Frameworks for structural reliability assessment and risk management incorporating structural health monitoring data

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SHM in broader context

Broad context: SHM Information in Asset Management Decision Making

Value of SHM Information

SHM
Sensing & Data Processing
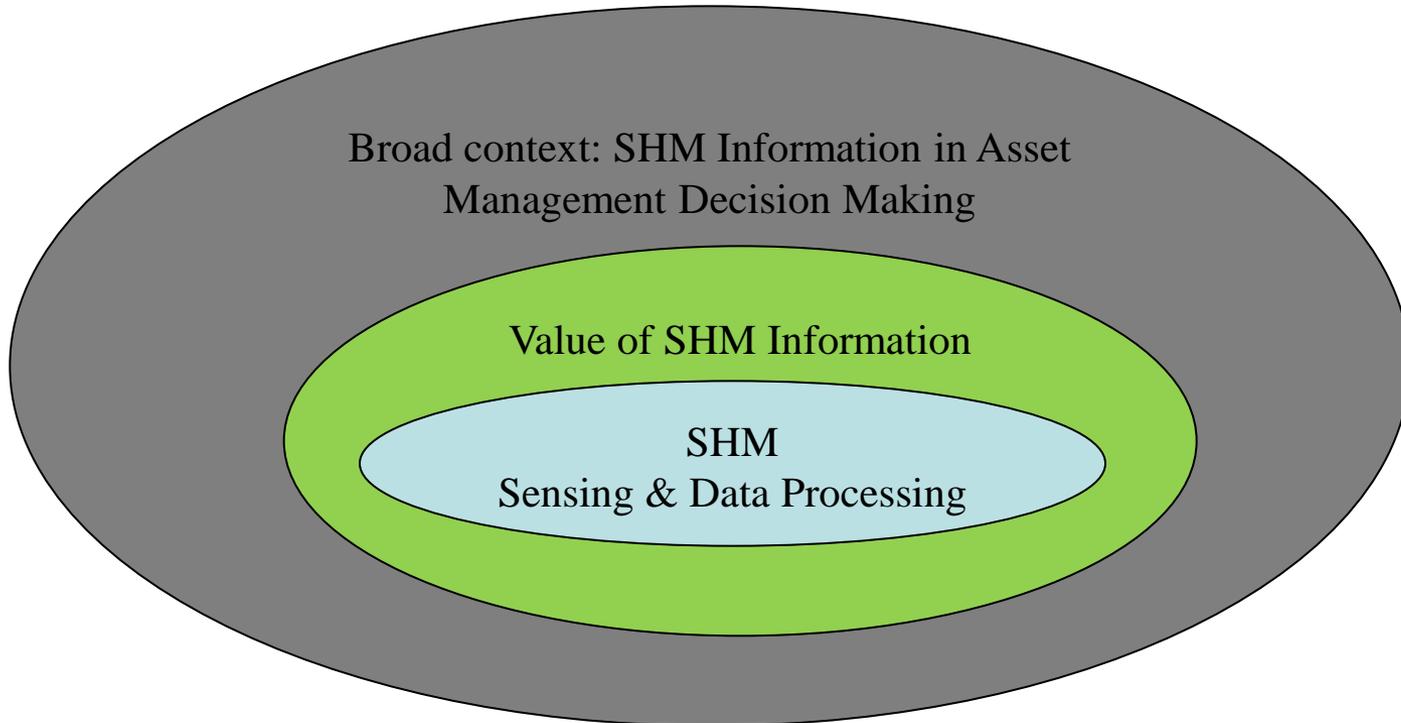
SHM = tracking *in-situ* structural performance or health by *measuring data* and *interpreting them* using application-specific knowledge so that *structural performance, condition and reliability can be quantified objectively* (Aktan et al 2002)

SHM in broader context

Sensors/algorithms > Structural systems >
> Infrastructure stock > Decision making 2

Areas where SHM can make a difference

- New structures, innovative designs, construction techniques, or materials

- Structures/assets with poorly understood risks (geological, seismic, meteorological, environment, operations, construction, and quality risks)

- New or existing structures which are representative of a larger population of similar structures (information can be extrapolated to the wider population)

- New or existing structures that are critical at a system/network level (failure or deficiency would have a serious impact on the system/network functioning)

- Existing structures with known deficiencies, problems and/or very low rating to extend their life

- Candidates for replacement or refurbishment (real need for interventions can be assessed and repair efficiency evaluated)
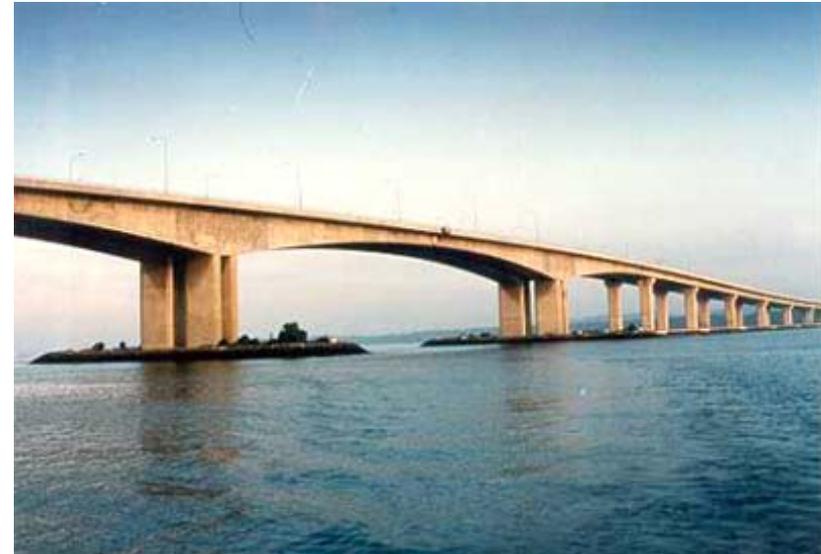
Impacts of SHM

- Reducing uncertainty about structural condition and performance

- Discovering hidden structural reserves

- Discovering deficiencies that may be missed by traditional assessment techniques

- Increasing safety and reliability

- Ensuring long term quality of aging infrastructure

- Allowing better informed asset management

- Increasing knowledge about in-situ structural performance

Challenges

The snake-oil effect in civil SHM
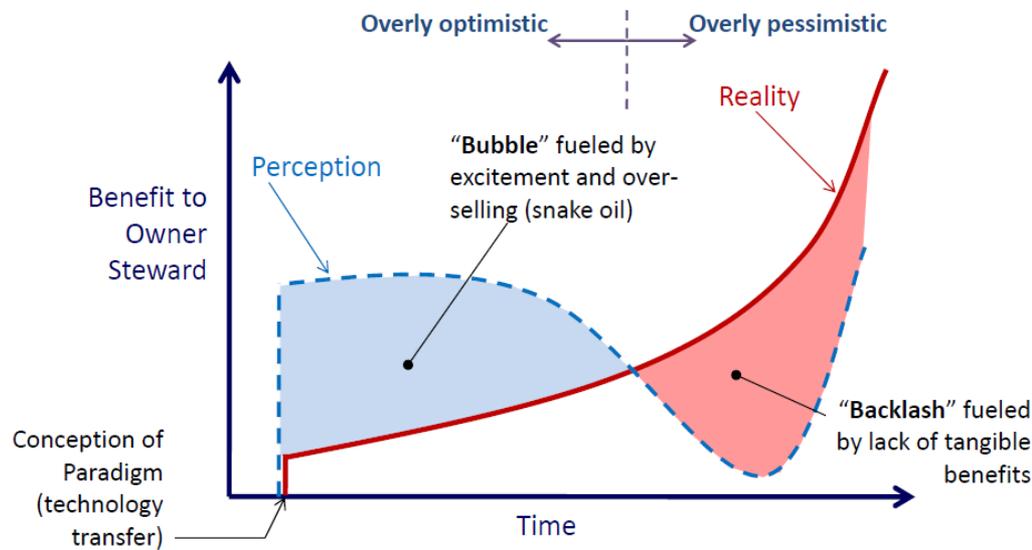
By courtesy of Franklin Moon, Drexel University

- Need for realistic assessment of SHM capabilities (**value of SHM**) and strategic, planned deployment that is closely integrated into asset management/emergency response process

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Presentation outline:

- Introduction (done)

- Framework I: Integrating SHM into asset management/emergency response decision making and prioritisation of structures for SHM use

- Framework II: SHM in a value chain of technologies

- 'Big data' perspective on SHM

- Example of monitoring of a major bridge

('Bridge flavoured' yet general discussions)

**Framework I:
Strategies for integration of
SHM into asset
management/emergency
response and prioritisation of
structures for SHM
deployment**

Building blocks for integration of SHM into wider data collection and asset management/emergency response

- Prioritisation of bridges for application of SHM based on bridge importance in the network and a broad spectrum of risks affecting the bridge that need to be treated with an interdisciplinary approach.
- Guidelines for instrumentation to be installed on bridge structures and in their vicinity (e.g. surrounding soil or watercourse), or even monitoring entire transportation networks and hydrological systems, for measuring operational/environmental effects, loads/demands and responses:
  - Cost-effective hardware platforms
  - Relatively simple measurements which can help in assessment
  - Need to better quantify statistically the methods' performance, e.g. minimum damage size detectability
- Methodologies for reliable condition, damage and performance assessment based on information extracted from SHM data for structure, foundation and soil.
- Integration of SHM-assisted assessment results into the asset management and, where necessary, emergency planning and response practices of organisations responsible for functionality of transportation networks.

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Risk and criticality based data collection strategy for vast asset (bridge) stock

- Data is critical for asset management to assess goal achievement and plan maintenance and investment
- Principles of strategy:
  - Prioritise bridges for data collection based on risk and criticality
  - Direct limited resources more towards bridges that need them most
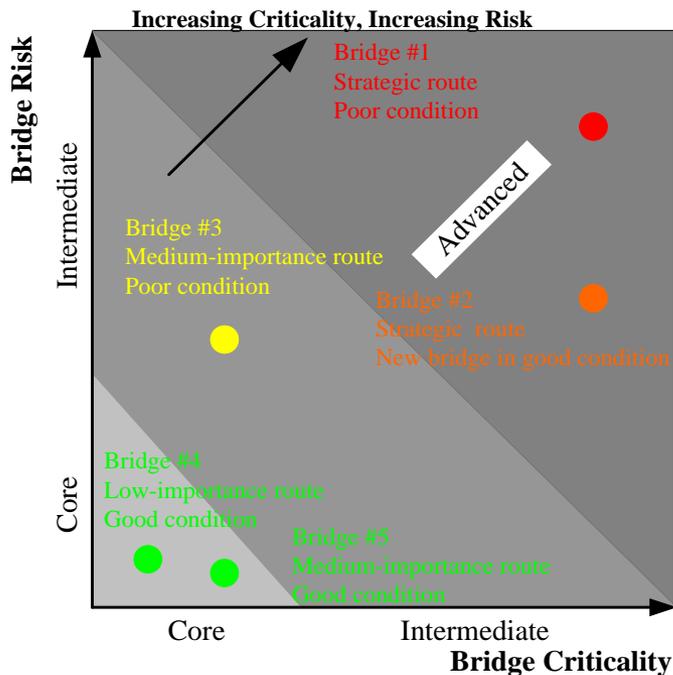
Data collection regime	Bridge criticality /risk	Data collection tools / frequency
Core	Low	Visual inspections/up to every 6 yrs Limited SHM
Intermediate	Intermediate	Visual inspections/ every 2-3 yrs Some SHM
Advanced	High	Visual inspections/ frequent, as needed Advanced SHM

Frameworks II:
SHM in a value chain of technologies

SHM and reliability assessment in a value chain (Wong&Yao 2001)
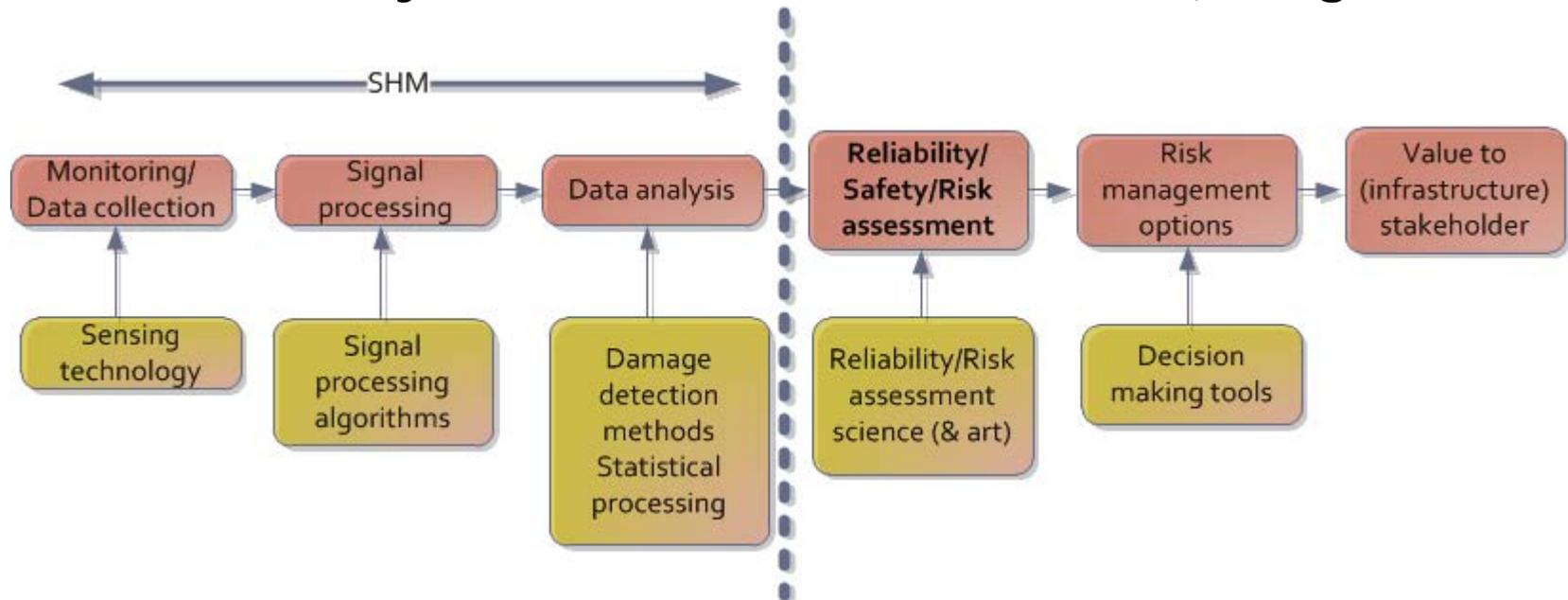
- SHM is a part of **value chain**: end-to-end solution to a problem of delivering value to (infrastructure) stakeholders:
  - o Delivering **safe, reliable and efficient infrastructure at minimum cost**
  - o **Enabling technologies** (e.g. SHM, reliability/safety/risk assessment tools)
- So far only **tenuous link (or gap?)** between SHM and reliability/safety/risk assessment
- Need for a **clear, strong link** to be developed and **value of SHM** to stakeholders clearly articulated
- **Condition for widespread adoption** of SHM to technological/societal challenges

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'Big data' perspective on SHM

What makes SHM data 'big data'

- Even modest monitoring systems generate data that are a challenge to handle/interrogate for traditional techniques.

- 'Big data':
  - Extraordinary **volume**,
  - Extraordinary **velocity**,
  - Extraordinary **variety** and/or
  - Extraordinary **veracity**.

Volume/velocity:

- Large bridges ~10^3 sensing channels
- Knobbe et al. (2011): 145 sensors sampling at 100Hz produce ~56 kB/sec, 5GB/day, 1.7 TB pa; video camera produces 46kB/s
- Transfer, storage, timely and efficient interrogation puts pressure on resources, capabilities and analytical techniques
- How much data to collect and how much local vs. centralised data processing to conduct?
- Use of 'indicator structures' (but structural systems are unique)

Accelerometers (58)
Temperature Sensors (388)
Dynamic Strain Gauges (678)
Static Strain Gauges (158)
Global Positioning Systems (20)
Displacement Transducers (34)
Bearing Sensors (12)
Barometers/Rainfall Gauges/Hygrometers (28)
Corrosion Cells (33)
Digital Cameras (18)
Weigh-in-Motion Stations (4)
Total No. of Sensors : 1505
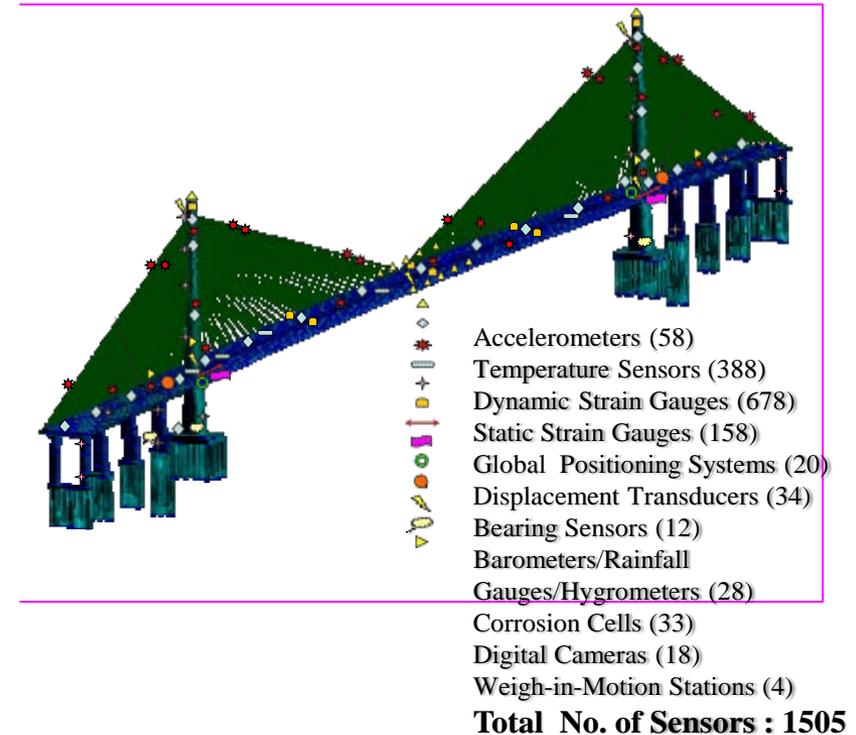
Stonecutters Bridge (Ni & Wong 2012)

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What makes SHM data 'big data'

- <u>Variety/veracity</u>:
  - Comprehensive SHM system will have a large number of various sensors
  - Data sampled at different intervals
  - Different actions and demands and responses
  - Different accuracy
  - Diverse technologies (legacy SHM systems installed during construction and new upgraded sensing platforms)
  - Missing/intermittent data
  - Dubious accuracy (sensors misaligned, poorly fixed or malfunctioning)
  - Latent factors (e.g. temperature or response magnitude) can influence measurands
  - SHM is only one source of data and information; visual inspections, to remain the main source of knowledge; results of tests on material samples are another
  - Data stored as drawings or descriptive and qualitative reports.
  - Necessary to merge/fuse diverse data sets and formats
  - Data analytics/statistical techniques/machine learning must be integrated with human skills for insight into the meaning of data.

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'Digital twin'

- SHM data interpretation is immensely assisted by creating physics based numerical models of the system.

- Concept of **'digital twin'** can be realised thanks to abundance of data.

- Digital twin integrates high fidelity multi-physics and multi-scale models/simulations (e.g. finite or boundary element models), with SHM data, maintenance history and all available historical data to mirror the life of its physical twin.

- Future digital twins can be much more realistic than contemporary models (e.g. include information on individual defects and loading and distress histories unveiled in extensive SHM data).

- Digital twin can continuously forecast and update information on health, condition, reliability and remaining life of physical system.

- New and enhanced levels of safety and reliability without overdesigning infrastructure.

SHM of the Newmarket Viaduct

The bridge

- Located in Auckland, NZ

- <u>Old structure</u> built in the 60s
- Twin parallel bridges
- Largest vehicle counts in NZ
- Suffered from thermal stresses cracking and insufficient live load capacity

- <u>New structure</u> opened in 2010/11
- Pre-cast, posttensioned, balanced cantilever construction
- 468 precast box-girder segments
- Two parallel bridges joined by a concrete stich
- 12 spans, total length ~700m, ~60m average span length

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Time dependent reliability of Newmarket Viaduct

Pdf of creep coefficient

Posterior

Prior
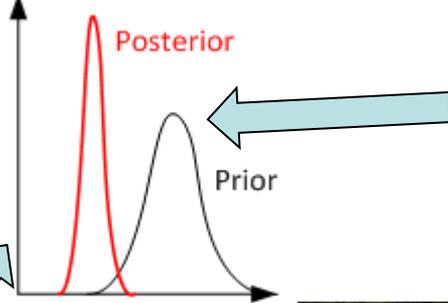
Long-term monitoring (90 channels of strain/deflection/temperature/environment):
- Calibration (updating) of FEM model (time dependent)
- Models for gravity & 'slow' load effects (time dependent pdf)
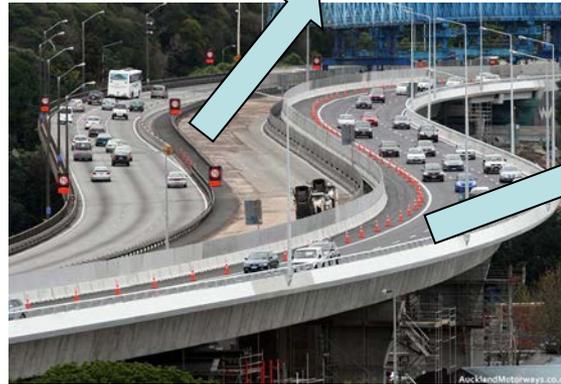
Dynamic monitoring & one-off tests:
- Calibration (updating) of FEM model (time dependent)
- Models for live loads and their effects (time dependent pdf)

Lab tests:
- Concrete strength
- Young's modulus
- Creep & shrinkage

Outcomes:
- Calibrated (time dependent) structural models for reliability simulations
- Probabilistic models of actual responses, loads and their effects
- Enhanced, more realistic reliability analysis

PDF of demand

PDF of capacity

overlapping area ~P(F)

without SHM

PDF demand

PDF capacity

overlapping area ~P(F)

with SHM

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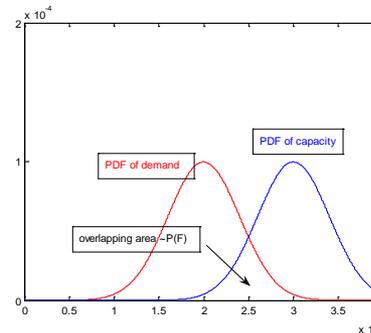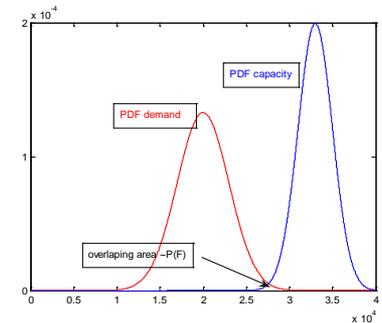
One-off ambient dynamic testing exercises
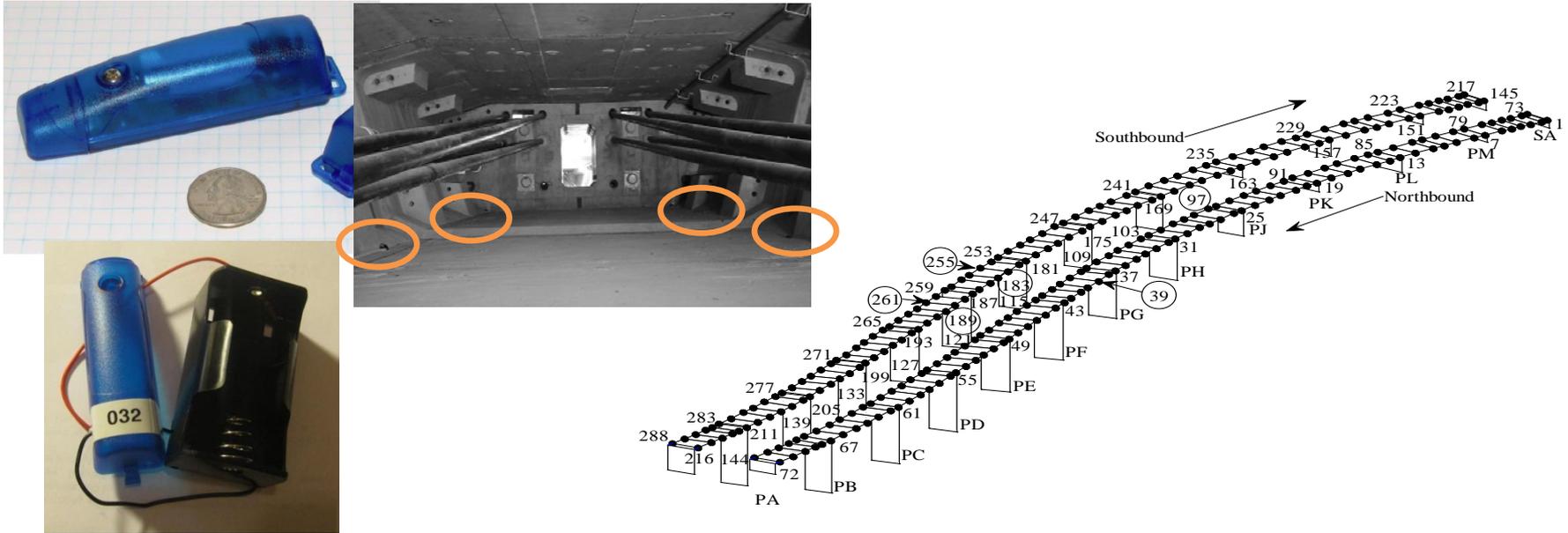
- Two testing campaigns, each lasting <=2 days, under vehicular traffic:
  - Nov 2011: Only Southbound Bridge (Northbound bridge under construction, not connected)
  - Nov 2012: S-bound & N-bound Bridge (connected via cast in-situ stitch)
- 'Wireless' MEMS sensors with data storage capacity (microSD card) powered by internal/AA/D battery
- 56 roving 3-axial accelerometers, 6 setups, 288 measurement points
- Spacing span/6, both sides of girder for 3D mode shape mapping (vertical/torsional/horizontal)
- Sampling rate 160Hz, 1 hour long records for each setup

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Modal identification and comparison with numerical results

9 transverse, 14 vertical and 12 torsional modes below 8 Hz

Mode	Natural frequencies [Hz]			Damping ratios [%]	MAC with EFDD	
	EFDD	SSI	Numerical	SSI	SSI	Numerical
Transverse modes						
T1	1.25	1.25	1.30	1.3	0.98	0.96
T2	1.56	1.55	1.60	1.5	0.92	0.83
T3	2.15	2.17	2.14	1.4	0.89	0.75
T4	2.81	2.80	2.95	1.3	0.98	0.62
T5	3.94	3.91	3.87	1.1	0.98	0.69
Vertical modes						
V1	2.03	2.04	2.10	1.4	1.00	0.96
V2	2.15	2.15	2.19	1.4	0.95	0.97
V3	2.34	2.35	2.40	1.4	1.00	0.88
V4	2.55	2.55	2.61	1.5	0.96	0.85
V5	2.82	2.82	2.85	1.5	0.92	0.91
Torsional modes						
Tor1	3.17	3.14	3.16	1.5	0.90	0.86
Tor2	3.20	3.20	3.22	1.5	1.00	0.83
Tor3	3.34	3.33	3.37	1.5	0.84	0.90
Tor4	3.55	3.52	3.54	2.5	0.94	0.87
Tor5	3.71	3.74	3.69	1.6	0.88	0.69

Summary and Conclusions

- SHM needs and will benefit from a clear link to reliability assessment of structures and overall asset management/emergency response decision making process to articulate and assess objectively its value.

- Two frameworks to underpin such integration were discussed:
  - Framework I prioritizes structures for monitoring, calls for unified guidelines for instrumentation and SHM data analysis, and ends with the integration of SHM results into asset management and disaster emergency plans and decisions.
  - Framework II understands SHM as a starting point in a value chain of enabling technologies delivering information to infrastructure stakeholders.

- 'Big data' presents emerging and important challenges and opportunities for SHM (e.g. creating digital twins).

- A major bridge has been instrumented for long-term continuous collection of strains, displacements, temperatures, accelerations, and environmental data in view of quantifying its loads, responses and creating models to assess and forecast its reliability.

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Acknowledgements

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