</tr>
<tr>
<td>Bridge</td>
<td>Live Load Strains</td>
<td>Q.B. Strain Gage</td>
<td>56</td>
<td>C, D, E, F</td>
</tr>
<tr>
<td>Responses</td>
<td>Environ. Strains</td>
<td>V.W. Strain Gage</td>
<td>148</td>
<td>A, B, C, D, E, F, J</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>Thermistor</td>
<td>201</td>
<td>A, B, C, D, E, F, G, J</td>
</tr>
<tr>
<td></td>
<td>Displacements</td>
<td>V.W. Crackmeter</td>
<td>17</td>
<td>A, B, D, F, J</td>
</tr>
<tr>
<td></td>
<td>Tilts</td>
<td>V.W. Tiltmeter</td>
<td>36</td>
<td>A, B, C, D, F, G, J</td>
</tr>
<tr>
<td></td>
<td>Accelerations</td>
<td>Cap. Accelerometer</td>
<td>16</td>
<td>B, D, F, H</td>
</tr>
</tbody>
</table>
Commodore Barry Bridge Instrumentation LAN

- Campbell CR10X
- Optim MEGADAC
- Handar 555C
- Sony EVI
- Weigh-In-Motion
- Fiber LAN
- Internet (T1)
- Short Haul Modem
- Direct Copper

Bridge Module (LabVIEW)
Data Server Module (LabVIEW)
Administration Building

Administration Building

822' 1644' 822'

~1.25 Miles
DATA

Frequency-Time
- Real time (100Hz)
- Proxy Data (Observation/Year)

Space
- Geographical area (Satellite)
- Local data (Fatigue crack)

Content-Modality
- Image (Streaming video)
- Point Strain
Data Quality Assurance, Processing & Archival

Collection System
Field Collection
  Quality of sensing design
  Measurement system calibrations
  Installation quality
  Synchron. and formatting
  Intelligent data acquisition:
    Continuous, Programmed,
    Triggered and Manual Modes

Elementary Data Checks
  Time-range validity
  Sensor-range validity
  Repeated readings
  Sampling frequency
  Data smoothness
  Other

Online-Real Time Presentation
  Visual verification
  Real-time I/O correlation
  Logical consistency

Data Transfer
  Headers
  Handshake
  Receipts

Data Processing
  Time-series analysis
  Frequency analysis
  (Hilbert Transform)
  Visualization tools

Data Archival
  Synch. and formatting
  Structure and integrity
  Data change tracking
  Backup and safety
  Authorization protocols

Information Design
  Graphical presentation
  Heuristic interpretation
  Multivariate correlations
  Anomaly and damage
  Index evaluations
  Fuzzy and ANN models

Legacy Data Access
  Design
  Construction
  Operation
  Inspection
  Maintenance
  Interpretations

Authorized Access / Firewall
Online via Internet
Internet Front Page for Real-Time Monitor Data
Secondary Internet Page for Real-Time Monitor Data
Multi-Hazards Risk Management in Metropolitan Regions

• Risk = Hazard * Vulnerability * Exposure

• Identification of Systems and Exposure:
  – Human/Engineered Assets at Risk, Organizational and Response Systems, Operational and Natural Systems

• Hazard/Threat Assessment: Manmade and natural

• Vulnerabilities: Organizational interdependencies, physical/operational interconnectedness, cascading incidents, freezing and breakdown of communications and response capability

• Partnerships, effective communications, effective resource management, capitalizing on technology for real-time health and security monitoring/management
### Performance Expected From Critical Infrastructure Systems

<table>
<thead>
<tr>
<th>Utility, Serviceability and Durability</th>
<th>Safety and Stability of Failure</th>
<th>Safety at Conditional Limit States</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Daily-to-Frequent Events With 25-75 Year Return:</strong></td>
<td><strong>Occasional Events With 250-500 Year Return:</strong></td>
<td><strong>Rare Events With 2,500-5,000 Year Return:</strong></td>
</tr>
<tr>
<td><strong>NORMAL OPERATION, MOMENTARY DISRUPTION OF FUNCTION</strong></td>
<td>SHORT-TERM DISRUPTION, LIFE SAFETY and QUICK RECOVERY</td>
<td>MONTHS OF DISRUPTION EXPECTED, MINIMIZE CASUALTIES</td>
</tr>
<tr>
<td><strong>Routine Maintenance</strong></td>
<td>Recovery, Repairs and Rebuilding Maybe Needed</td>
<td>Major Damage to Infrastructures, Longer-Term Recovery</td>
</tr>
</tbody>
</table>
Managing Risks Based On Return and Consequence

Probability: High
Return: Daily
Frequent

Probability: Very Low
Return: Rare
Occasional

Traffic Incident

Catastrophe
DRPA of PA and NJ Risk Management Study

- Inventory of DRPA’s infrastructure
- Inventory/analysis of organization and risk management measures that are in place
- Operational analysis of systems
- Analysis of threats and hazards
- Analysis of vulnerabilities
- Analysis of consequences and risk
- Risk mitigation alternatives benefit/cost analysis
- Recommendations for security measures
ArcPad 6 Now Includes Customization

Creating Safer Communities and a Better World
GIS and Homeland Security

Managing Chaos Relies on Fast, Accurate Information

New York City - Creating a Disaster Management GIS on the Fly
IIMS For Coordinating Incident Responses
Developed For NYC Agencies

Active Incident List – Displays the list of all active IIMS incidents. Each row displays key data for the respective incident.

Incident Data – Displays detailed data for the selected incident.

Map – Displays a map of the immediate area for the selected incident.

Picture – Displays a picture of the selected incident.
The Port Authority lost all of its critical offices and response capability when the towers went down.

Cellular phones went down because many of them worked off an antenna on top of the towers.

The F.B.I. Including its Joint Terrorist Task Force Office, C.I.A. and Secret Service had to evacuate their offices, lost files, e-information and phone service.

The NYC Police Department and FEMA lost their phone service.

Phone service was lost because underground cables routed through a Verizon building at 140 West Street and several switch facilities were damaged.

NYFD Radio communications failed.

Power to the subway south of Canal Street was lost.
"Fifth Avenue has a hole in it," said Joel A. Miele. Commissioner of the Department of Environmental Protection. "It's an enormous hole. And before we can fill it in, any of the infrastructure, the sewers, the water, the gas connections, the electrical connections that are in the street now that have been disturbed by the asphalt collapsing on top of them and taking them down with it, all will have to be rebuilt. So it will have to be a gradual job."
Metro Infrastructure Systems and Multi-Hazards Risk Management

- DRPA-Sandia NL-Drexel Partnership with additional academic and industry expertise
- DRPA systems is a microcosm of metro-US
- Develop a sound and systemic methodology for assessing and managing hazards risk
- Explore technology for optimal mitigation
- Design and implement security systems
- Scale-up to Delaware Valley Metro Area