The University Of Sheffield.

Department of Civil & Structural Engineering.

VIBRATION ENGINEERING SECTION

# Full-scale civil infra-structure performance: University of Sheffield experiences 2008-11

(sub text: Structural health monitoring)


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# Vibration Engineering Section:



## Relevant portfolio of grants and experiences

- Novel data mining and performance diagnosis systems for structural health monitoring of suspension bridges. EPSRC ~£0.5M
- IRIS: Integrated European Industrial Risk Reduction System. EU/FP7 ~0.25M
- Dynamic performance of large civil engineering structures: an integrated approach to management, design & assessment. EPSRC Platform, ~0.8M
- ~£2.5M other grants now or soon: active control, fellowship, pedestrian loads due to synchronisation (with Birmingham psychologists)

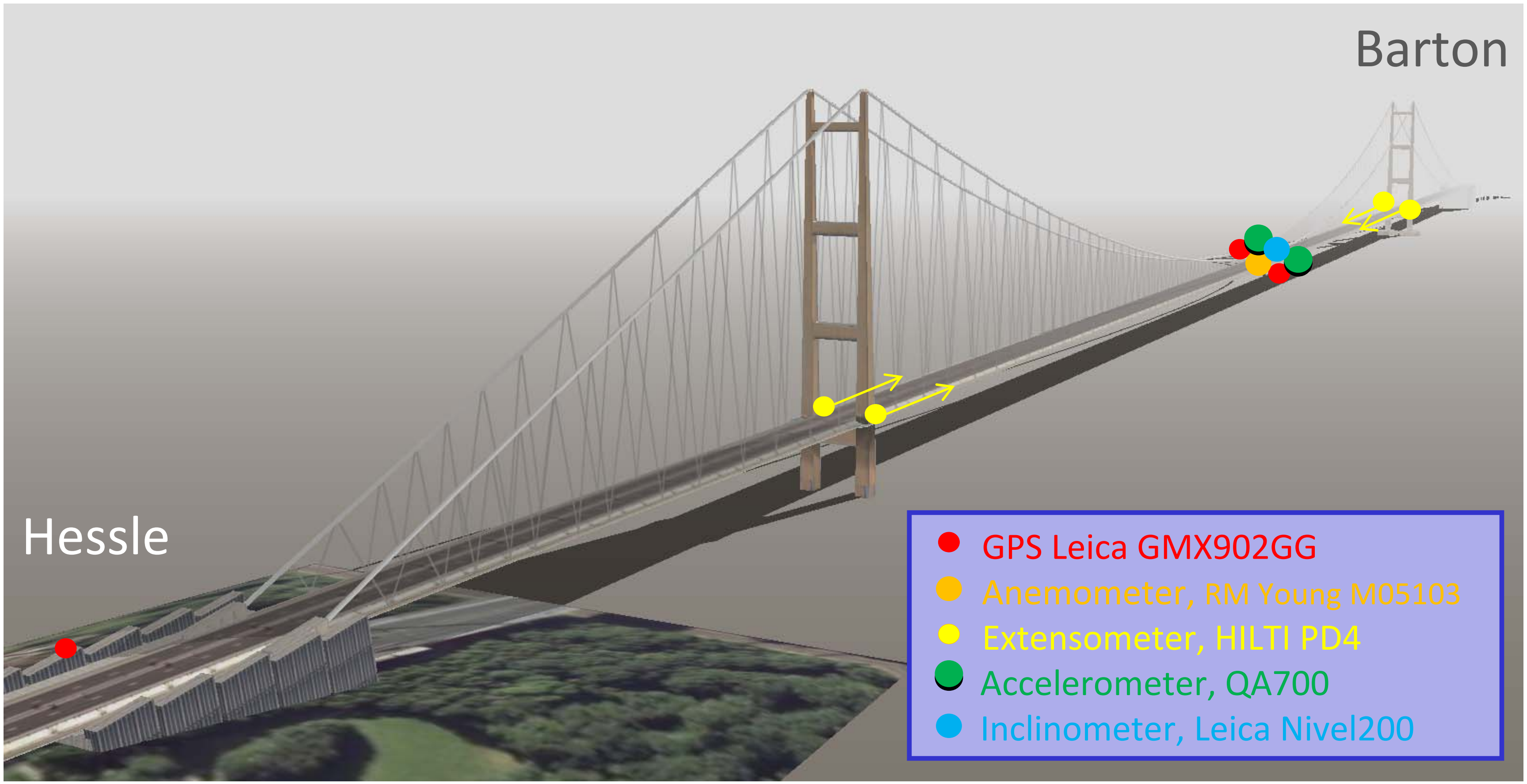
200+ dynamic investigations of highway bridges, footbridges, dams, high and low rise buildings, floors, chimneys etc. etc., + dozen structures monitored.

Commercial applications now managed by:

FULL SCALE DYNAMICS LTD
REAL WORLD CONDITIONS
REAL WORLD SOLUTIONS

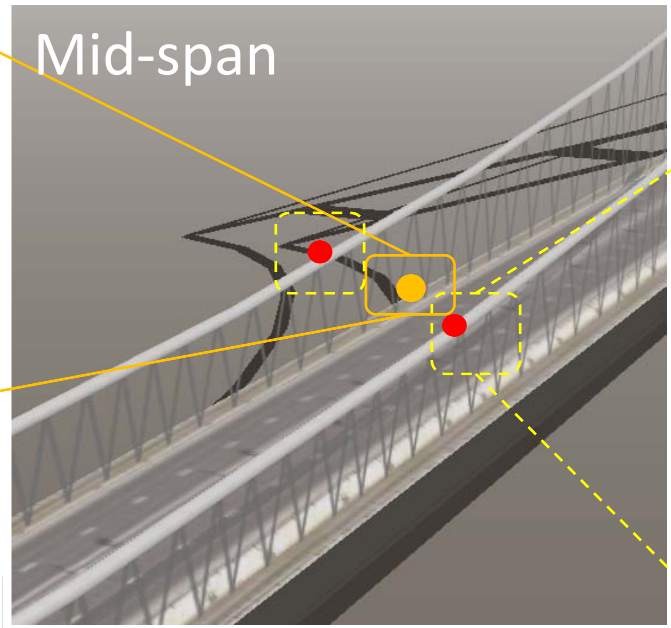
- Experience 1: Humber Bridge
- Experience 2: Tamar Bridge
- Experience 3: Rugeley Chimney
- Experience 5: International Bridge

# Experience 1: Humber Bridge
## Structural Health Monitoring System
## (optimised sparse array)

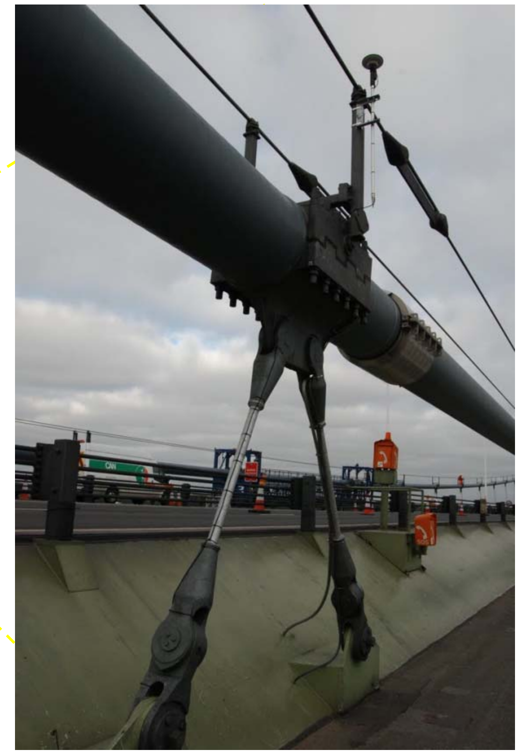


# GPS & Wind monitoring System

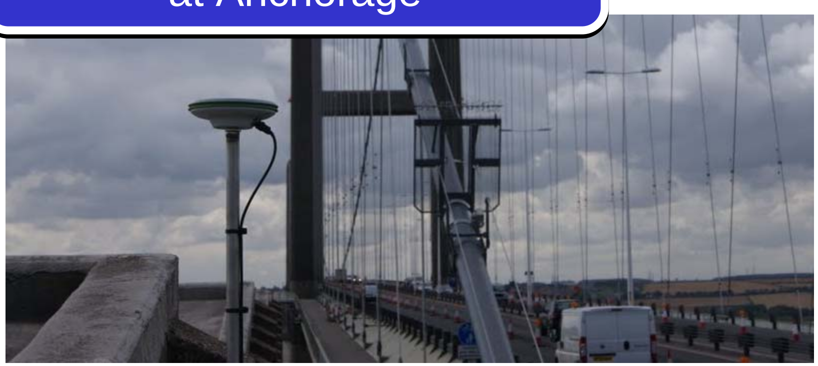
Anemometer




Monitoring GPS antenna

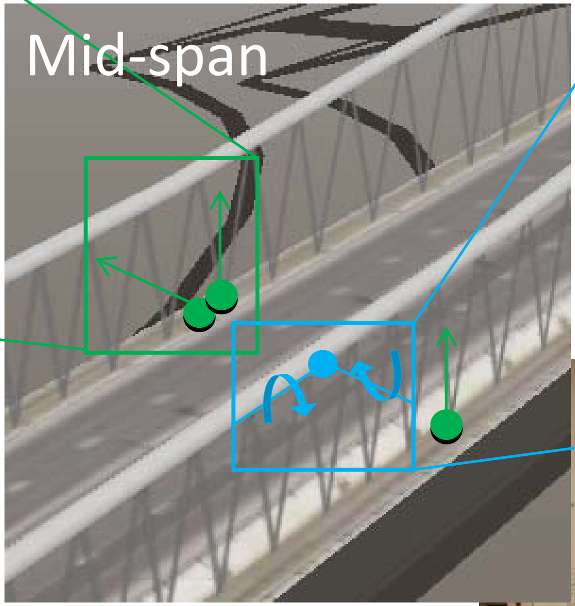


Reference GPS Antenna at Anchorage



# Accelerometers & Inclinometer

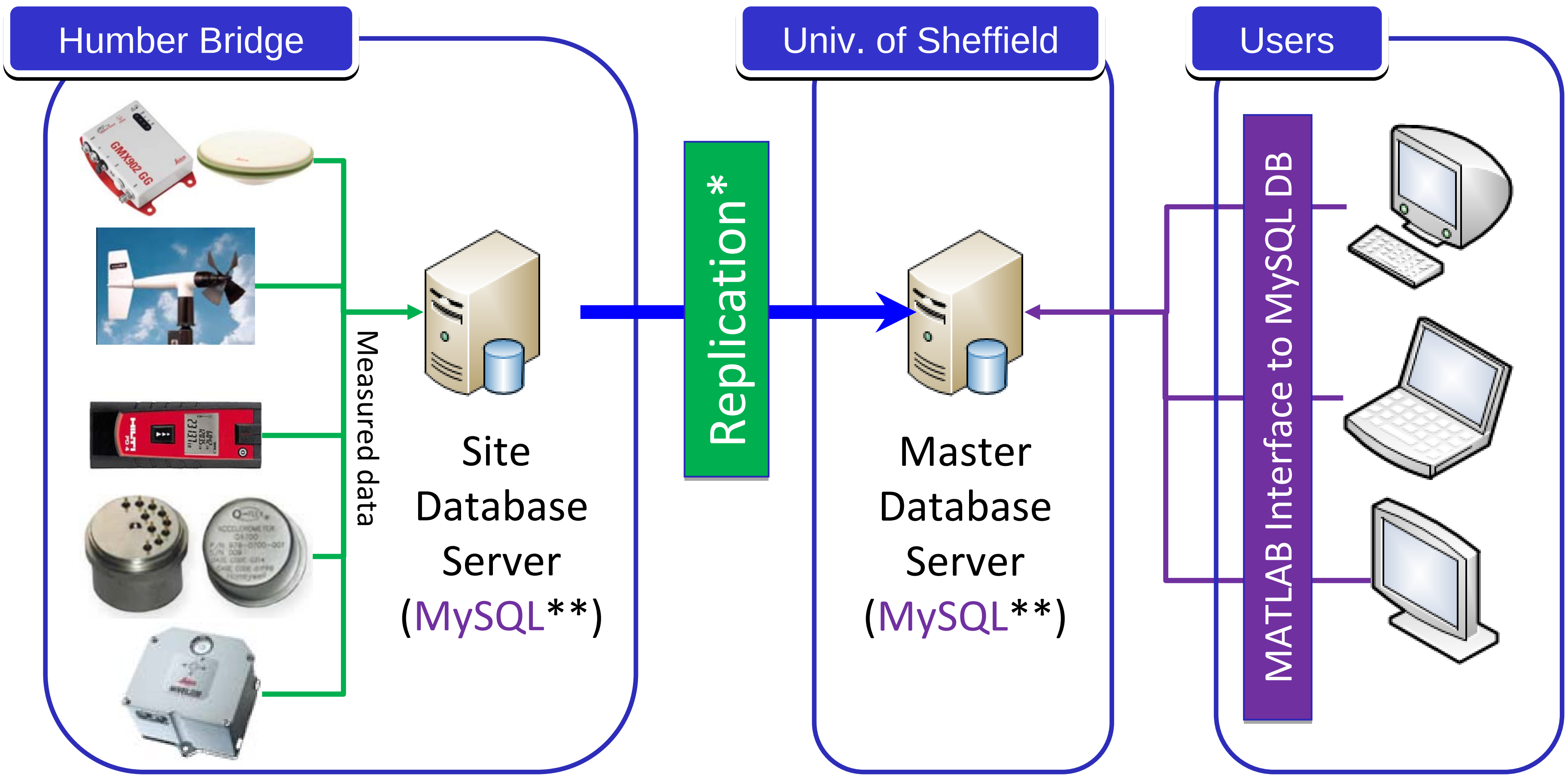
Honeywell QA700 Accelerometers




Leica Nivel220

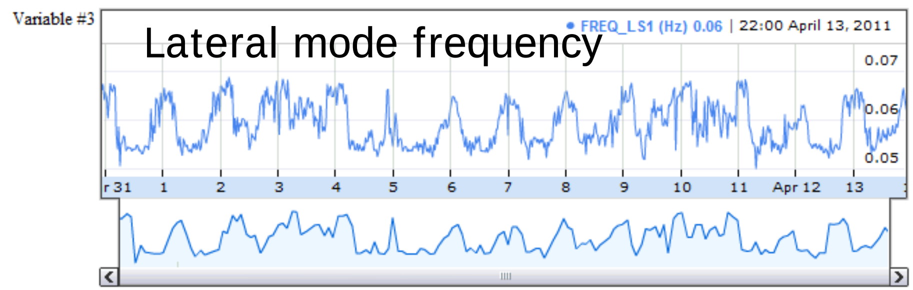

Equipment enclosure

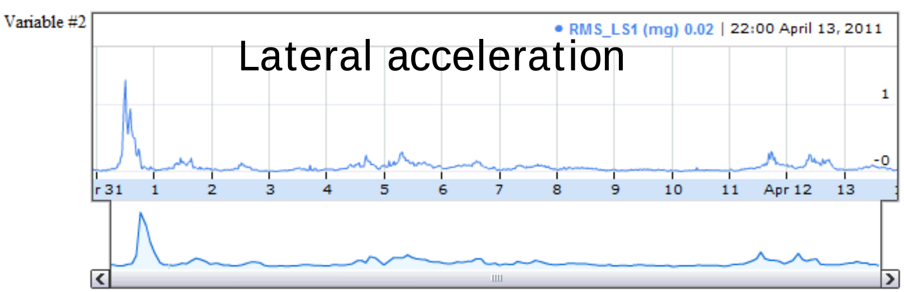
# SHM Data management SQL database accessible via MATLAB and Google Apps: powerful data interpretation

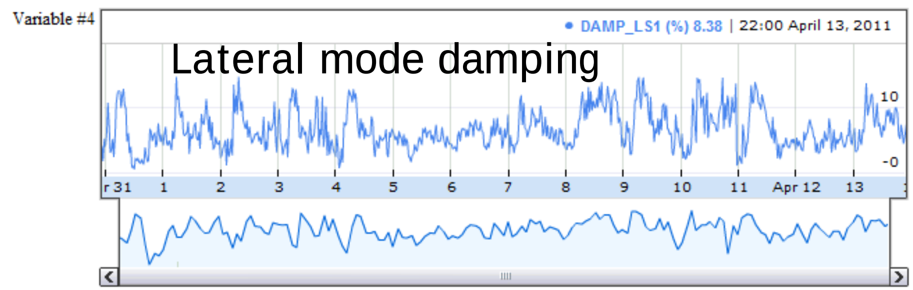


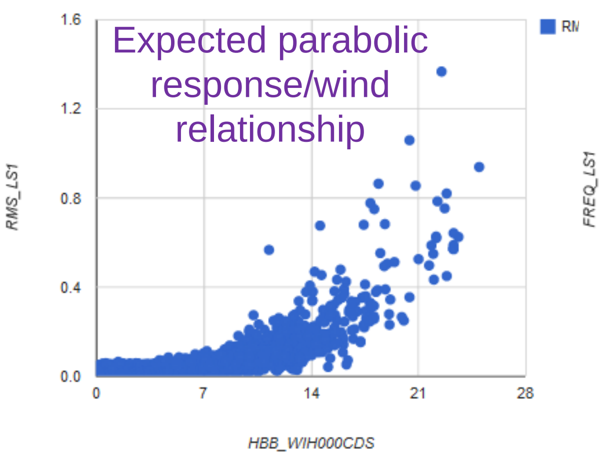

***Replication**: Robust process of data synchronization even when network link is unstable
** MySQL: a database management system free for non-enterprise uses, owned by Oracle

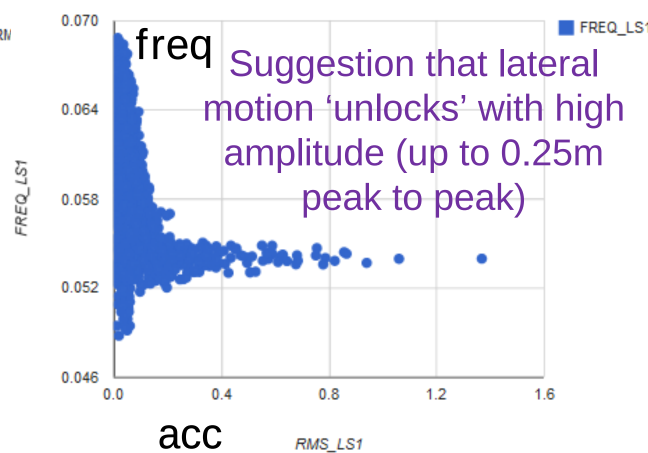
# Internet viewer shows effect of wind on response levels & modal properties for first lateral mode (2011)

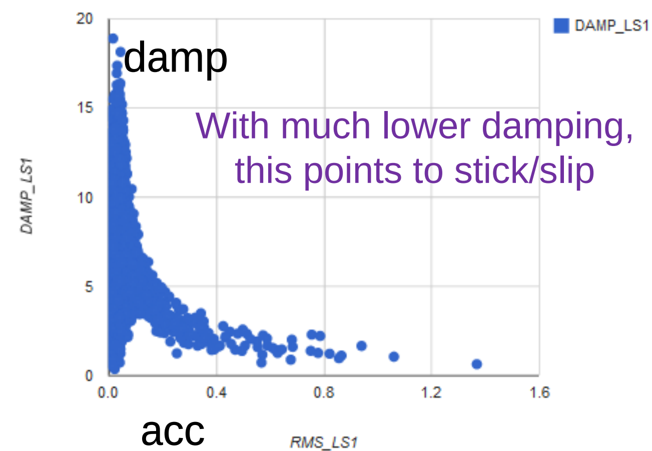



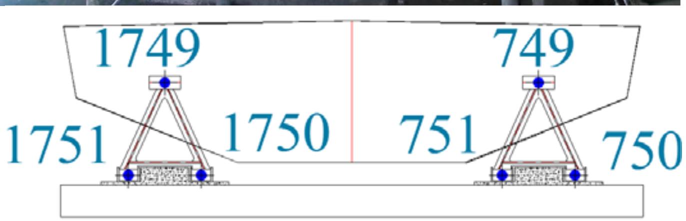



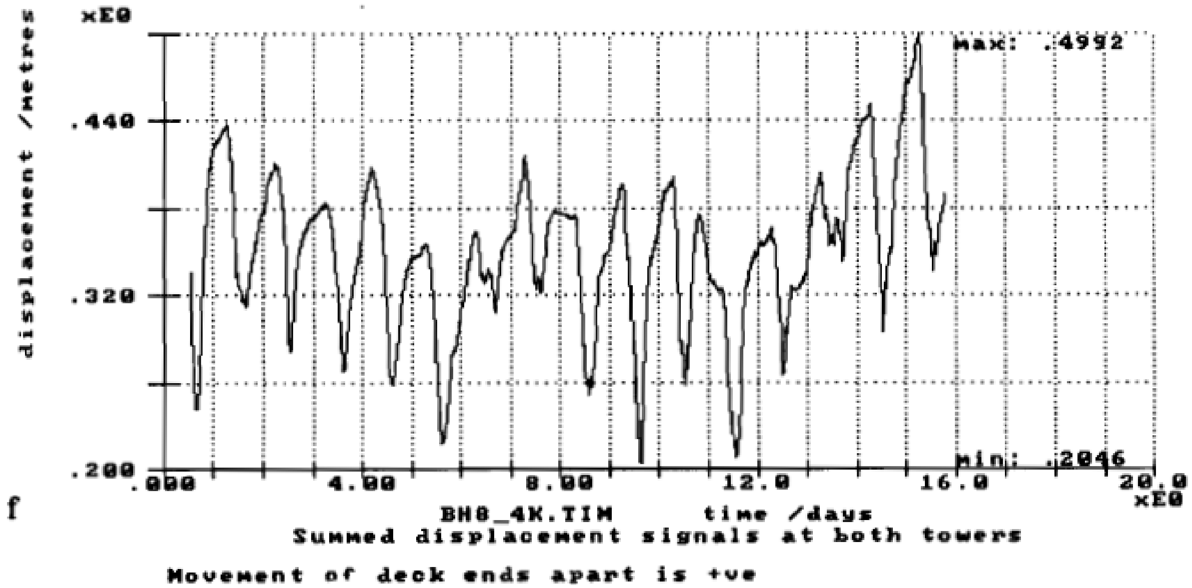



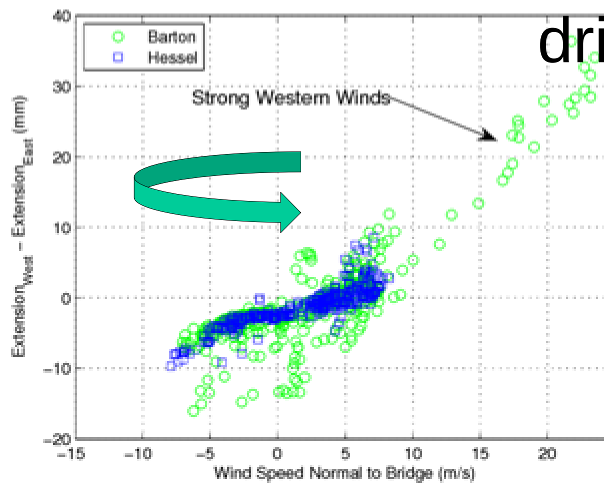



# Axial bearing movement: Exceeds expectation, so redesign modified

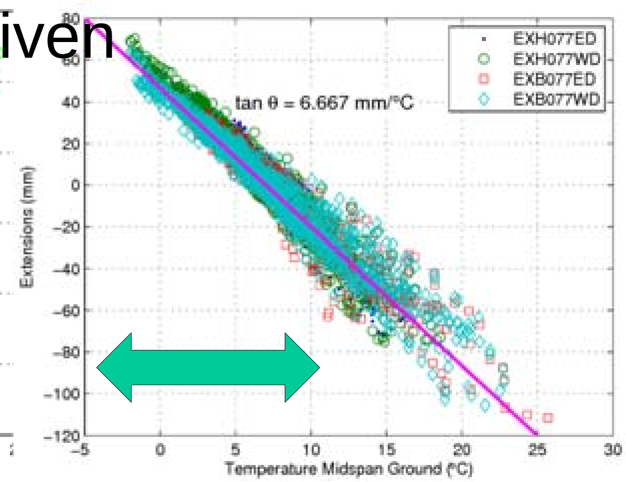



Wind-driven




Temperature-driven



# What does it mean?

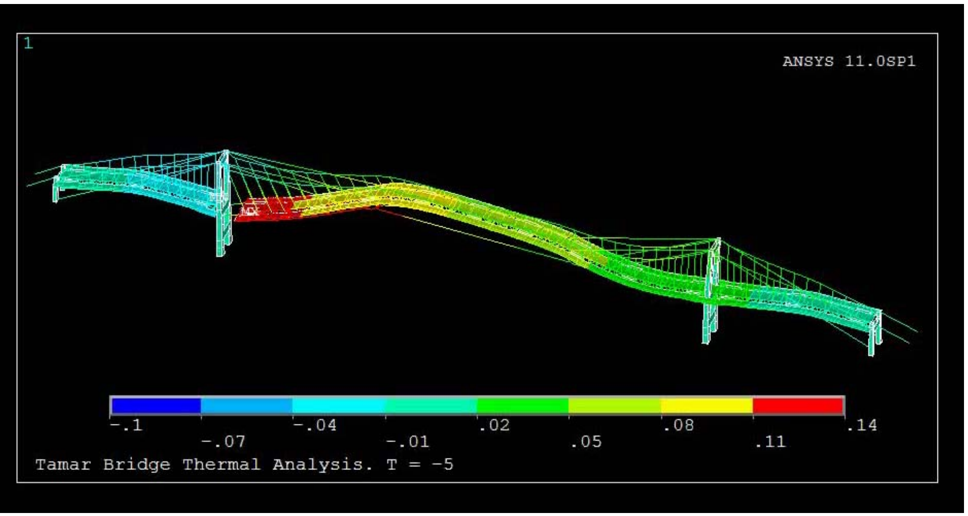
- Bearings look in bad way, but performance is little changed in 20 years. Replacement design influenced (a bit) by our data
- The same bearings probably cause the large swings in lateral mode parameters (0.054Hz is an *extremely low* frequency!)
- Wind has a very strong effect on bridge dynamics

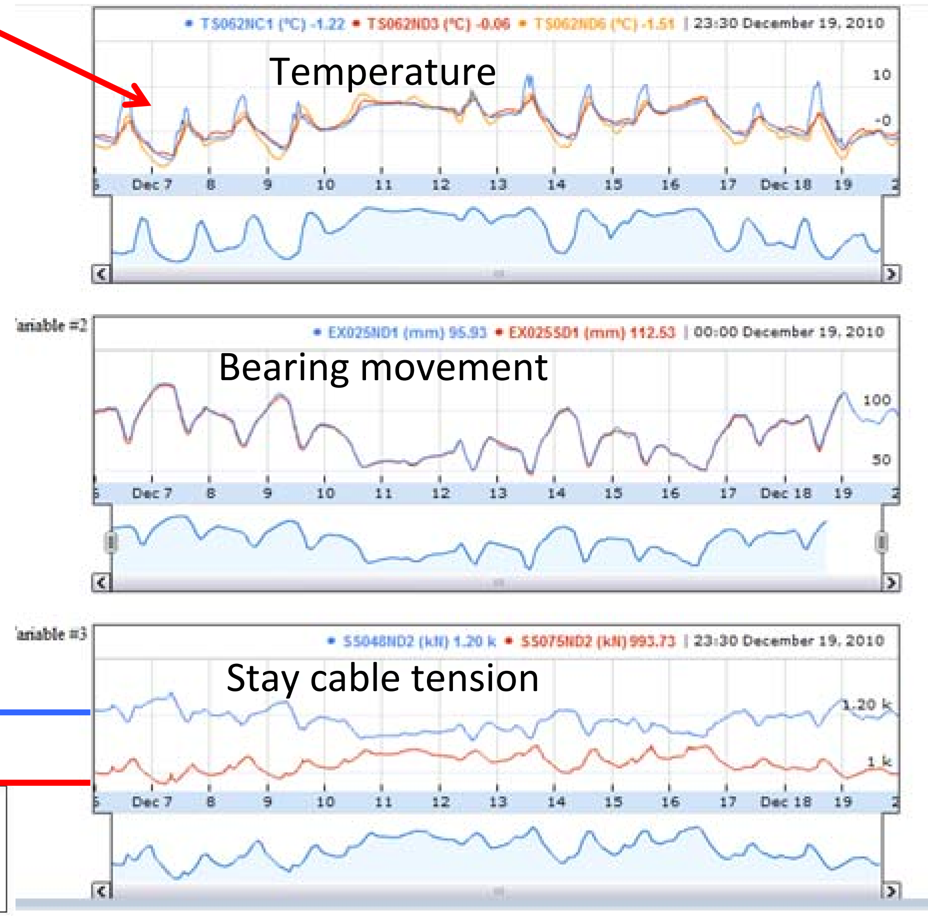
# Experience 2 :Tamar Bridge (not so sparse array)

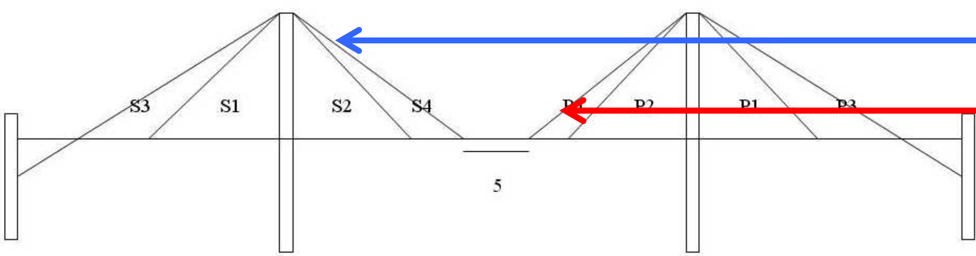



# Displacements from (R)TS show daily pattern

## Follow structural temperature and drive tensions in cables



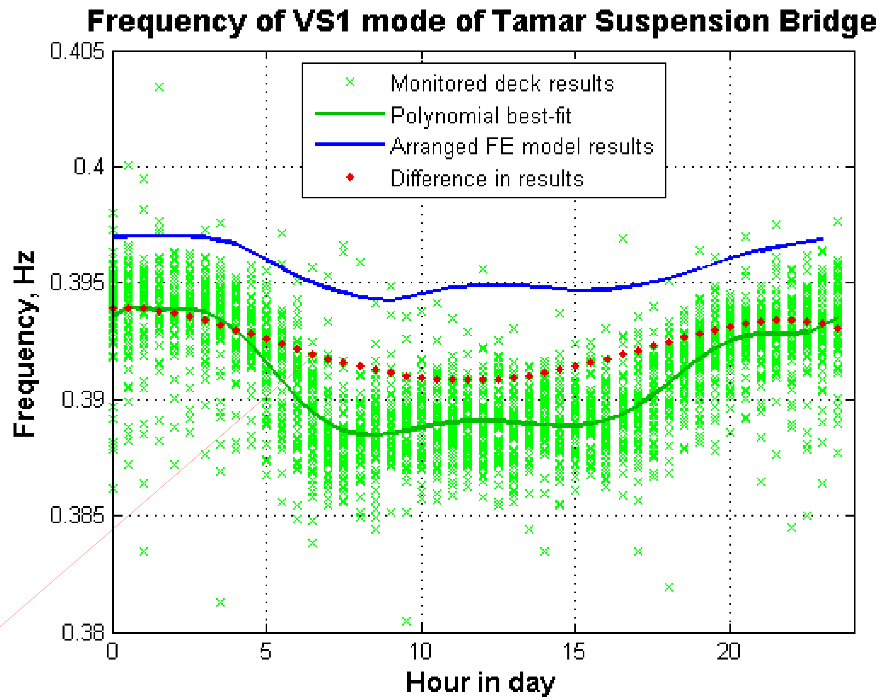



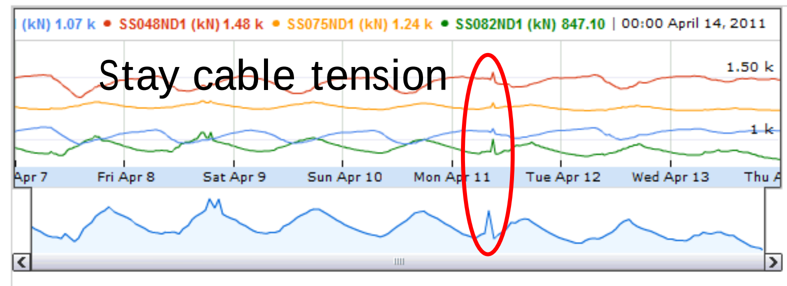

**RTS vertical positioning:**

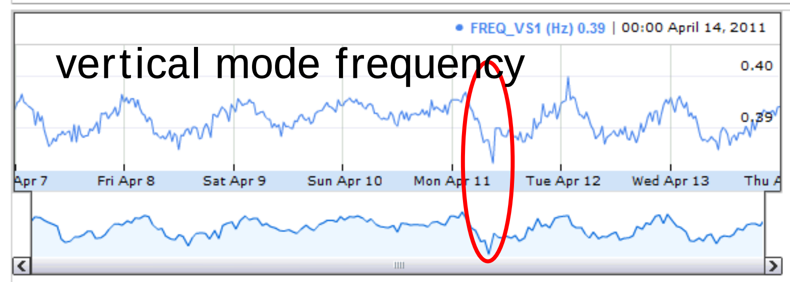
- Linear relationship with extensometer readings & longitudinal data
- At lower temperatures, cables contract & 'pull' deck up
- Vertical motion (~210mm) > longitudinal motion (~85mm)

# Fundamental vertical vibration mode frequency VS1: primary factor is traffic load, secondary is temperature



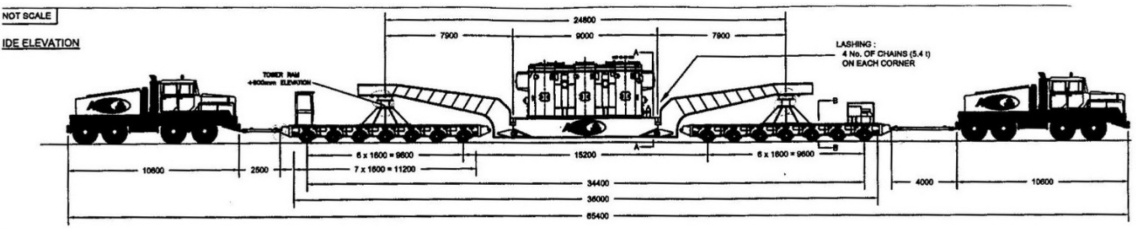

Rush-hour traffic jam

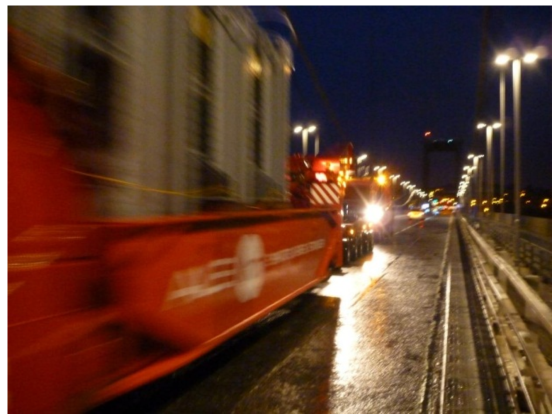


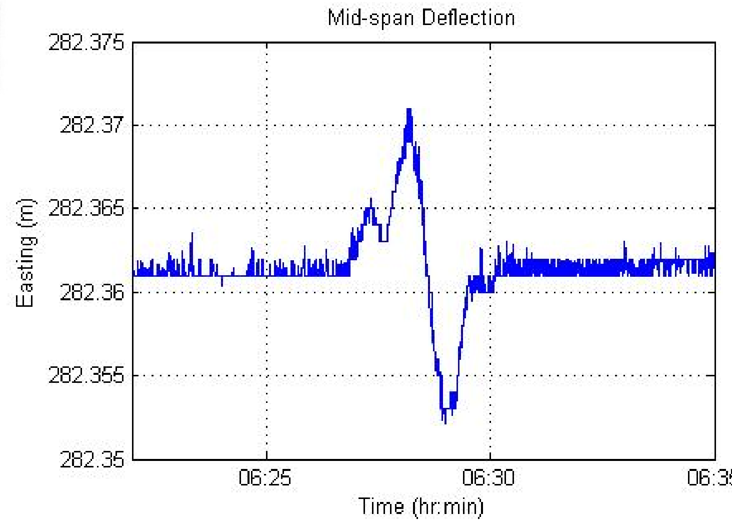

Red line is 'residual' effect on dynamics due to thermal effects on structure configuration (e.g. cable tension changes)


# RTS-measured displacements for 230 t vehicle

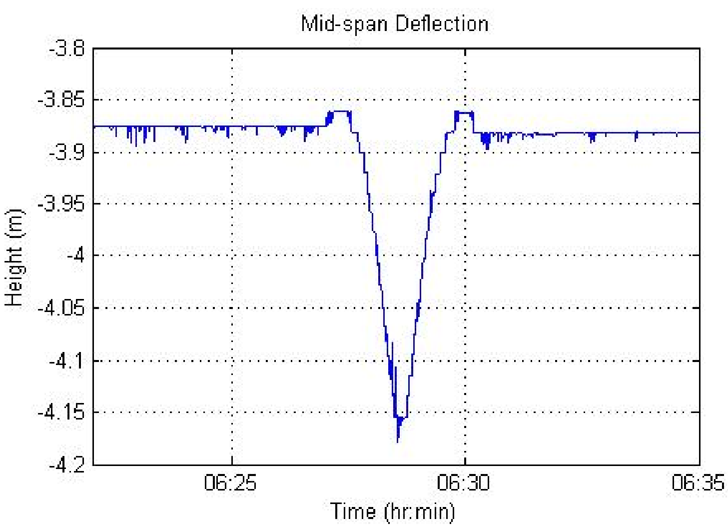


## Mid-span longitudinal

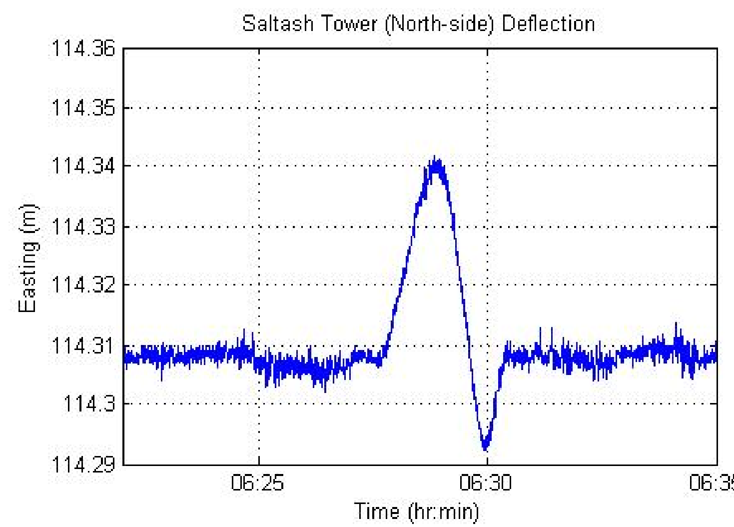



## Mid-span vertical




Consultant (AECOM) prediction validated

## Saltash Tower longitudinal

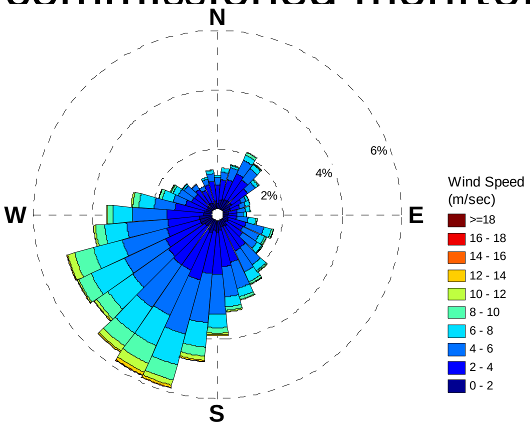


# How does this inform us?

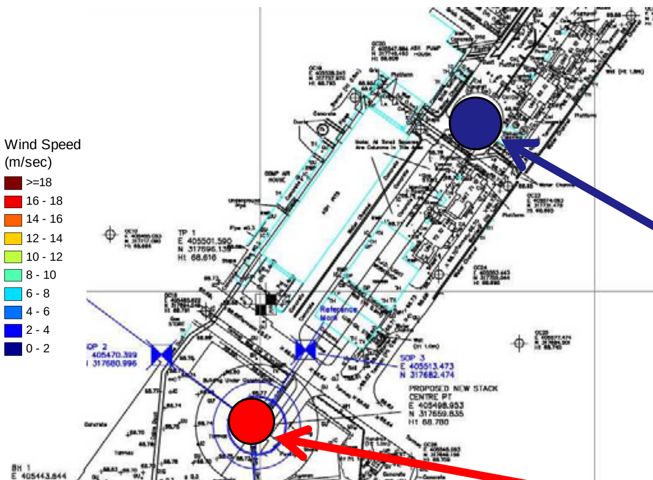
- Complex static performance (daily dance) mainly driven by temperature
- Dynamic response for vertical modes strongly driven by traffic
- We suspect bearing effects on dynamic performance as at Humber, but harder to pin down
- Consultant and VES FEM validated
- Robotic Total Station data useful for retrofit evaluation and extreme load performance assessment

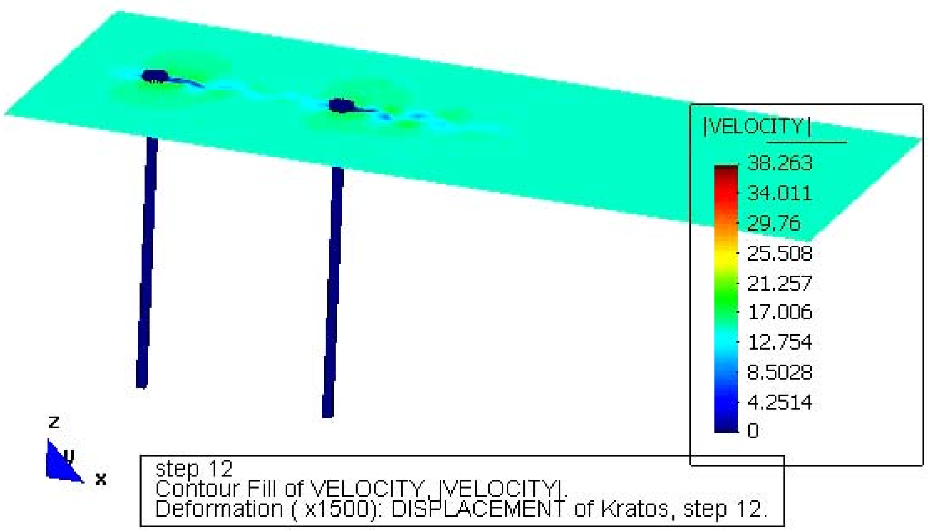
# Experience 3: Rugeley Chimney

New chimney constructed in 2006 for flue-gas desulphurisation (FGD) system. Consultant expected problems due to wind ‘interference’ effects and commissioned monitoring system and tuned mass damper (TMD)

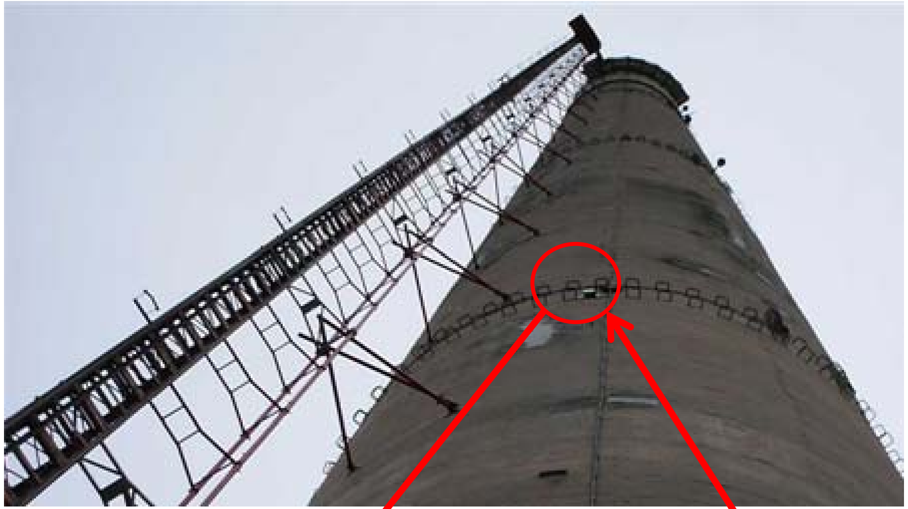


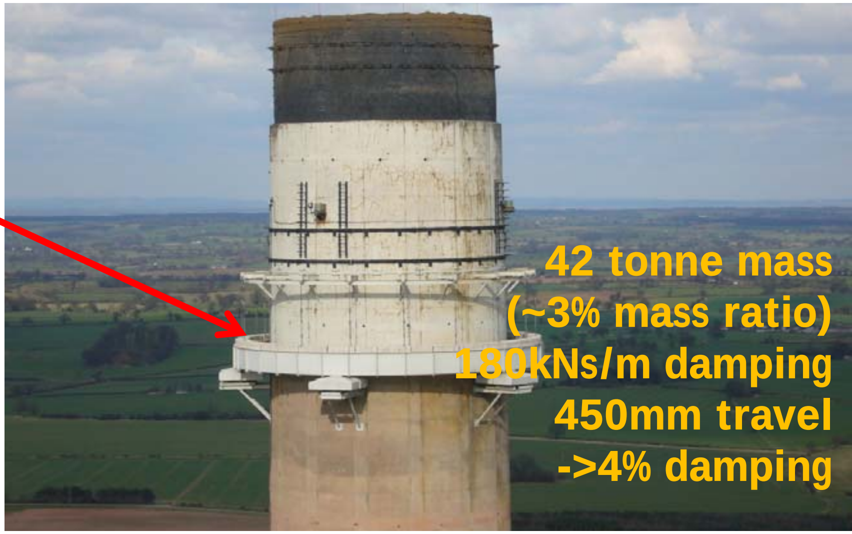

Distribution of wind speeds

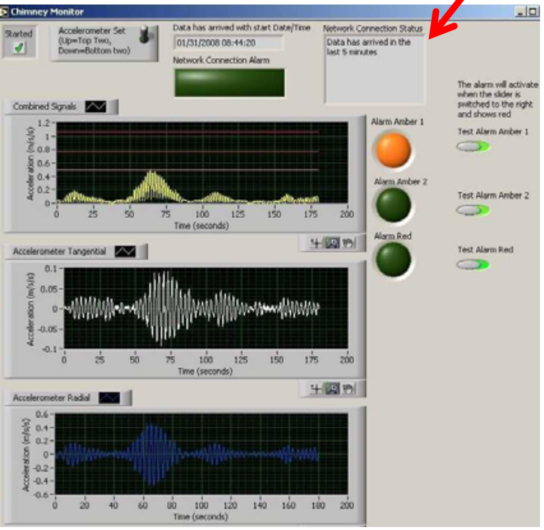


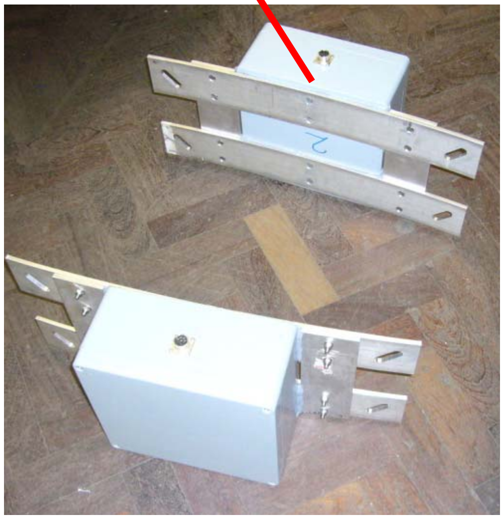



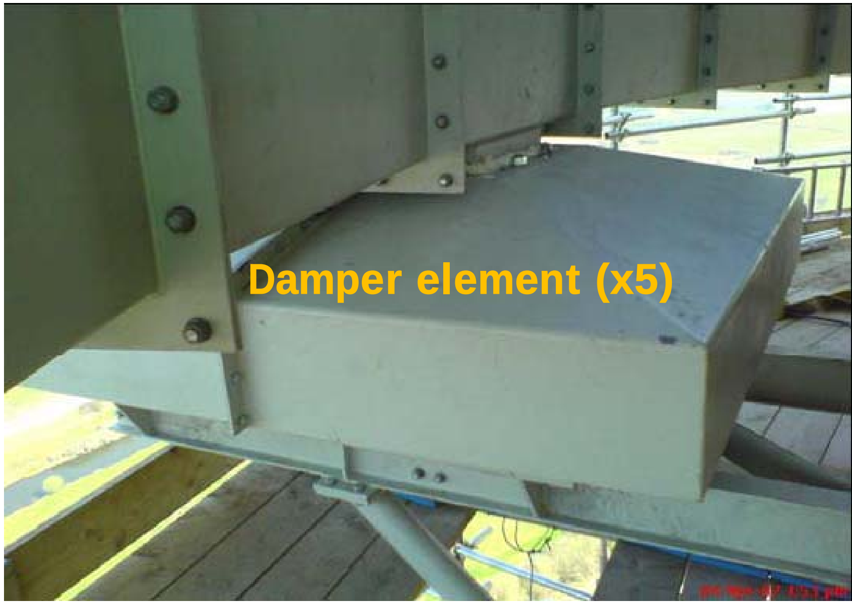
# TMD:
# largest ever on RC chimney





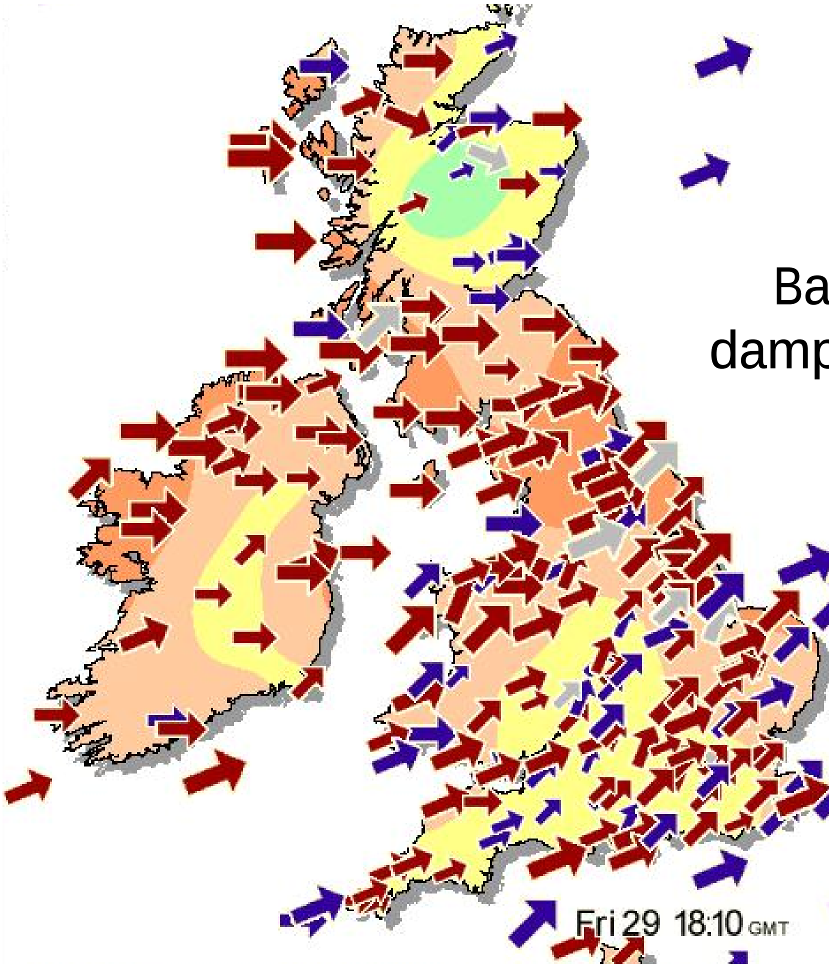





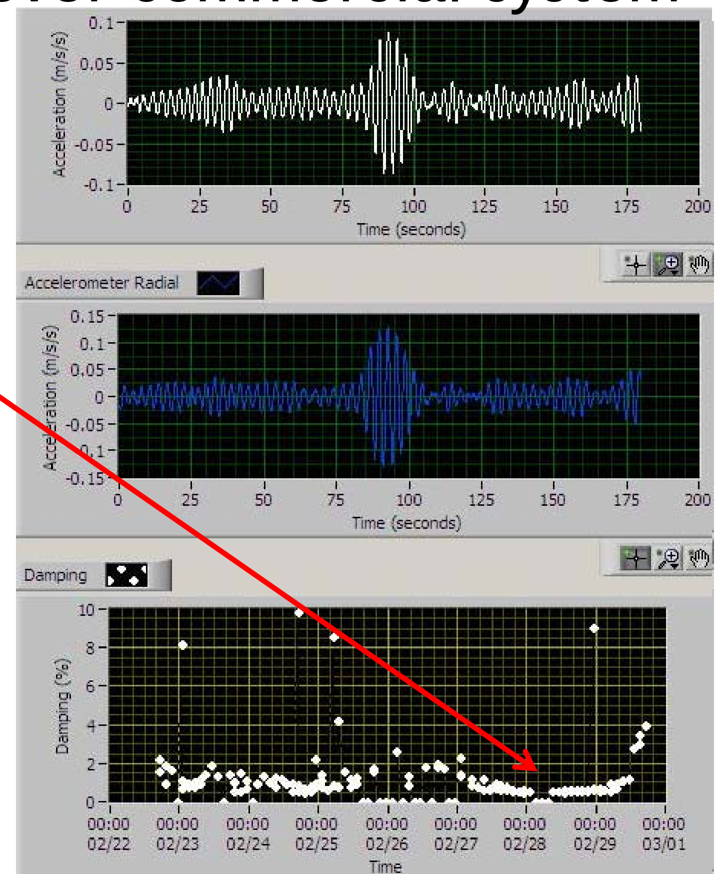

Accelerometers and internet viewer

# Real time frequency and damping estimation shows max performance of TMD around 4% (29 February 2008)



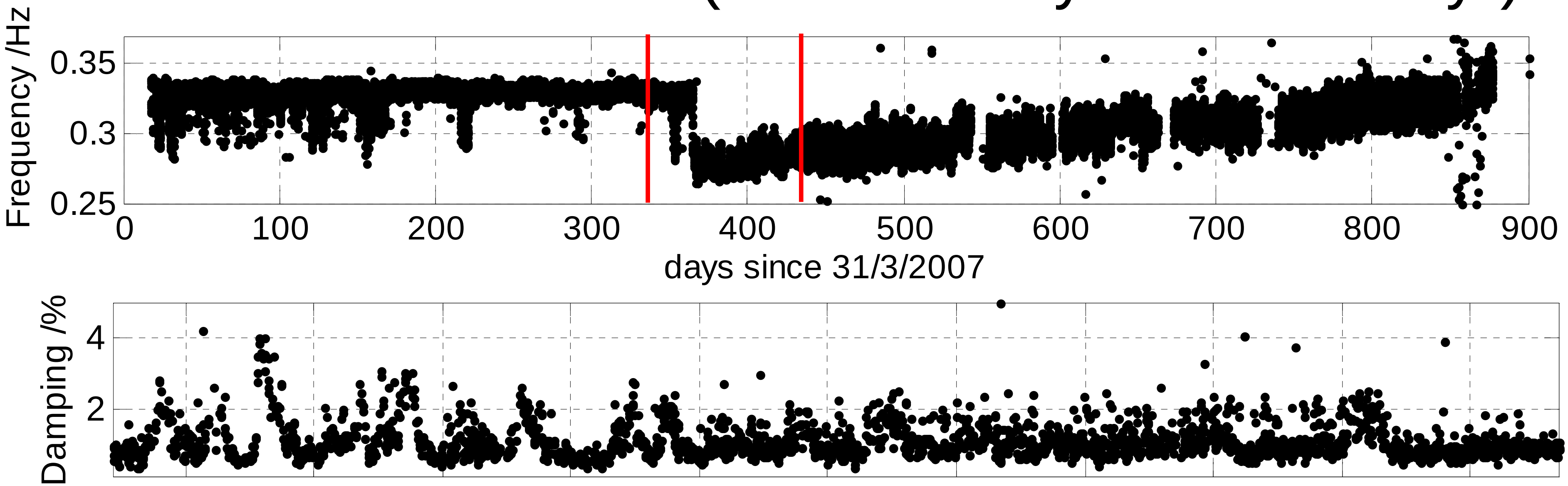

*First ever commercial system

Baseline damping 0.7%

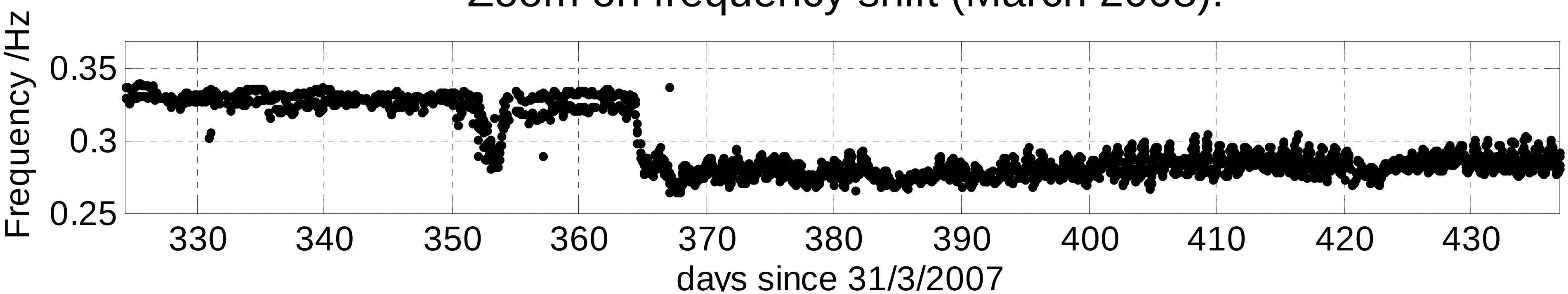



Shows TMD is working and chimney is in safe displacement range

# We tracked modal performance for 28 months until it was demolished (took over a year to destroy!)

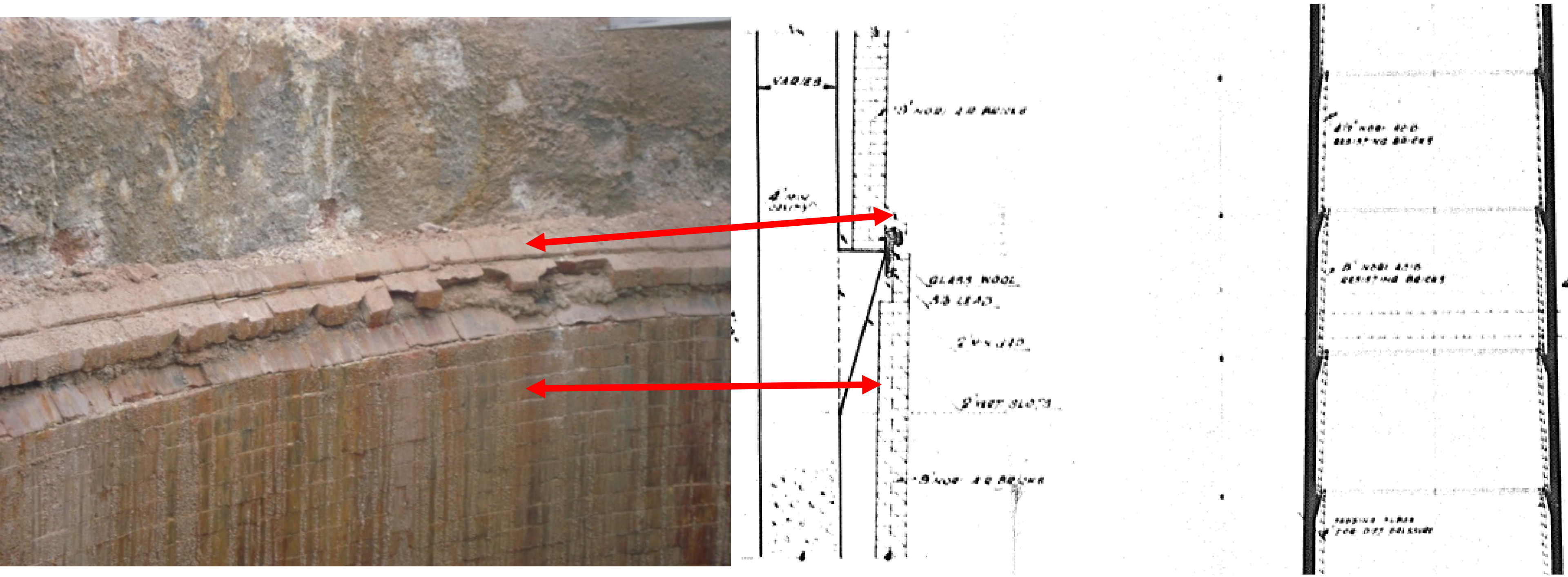



Zoom on frequency shift (March 2008):

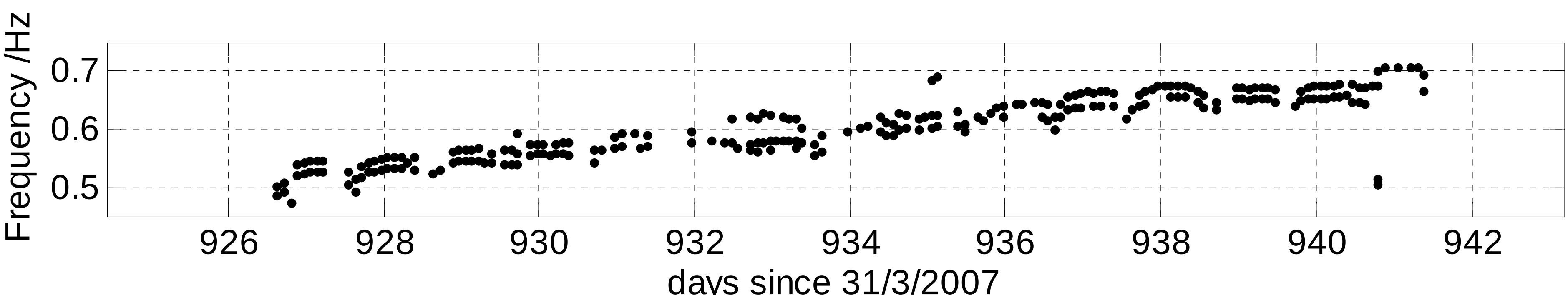


# Why the jump-shift?

Vertical sequence of masonry rings with small ‘dust’ were filled expansion joint. Data suggest *composite action* of concentric cylinders when gap is closed due to liner expansion. Composite action increases stiffness, hence frequency.



# Chimney has now been demolished

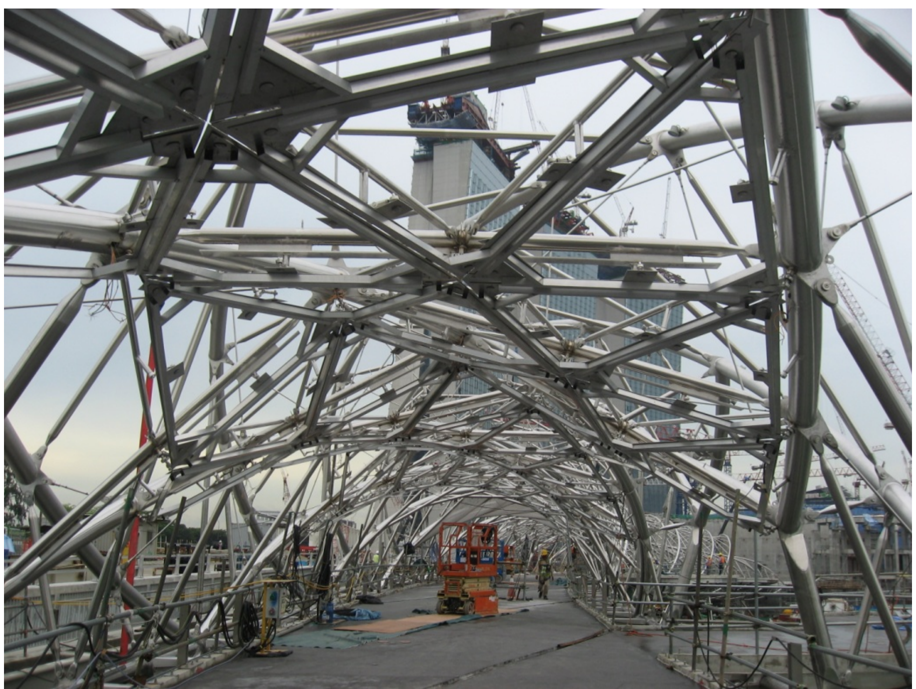
# How does this inform us?

- Monitoring and real-time modal analysis showed TMD was working well, even after large frequency shift
- Response data showed chimney was in safe working range
- Response data validated the theory of ‘enhanced vortex shedding’
- Change in frequencies after taking chimney offline believed to be due to composite action
- Some performance phenomena remain unexplained

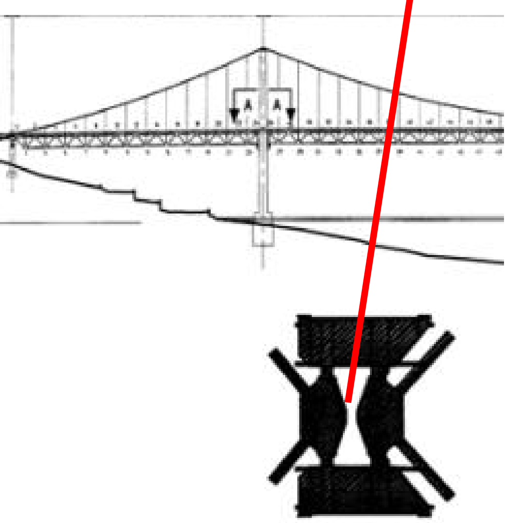
# Experience 4: Wireless sensors:
## a) Imote2 in practice, Helix Bridge Singapore

- Dense mesh of steel sections…
- … winding around R.C. deck
- Imote2s placed near slab surface

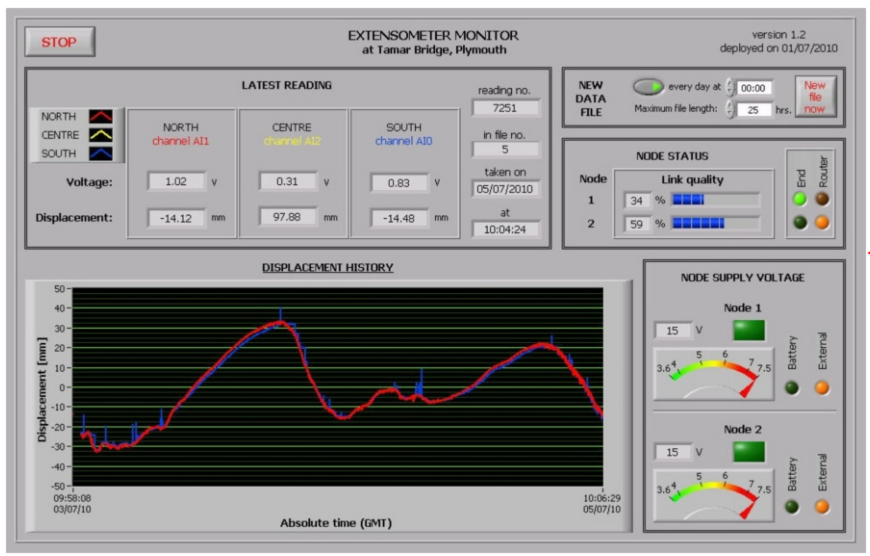
- Antenna close to concrete slab
- Steel structure disrupts radio waves
- High gain antennae and extensions (1m to 2m) proved helpful



# b) NI system checking bearings at Tamar Bridge. Standard solution with exceptional transmission distances


SECTION A-A




# Experience 5: 'International Bridge'



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# US 202/NJ 23 Bridge, Wayne, NJ

Fiddly and U/S bearings

Is this hammerhead falling off? So what?

Knackered expansion joints

- Built 1983
- ‘Typical’ structure
- Worst rating by NJDOT
- Four span, dual bridge, 7 lane
- Up to 130’ by 62’
- Concrete slab on steel stringer
- Visually deficient

Pointless lateral bracing

# US-202/NJ-23 Bridge: Adopted by FHWA LTBP; International collaboration, driven by Drexel


# VES designated role was system identification

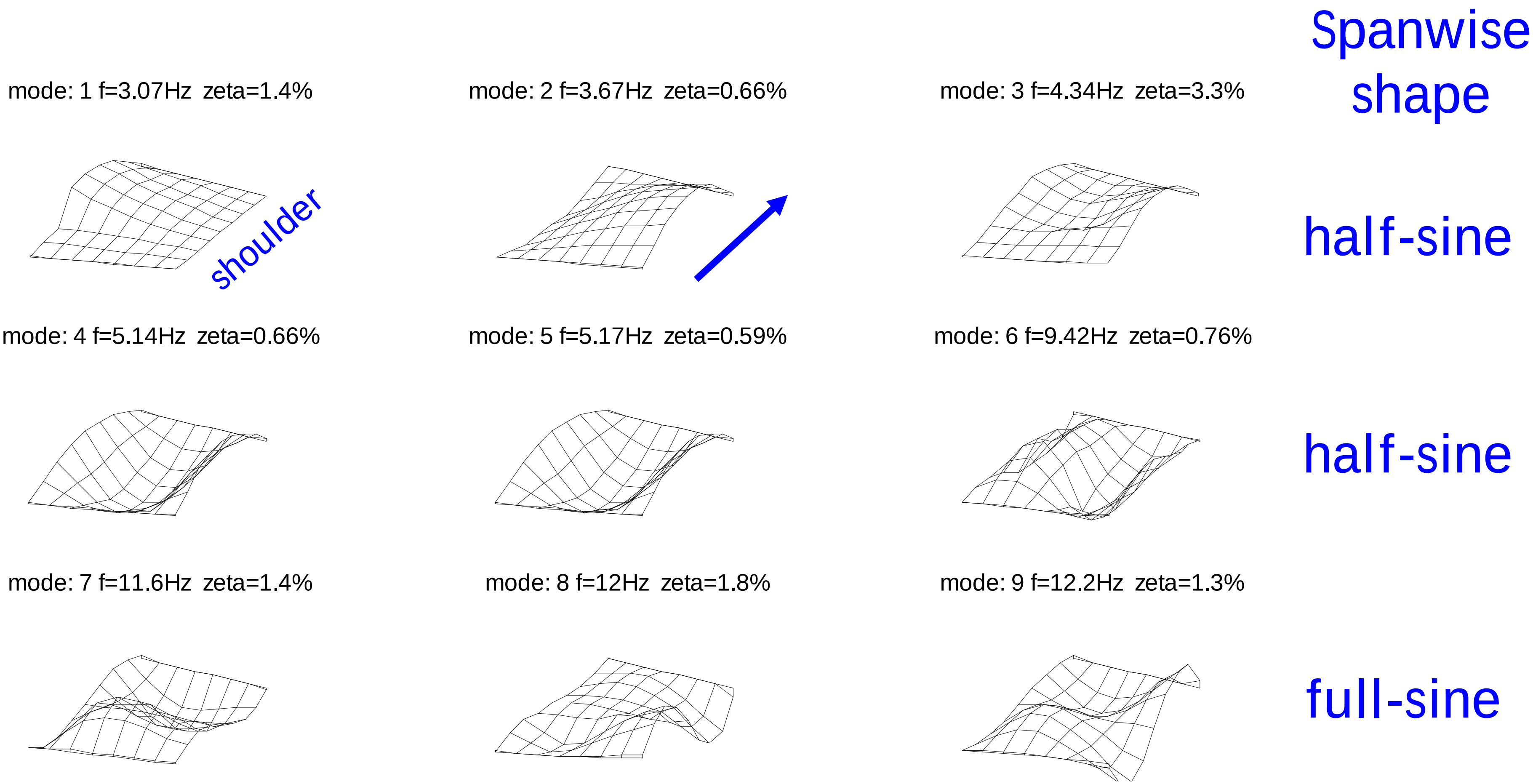
(we have ‘tested’ over 200 civil structures worldwide)

Vibration test kit: APS400 shaker

QA 750 servo accelerometers,

(shadowed by Georgia Tech wireless accelerometers)


# Modal analysis using NExT/ERA, from random excitation. Mode shapes show transverse mode order, effect of asymmetry and orthotropic properties

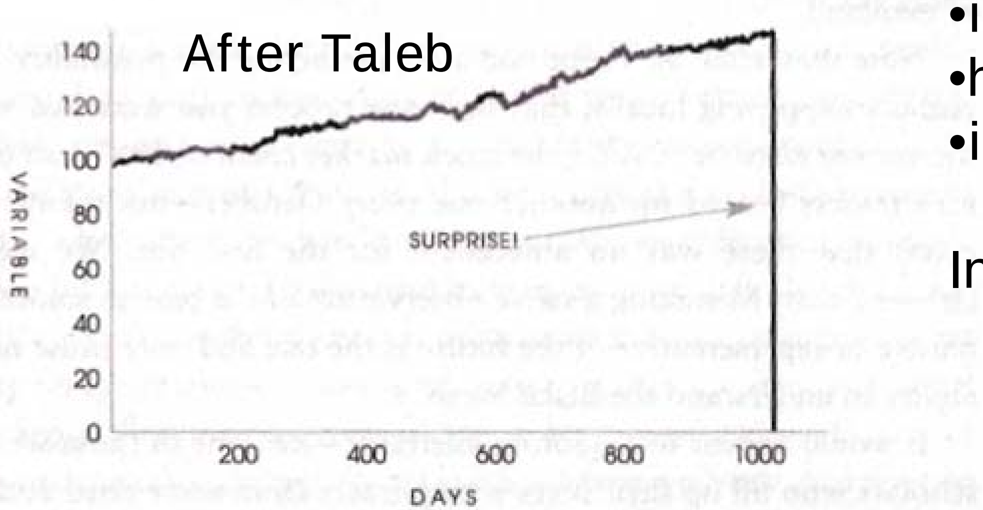


# How does this inform us?

- Vibration test is only part of an array of tools: Full program of condition assessment included static load test, GPR, visual inspection (US/Austria/Japan standards) etc. etc..
- Excessive dynamic response needs fixing
- Bridge in in better state than it looks, some defects are cosmetic
- Bearings need replacing
- Multi-span bridge not such a great idea
- Some redundant steel work causes problems

Note: despite extensive and expensive assessment demonstration campaign using every technology you can imagine, no continuous monitoring

# Monitoring, black swans & what we don't know




A turkey before and after Thanksgiving. The history of a process over a thousand days tells you nothing about what is to happen next. This naïve projection of the future from the past can be applied to anything.

Features of a black swan event
- is a surprise (to the observer)
- has a major impact
- is rationalized by hindsight

Infrastructure black swan events?
- Tacoma Narrows
- Millennium Bridge
- 9/11
- Fukushima
- Katrina

- We don't know what we know
- We don't know what we don't know
- Conclusion?
- We have to learn (share failure stories and remember) from past and be sensitive (use SHM?) to find precursors of doom