Wireless Structural Health Monitoring and the Civil Infrastructure Systems: Current State and Future Applications

Anne Kiremidjian
Professor
Department of Civil and Environmental Engineering
Stanford University
Stanford, California

MEMSCON
October 7, 2010
Bucharest, Rumania

Objectives

- Present the current state of wireless structural health monitoring
- Outline challenges
- Present future directions

Outline

- Motivation
- Wireless Monitoring System Design
- Example application
- Current barriers
- Conclusion
- Future Directions

Outline

- Motivation
- Wireless Monitoring System Design
- Example application
- Current barriers = future opportunities
- Conclusion

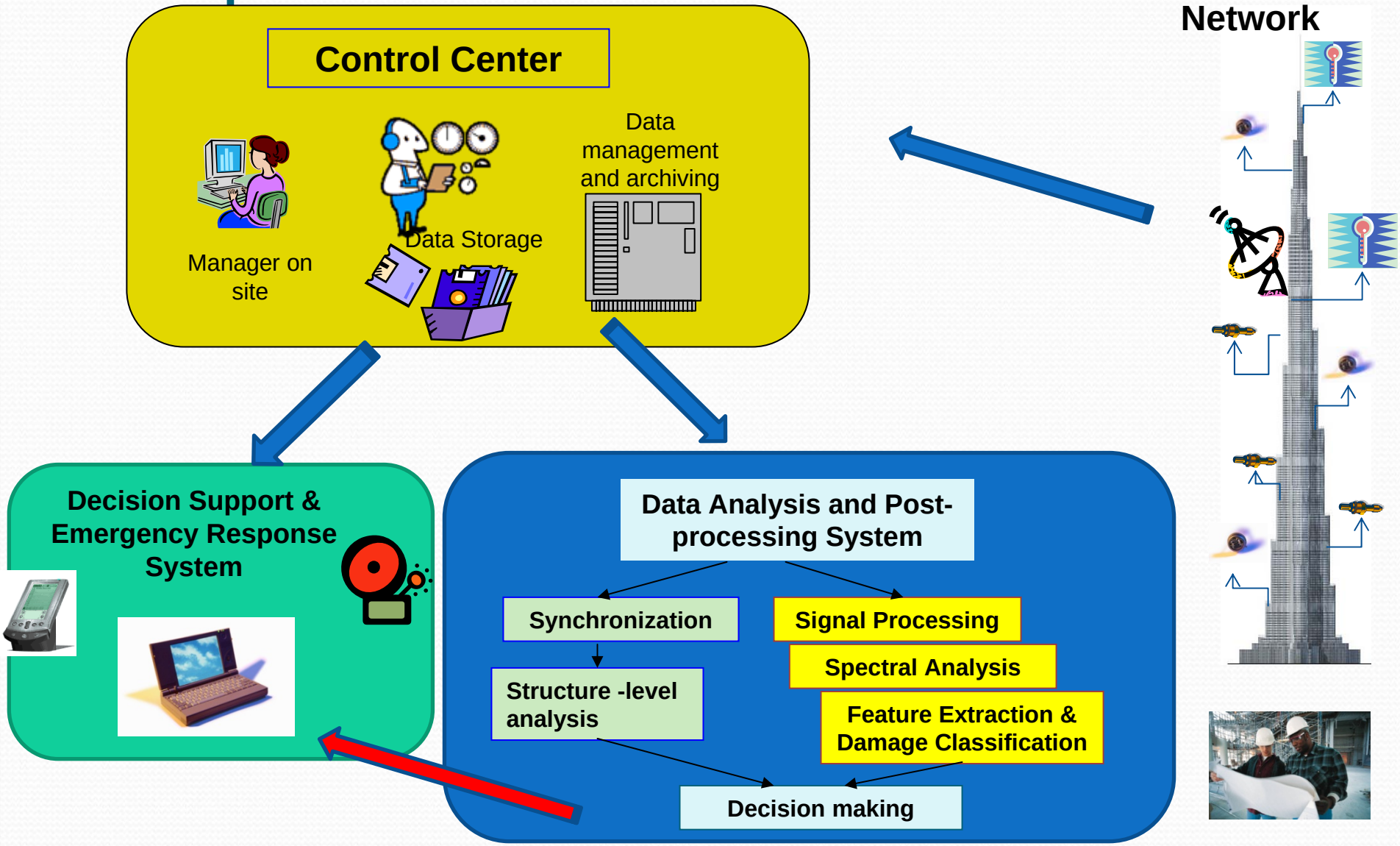
Motivation - Why wireless?

- Advances in electronics –
  - sensors,
  - wireless radios – range, bandwidth, reliability
  - power harvesting to extend life
- Low-Cost solution
  - No wires
  - No installation of wires
  - Cheaper sensors
  - Small form factor
- Flexible network architecture – reconfigurable system
- Flexible computational platform – options for computing
  - Local – sensor level – embedded and updatable
  - Centralized

Outline

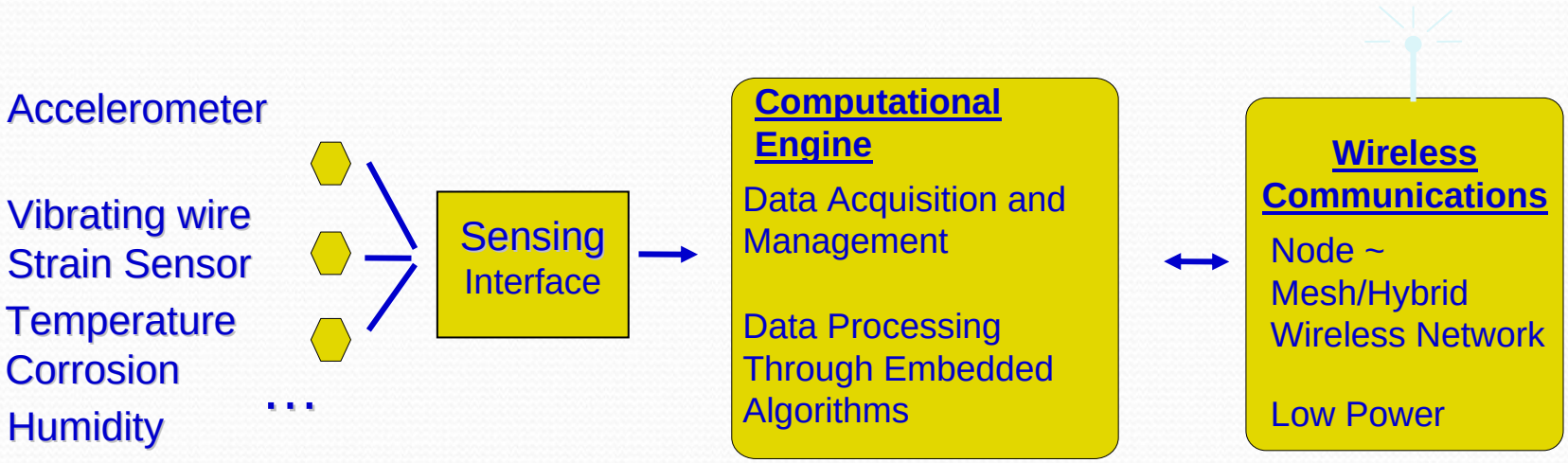
- Motivation
- Wireless Monitoring System Design
  - Overall System Design
  - Hardware Features
  - Software Features
- Example application
- Current barriers = future opportunities
- Conclusion

Wireless Structural System Components



Sensing Unit Design

Sensing Unit Design



- Multiple sensors
  - Acceleration –
    - Strong motion – 3D
    - Ambient vibrations -3D
  - Strain
  - Temperature
  - Humidity
  -

- Data stored on board on SD card
- Multi-sensor data collection
- Data converted into damage assessments and alerts
- Wireless transmission of processed information
- Low power – long-duration autonomous operation
- Small size and low cost

Sensing Unit Design - Chronology

- Five Generations of Sensing Unit Design
  - 1996 – Straser, Kiremidjian and Meng
    - Single 2D accelerometer, wireless modem, single supervisory microprocessor
    - proof of concept with field test of 5 units
  - 2000 – Lynch, Law and Kiremidjian
    - Single 2D accelerometer, wireless modem, dual microprocessor, smaller form, lower power consumption
    - Verification with laboratory test followed by subsequent field tests
  - 2002 – Mastroleon and Kiremidjian – multiple sensors
  - 2006 – Wang and Law – multiple sensors, increased wireless transmission range, data streaming with embedded compression algorithms
  - 2007 – current unit

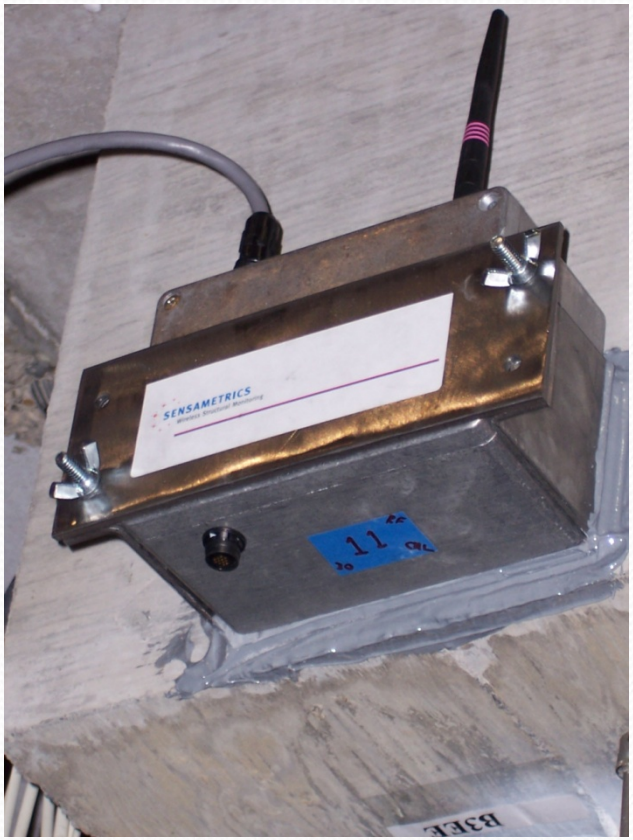
Sensing Unit Design

- Features of 5th Generation Design
  - Sensors
    - Dual accelerometer – 24 bit A/D converter
      - 3D strong motion – +2/10g, 200Hz sampling rate
      - 3D ambient vibration – 10^{-4}g, 200Hz sampling rate,
    - Strain gages with three resistances
    - Temperature sensor
    - Humidity sensor
  - Dual microprocessor
    - Supervisory
    - Computational
  - 802.15.4 radio module – Zig-Bee compliant for wireless sensing
  - Local storage – mini SD card

Sensing units

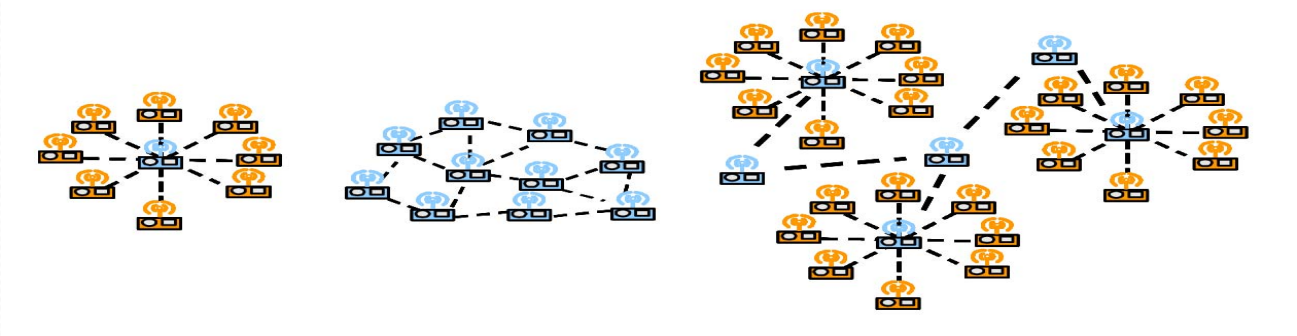
- Internal view

- Mounted unit

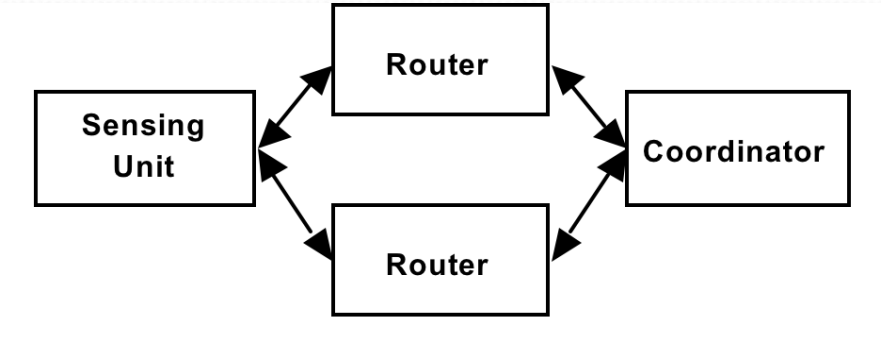


Wireless Communications Network

- Star, mesh and hybrid topologies for wireless communications networks



- Fundamental Building blocks

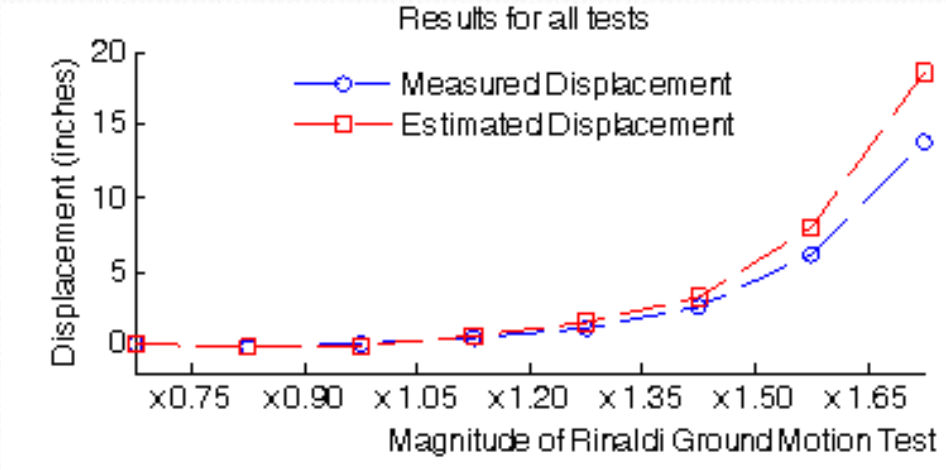


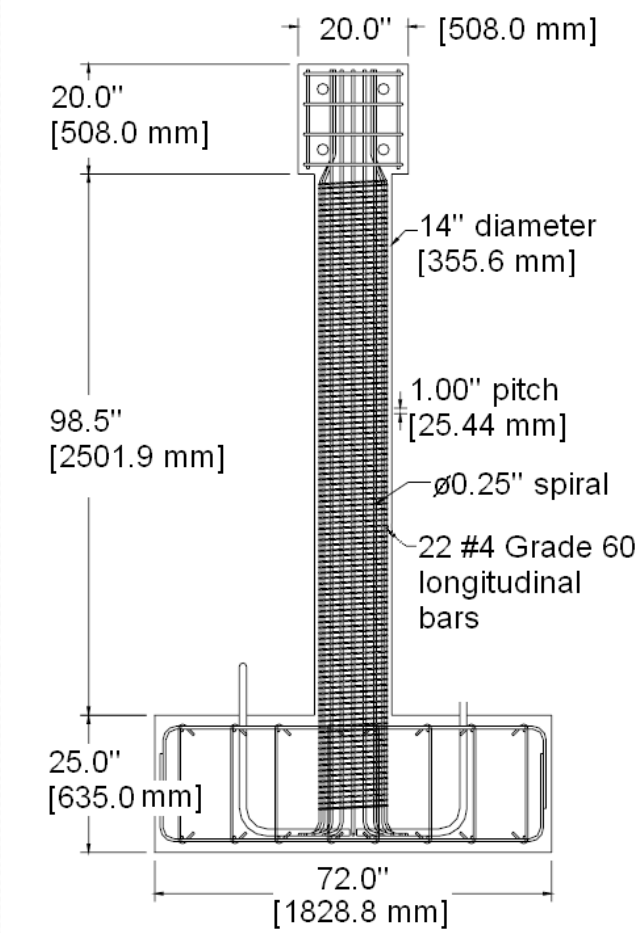
Damage Detection Algorithms

- **Main approach**
  - Use statistical pattern classification and signal processing methods
  - Use single sensor pre- and post- damage measurements
  - Computationally efficient - local micro-processing
  - Independent of the sensor – can be used with acceleration, strain, etc.
  - Scalable with increased sensor density
  - Reduces amount of transmitted data – power saving

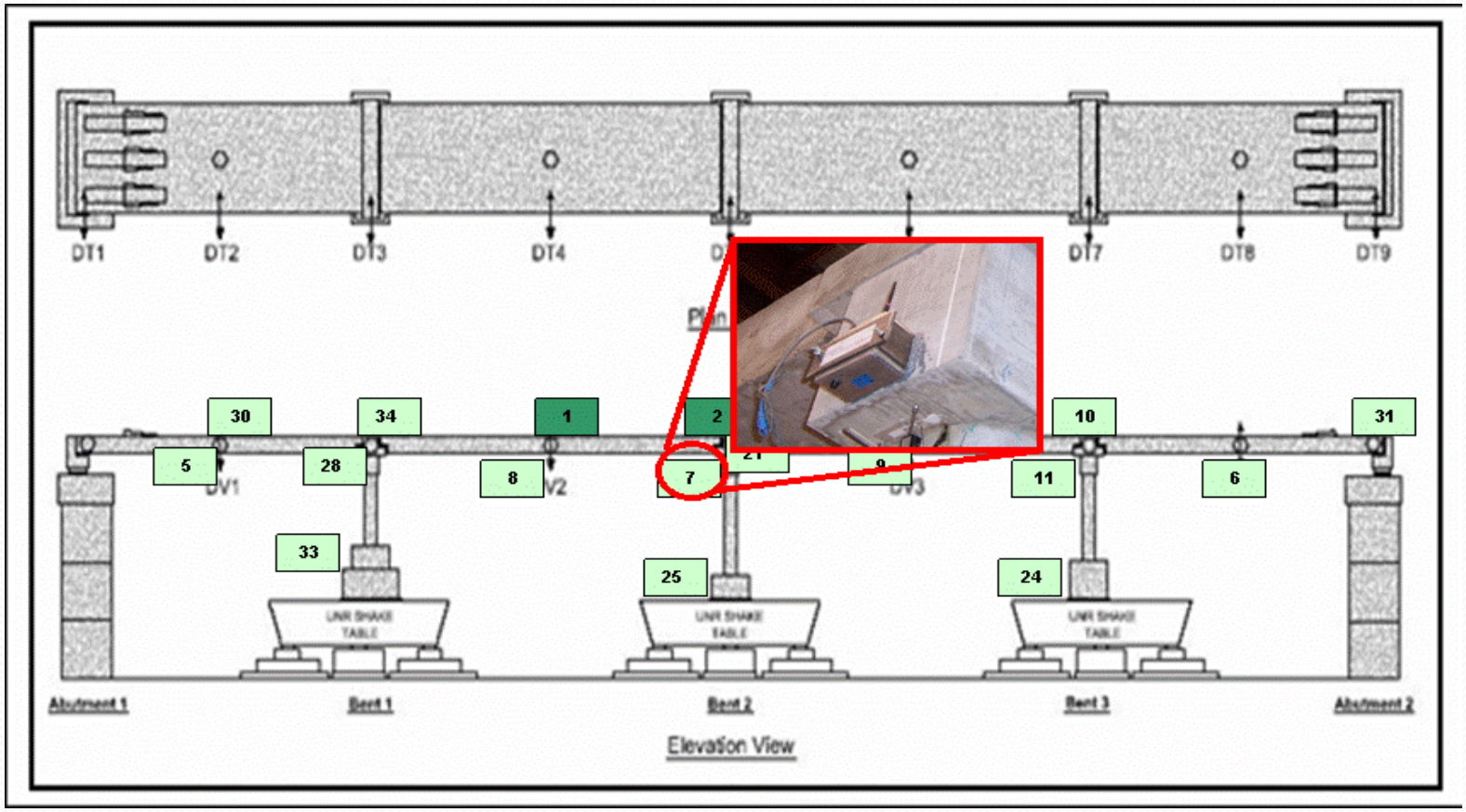
NEES Multi-Scale Approach

- Single column tests –UNR and UC-Berkeley
- Development of rotation algorithm for wireless sensors (Allen Cheung, Stanford, 2008)
- Direct earthquake damage identification

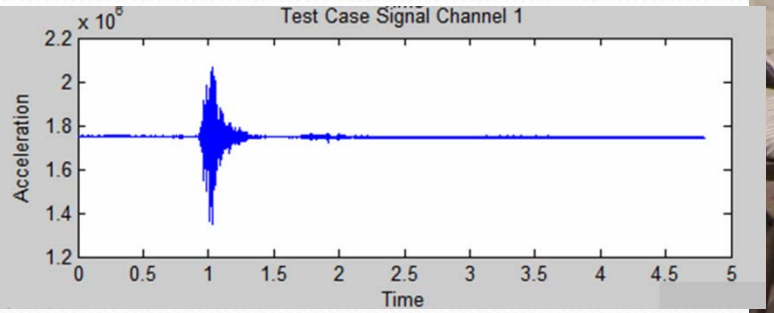


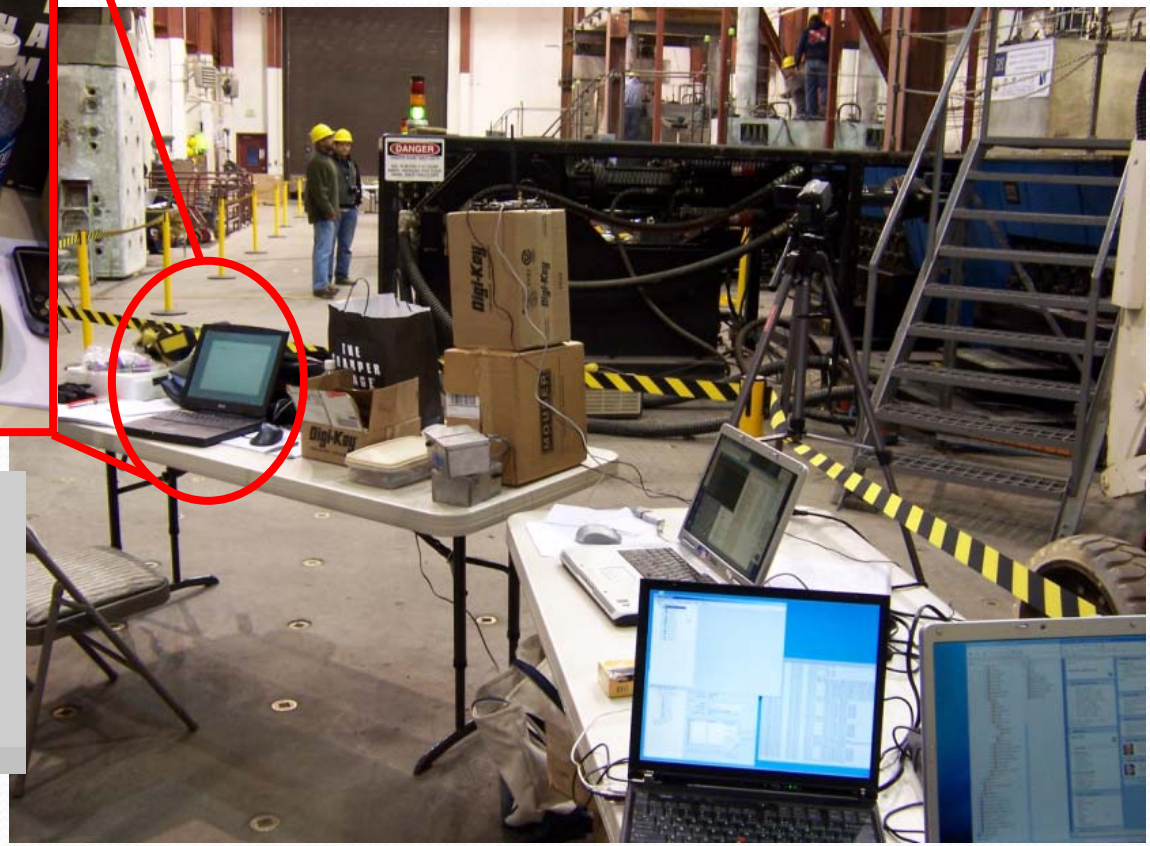


Layout of Test Bridge and Instrumentation



Decision Support System- Monitorin Mode





Test Schedule – 4-span Bridge Test at UNR

Complete test schedule for shake table tests

Test No.	Test Date	Motion Level	Test Type	Motion PGA (g)		Estimated D_{max} (in)						Notes
						Pier 1		Pier 2		Pier 3		
				Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	
WN01	Feb. 12, 2007		White Noise (Trans.)									
WN02			White Noise (Long.)									
1A		1	W/Restrainer1	-	0.09							
1B		1	W/Restrainer2	-	0.09							
1C		1	Longitudinal	-	0.09							
1D		1	Biaxial	0.075	0.09	0.40	0.40	0.30	0.40	0.24	0.40	
WN11			White Noise (Trans.)									
WN12			White Noise (Long.)									
2		2	Biaxial	0.15	0.18	0.70	1.00	0.60	0.95	0.60	1.00	
WN21	Feb. 13, 2007		White Noise (Trans.)									
WN22			White Noise (Long.)									
3		3	Biaxial	0.25	0.30	0.80	1.40	0.80	1.60	0.90	1.60	
WN31			White Noise (Trans.)									
WN32			White Noise (Long.)									
4A		4	W/Restrainer1		0.60							
4B		4	W/Restrainer2	-	0.60							
4C		4	Longitudinal	-	0.60							
4D		4	Biaxial	0.50	0.60	1.60	2.65	1.50	2.60	1.50	2.70	
WN41	Feb. 15, 2007		White Noise (Trans.)									
WN42			White Noise (Long.)									
5		5	Biaxial	0.75	0.90	2.50	3.40	2.55	3.40	2.80	3.40	
WN51			White Noise (Trans.)									
WN52			White Noise (Long.)									
6		6	Biaxial	1.00	1.20	3.60	4.20	3.60	4.20	3.85	4.30	
WN61			White Noise (Trans.)									
WN62			White Noise (Long.)									
7		7	Biaxial	1.33	1.60	5.00	5.70	4.90	5.70	6.00	5.75	

Baseline Signals

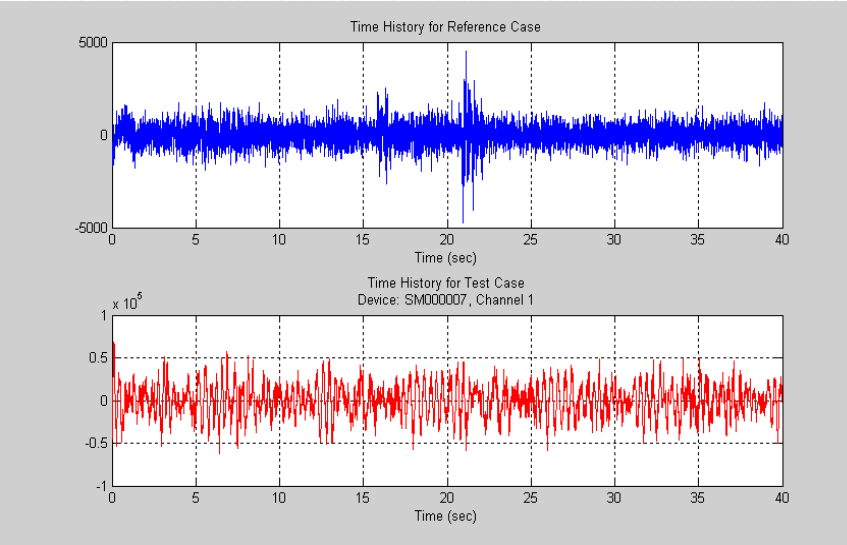
Minor cracks at base of column

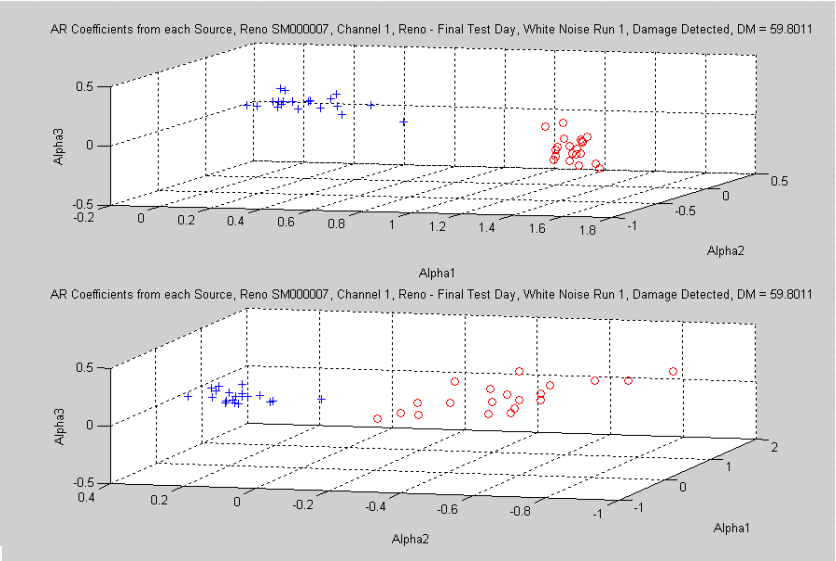
Major cracks at base of col. & spalling

Concrete spalling and exposure or rebar

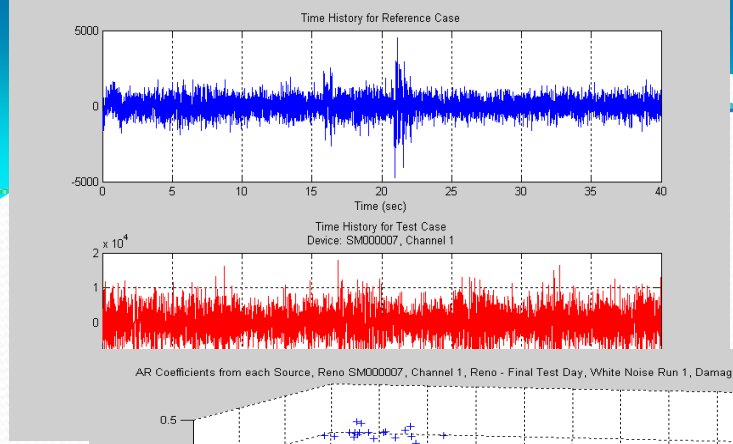
Rebar buckling/ breaking; concrete pouring out of core

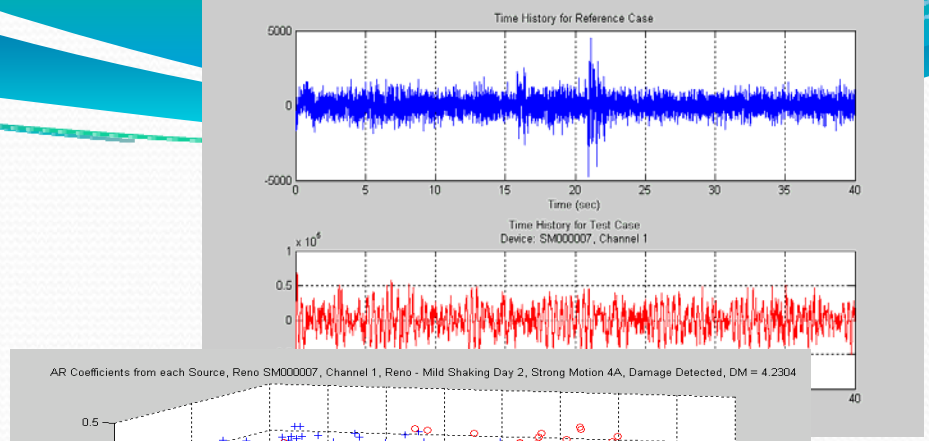
Final Test – White Noise

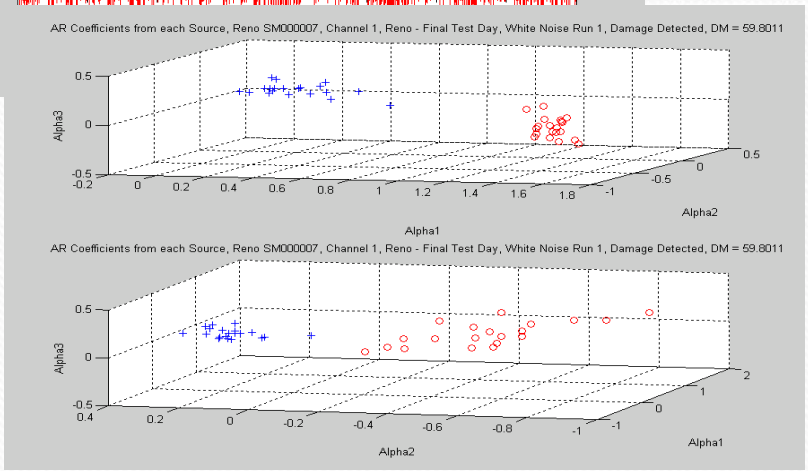


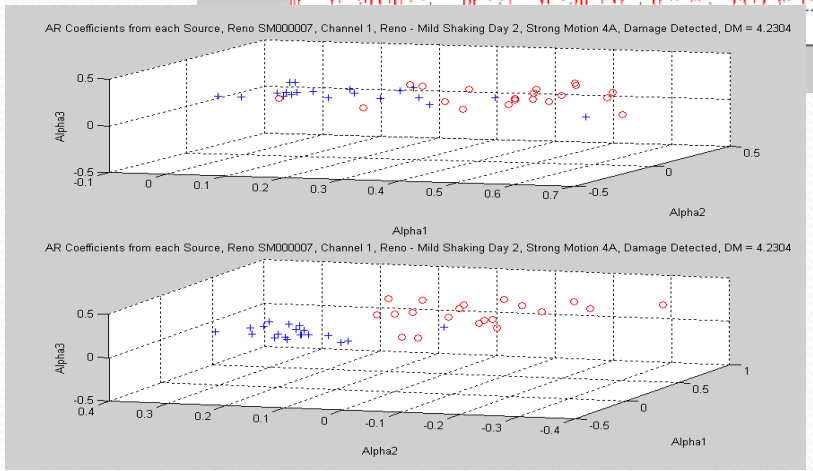


Test	Damage Measure
Reno - Setup Day DC1 and DC2	baseline
Mild Shaking Day 1, White Noise	21.05
Mild Shaking Day 2, White Noise 21	36.79
Mild Shaking Day 3, White Noise 41	56.97
Final Test Day, White Noise Run 51	**59.80**



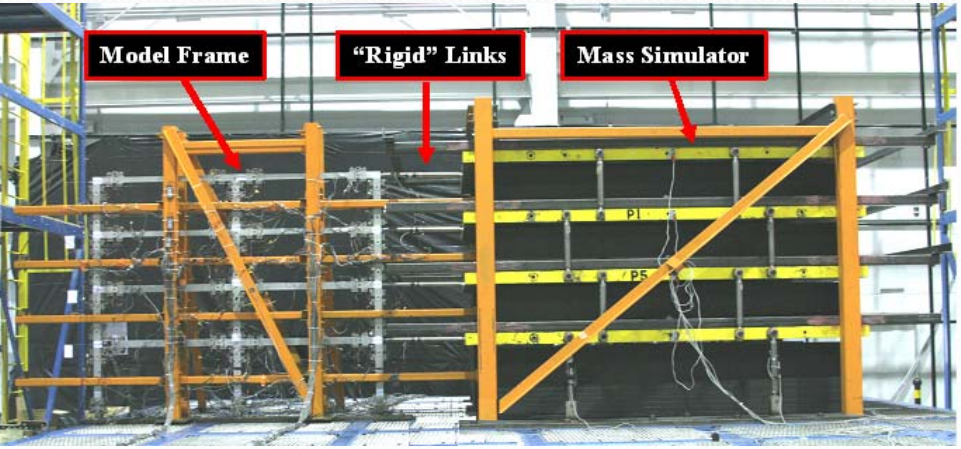


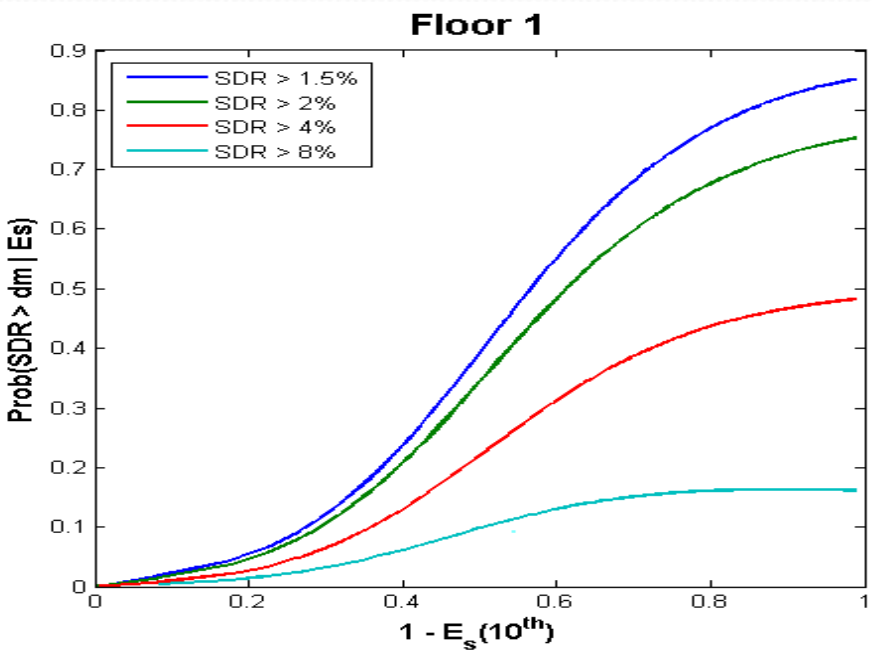




Test	Damage Measure
Reno - Setup Day DC1 and DC2	baseline
Mild Shaking Day 1, White Noise	21.05
Mild Shaking Day 2, White Noise 21	36.79
Mild Shaking Day 3, White Noise 41	56.97
Final Test Day, White Noise Run 51	59.80

NEES Multi-Scale Approach





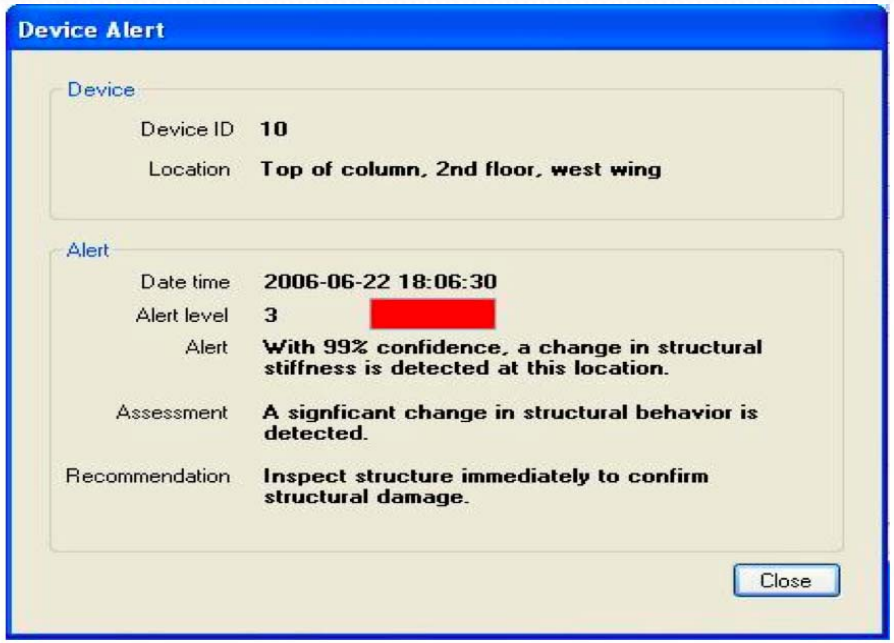
- Scaled structural system tests – Stanford/SUNY Buffalo
- Development of fragility functions in terms of structural response parameters obtainable from real time measurements – wavelet based fragilities (Hae Young Noh and Dimitrios Lignos, Stanford, 2009)

Decision Support System

- Visual representation of the structure
- Visual representation locations of the wireless system
- Interface to wireless network
- System command and control center
- Display results of monitoring analyses
- Issue alerts

Decision Support System

- Provide support for decision making for follow-on actions
- Enable web services for
  - wide distribution of alerts and other information
  - remote access by operators and other users.



Outline

- Motivation
- Wireless Monitoring System Design
- Example application
- Current barriers
- Conclusion

Current Barriers

- Sensors for specific types of damage - e.g.
  - Corrosion
  - Crack
  - Displacement
- Scalable and robust wireless network system
  - Signal loss
  - Communication barriers
  - Sensor durability and continued operation
- Robust and reliable damage diagnosis and prognosis algorithms
- Reliability of long term power supply

Current Barriers (cont'd)

- Limited demonstrations
  - Laboratory
  - Field ***
- No standards or guidelines for development and manufacturing sensing units, sensor networks, etc.
- Existing legacy sensor companies unwilling to invest in new developments
- Unwillingness of profession to take the risk (or invest in proofs of concept)

Outline

- Motivation
- Wireless Monitoring System Design
- Example application
- Current barriers
- Conclusion
- Future directions

Conclusion

- Wireless monitoring systems – inevitable part of the future
- Significant applications throughout Asia, very limited elsewhere
- Must combine structural with other monitoring systems, e.g.
  - Building environmental/energy/lighting/security monitoring
  - Bridge, highway, tunnel, pipeline, transmission line, etc. management systems
- Key to success is providing information and not just data

Outline

- Motivation
- Wireless Monitoring System Design
- Example application
- Current barriers
- Conclusion
- Future directions

Future directions

- Instrument key structures and demonstrate utility of such systems
- Have a multi-scale approach – provide different systems – one system does not fit all applications
  - Just an alarm
  - Complete damage diagnosis and decision support for future actions
  - Systems that combine diagnosis, prognosis and repair actions

Future directions

- Develop the means for providing information to designers/builders at various stages of construction/use for future design purposes
- Systems should have different levels of interface sophistication
  - Technical user/decision maker
  - Management level decision maker with limited technical expertise
  - Common citizen