# Resilient infrastructure: the role of structural health monitoring

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&
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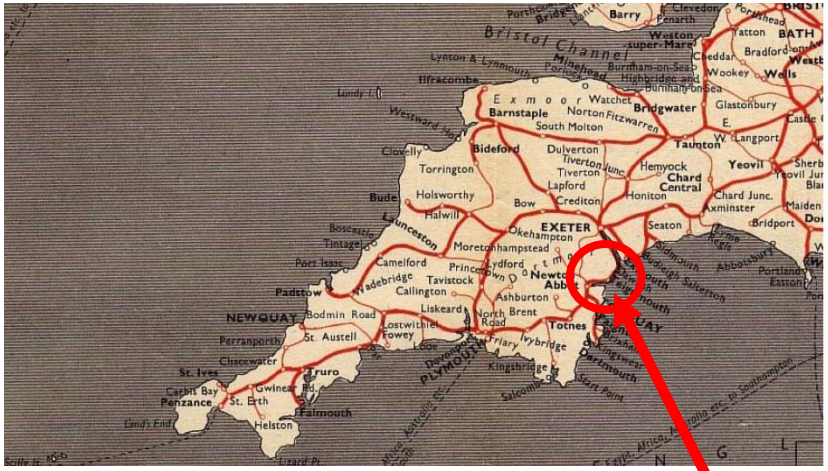
# UK Extreme weather 2014

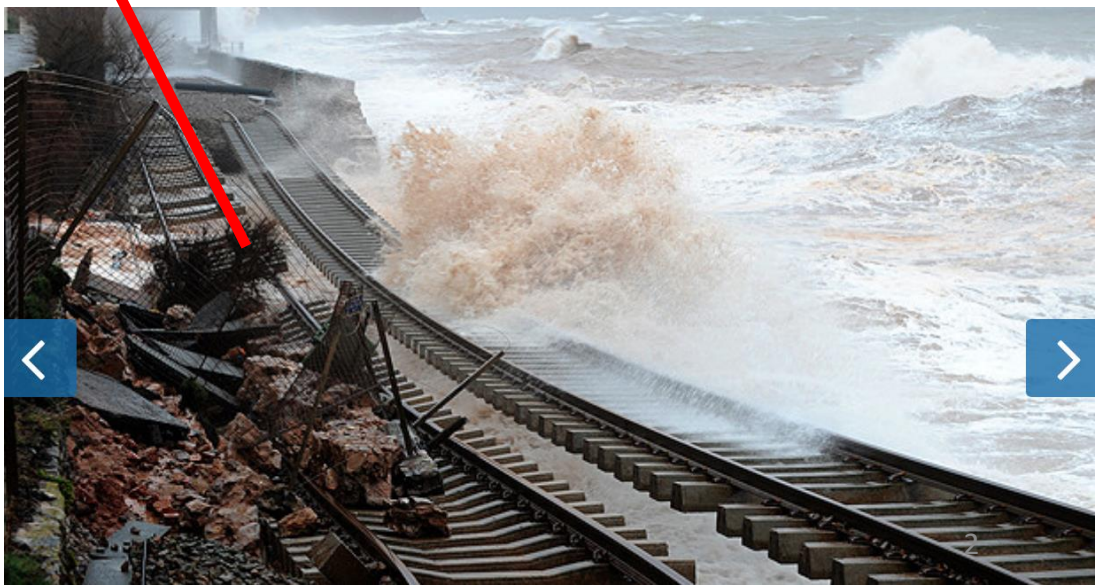
–demonstrated lack of network resilience

-these were recurrent events



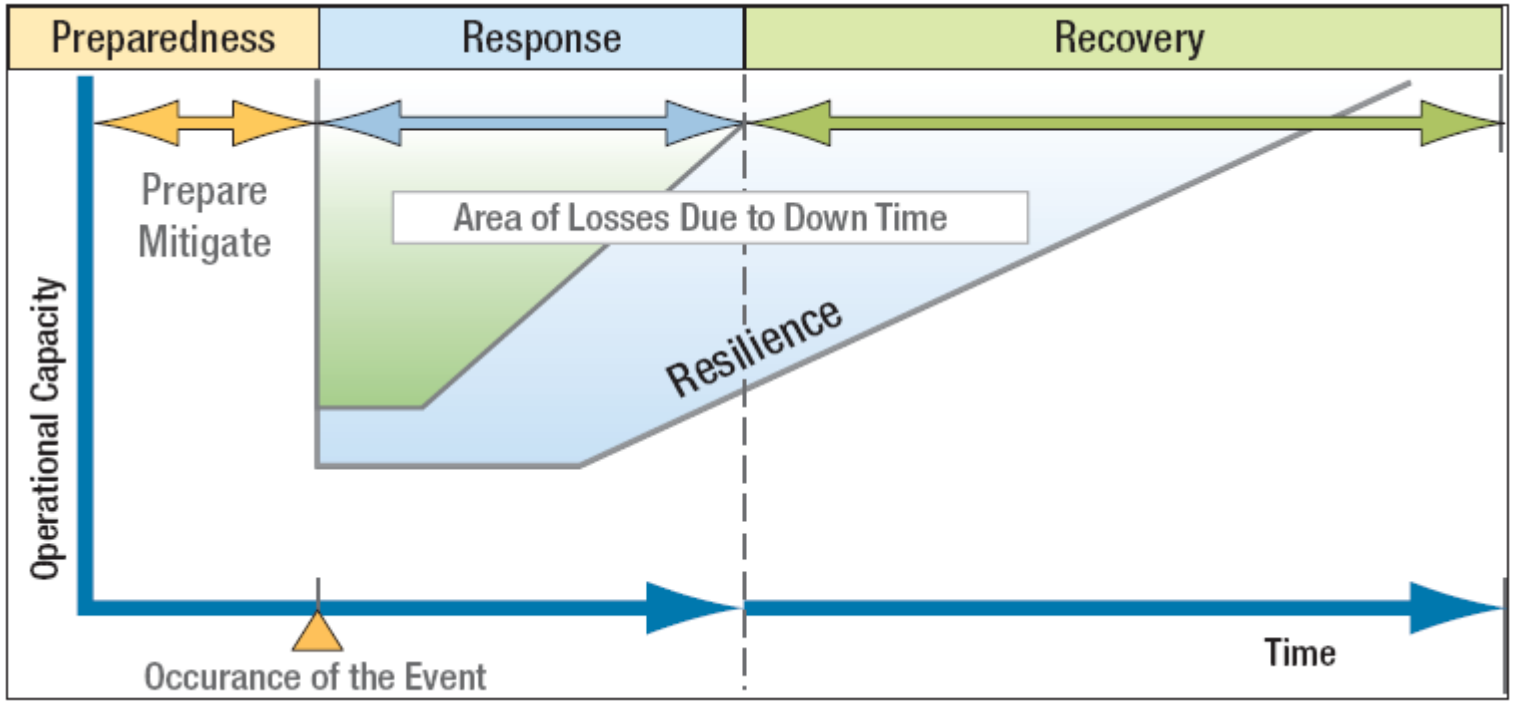


Economic cost £5m/day estimated.
Cornwall cut off by rail for 3 months



# What is resilience?

- *A function indicating capability to sustain a level of functionality or performance for a given asset or network over a period of time including the recovery period after damage in an extreme event. The recovery time is that needed to restore the functionality of an asset or network, allowing proper operation of the system* –Cimellaro et al., 2006




- Mitchell D Erikson, Dept of Homeland Security, Dec 2010

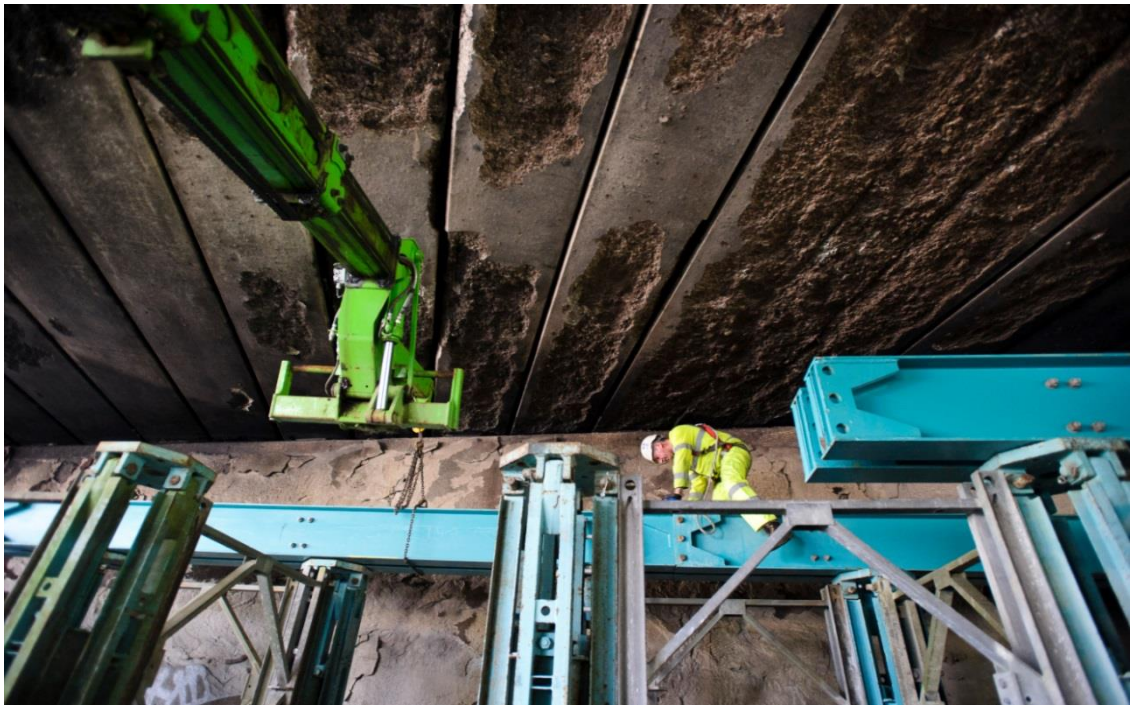
# London bridges lacking resilience: failures and collateral damage

- M1 bridge (2011) –closed due to fire damage
- Hammersmith Flyover (2011) –closed due to corroded tendons
- Boston Manor Flyover (2012) –closed due to cracks in steel beams

# M1 bridge

The extended closure of the M1 motorway near London in 2011 due to arson demonstrated disproportionate disruption of a vital national network and the need for reliable post-trauma structural assessment using pre-trauma measured data.

- **Overpass needs urgent repairs after blaze weakened it**
- **Residents evacuated after fears that gas cylinders could explode**
- **Thousands planning extended Easter break affected**
- **Boris Johnson questions the 'madness' of the extended closure**



# Hammersmith Flyover

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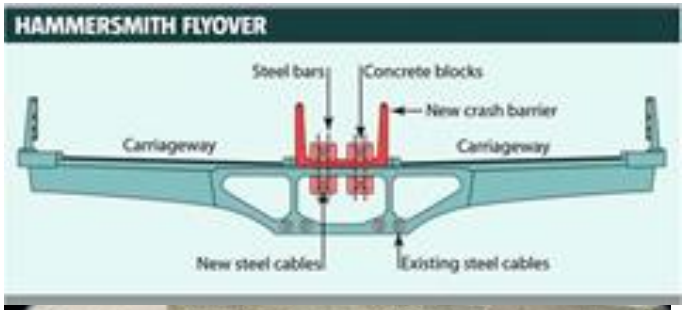
The 2011 closure of Hammersmith Flyover highlighted unreliable and disruptive low-tech inspection and maintenance regimes. Lack of prior structural performance track record and means to assess impact of discovered damage forced the usual conservative approach to safety yielding sudden bridge closure and transport chaos.

- Designed in 1960s as ‘maintenance free’, with electric deck heaters
- Major inspection involved acoustic emission monitoring:
- Increasing tendon strand breakage rate triggered inspection
- Inspection showed potential for catastrophic failure
- Bridge closed for 3 weeks for **all** traffic
- Strengthening by additional post-tensioning took 4 months
- Occurred during build up to 2012 London Olympics
- Major route from Heathrow to Olympics site


01:07:40:12


HAMMERSMITH FLYOVER
Steel bars
Concrete blocks
New crash barrier
Carriageway
Carriageway
New steel cables
Existing steel cables

# M4 Boston Manor Flyover

Key Olympic access route closed 3 weeks before the 2012 Olympics due to discovery of a new crack in a “sensitive location” during minor repairs of a fault found earlier by chance.

**Urgent inspections were taking place this week to work out how to repair cracks on a crucial M4 motorway structure in London in time for the Olympic Games.**

The 15mm long hairline cracks were discovered by chance in welds on the Boston Manor Viaduct just west of junction 2 near Hounslow last week.

## M4 fiasco: Cracks start to show in ministers' confidence that repair works will be completed by Thursday deadline

- **Road shut between junction 2 and 3 causing one-hour delays**
- **Labour attacks Government over last-minute works, pointing the finger at £435m cuts to road maintenance budgets**
- **Vital commuter route links Heathrow and Central London**
- **Business chiefs say the late closure will be costly and potentially disastrous**
- **Secondary crack causing current crisis is part of a £4m repair project at the Boston Manor Viaduct**

# Aerospace Resilience: Rolls Royce jet engines

## Qantas grounds A380s after engine failure

Updated 4 Nov 2010, 10:31am

**Qantas says it is suspending the airline's flagship A380 fleet until it is confident the planes are safe.**

Passengers say they heard two loud bangs when an engine failed on board this morning's flight from Singapore to Sydney.

The airline says flight QF32, with 433 passengers and 26 crew aboard, made an emergency landing at Changi Airport and all on board are safe and well.


The fault – a leaking pipe – **was quickly diagnosed. Rolls Royce Engine Health Management Centre used condition monitoring technology to perform real time diagnosis.**

The damage was limited: within weeks Rolls Royce had signed orders with Chinese carriers worth $3bn,and a further $5bn deal with British Airways

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# Condition monitoring in civil infrastructure: Structural Health Monitoring

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

*Phil. Trans. R. Soc. A* (2007) **365**, 589–622
doi:10.1098/rsta.2006.1925
*Published online* 13 December 2006

## Structural health monitoring of civil infrastructure

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Structural health monitoring (SHM) is a term increasingly used in the last decade to describe a range of systems implemented on full-scale civil infrastructures and whose purposes are to assist and inform operators about continued 'fitness for purpose' of

SHM is a continuous measurement of structural performance data allied to sophisticated interpretation technology using physics-based or empirical models..

# Civil SHM challenges are greater than in aerospace because each *civil structure* is a prototype. It has two main functions:

- **Diagnosis:**
- Prove structural fitness for purpose (as for auto, aero)
- Validate structural modifications & mitigation measures
- Track structural loads/overloads/extreme responses
- Evaluate 'servicability' –e.g. user comfort/safety
- Assess condition after major trauma or discovery of defect
- **Prognosis:**
- Track long term degradation to aid maintenance decisions
- Provide warning of impending failure (I never found any example)
- Prove effectiveness of repair after trauma or defect discovery – resilient recovery

# Resilient recovery of Forth Road Bridge -aided by SHM

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## Forth Road Bridge closure causes 11-mile tailback

36 minutes ago | Edinburgh, Fife & East Scotland


The bridge has been closed to all traffic since midnight

Full economic cost of closure estimated as £240m.
Quickly installed SHM instrumentation + load testing avoided the type of extended delay seen in Hammersmith viaduct.

# Forth Road Bridge (FRB):

Strain gauges and extensometers attached to the failed truss-end link identified large bending moments. So it acted like a beam not a truss, due to the seizure.

The three other links were OK.

'In my opinion, structural health monitoring on the current crossing is the way forward' -Amey engineer

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# Structural Health Monitoring:
# Recognised by UK government inquiry on Forth Bridge

The Scottish Parliament
Pàrlamaid na h-Alba

Official Report

**INFRASTRUCTURE AND CAPITAL INVESTMENT COMMITTEE**

**John Russell:** In the current circumstances, using the technology that we have at the Forth road bridge, that defect could not have been foreseen. If you are asking for an opinion about the future, the structural health monitoring that is being carried out on the new crossing covers an awful lot of the components and feeds into a new system. Previously as FETA, and now as Amey, we have suggested that we should have structural health monitoring on the current bridge too. We are doing some of that at the moment and getting data back to help us judge how some of the other components are doing.

It is all technology. It is a 51-year-old bridge with a 60-year design. In my opinion, structural health monitoring on the current crossing is the way forward.

# SHM in long span bridges: Humber Bridge

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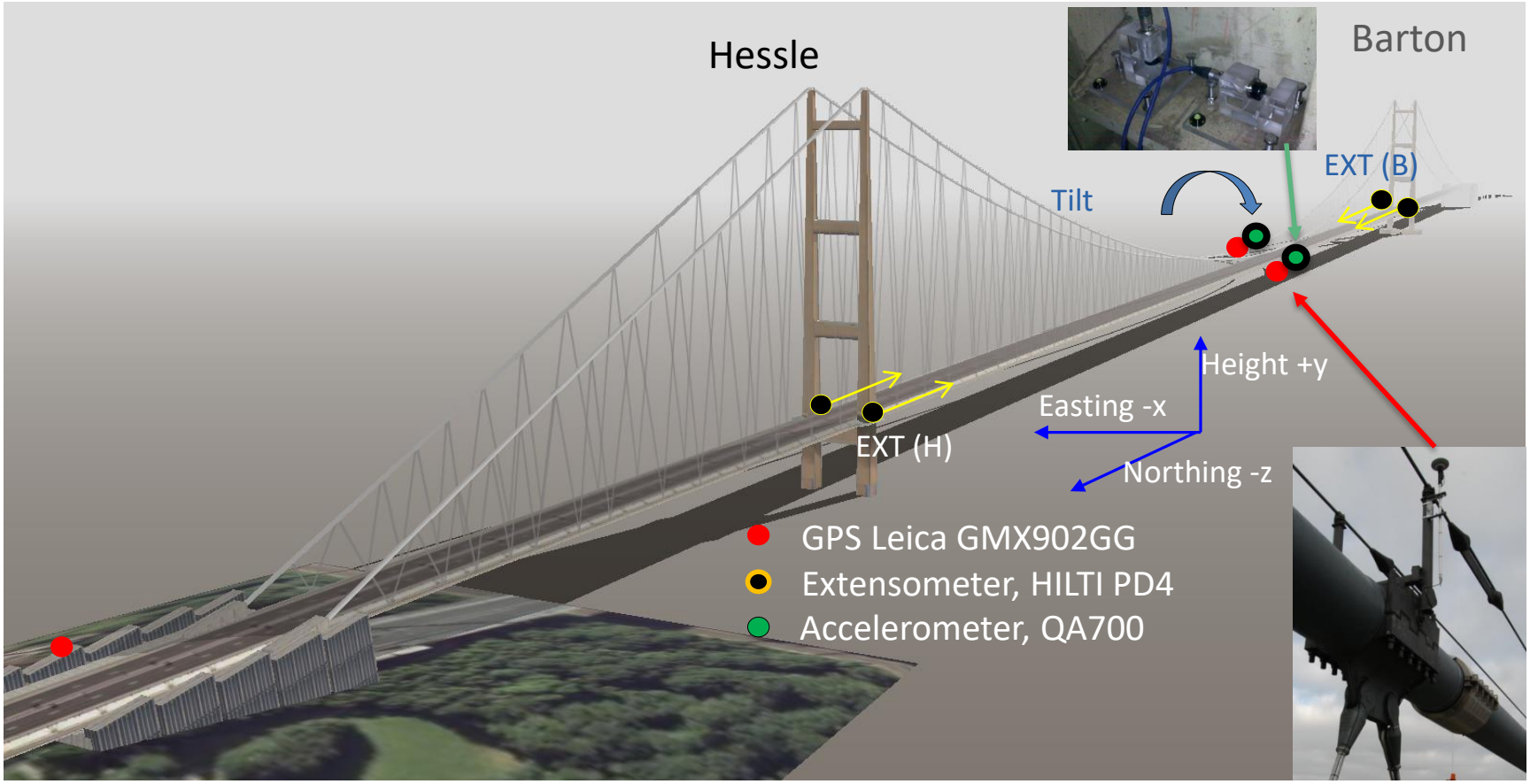
# SHM system operating 2010-present

3xGPS receivers, 3 accelerometers,
inclinometer, anemometer +7 thermistors around deck at midspan.



# Bearings & expansion joints

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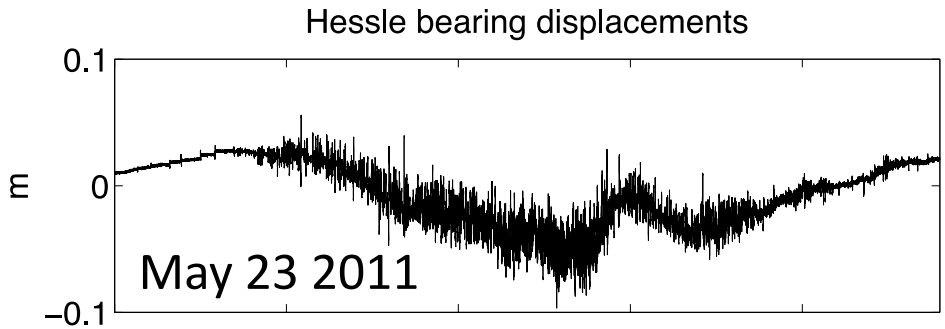
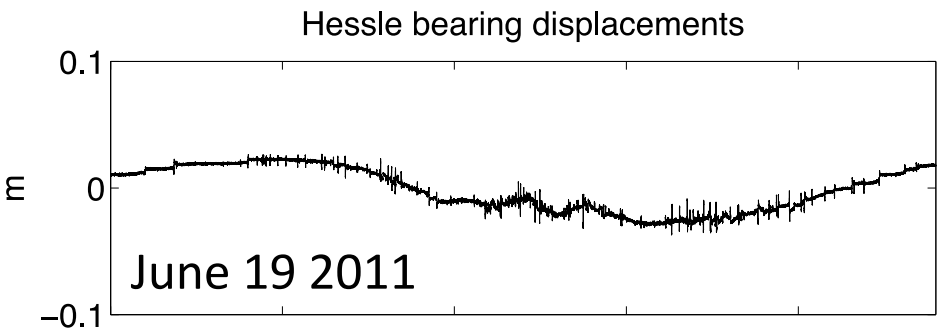
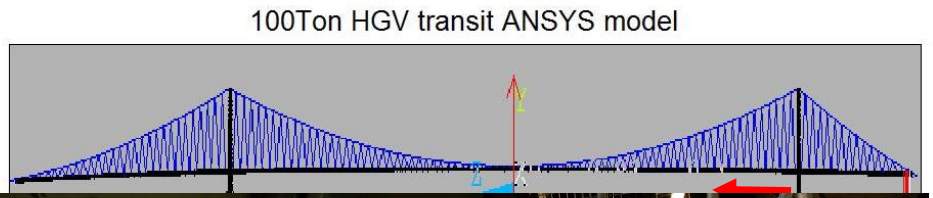
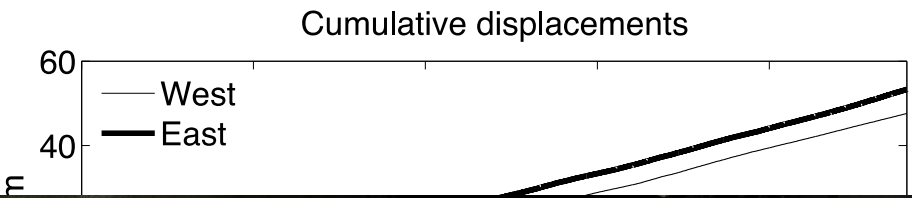
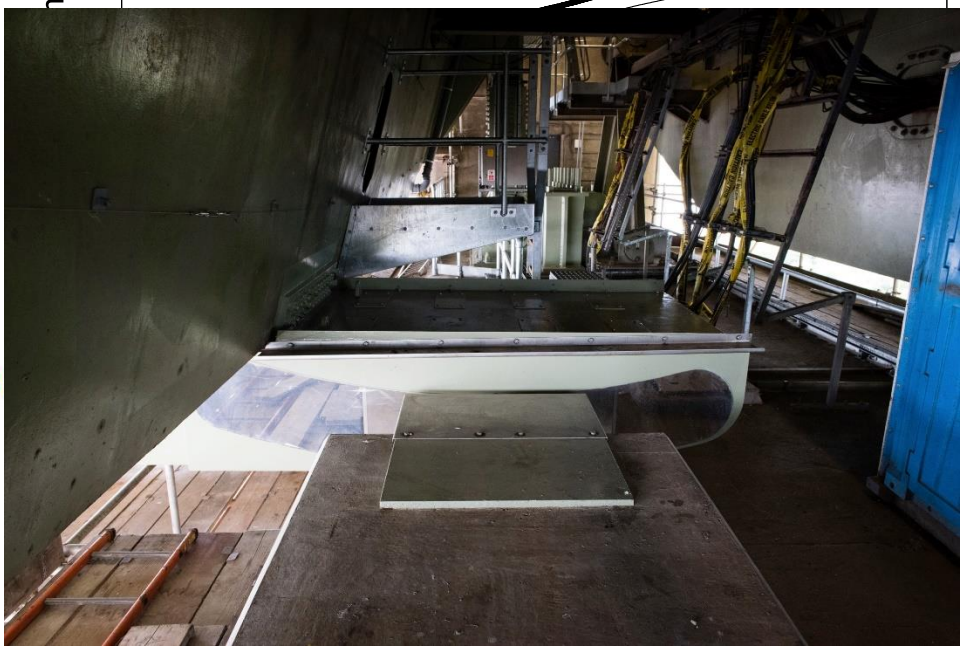
## Movement due to wind and traffic ➔ worn bearings:



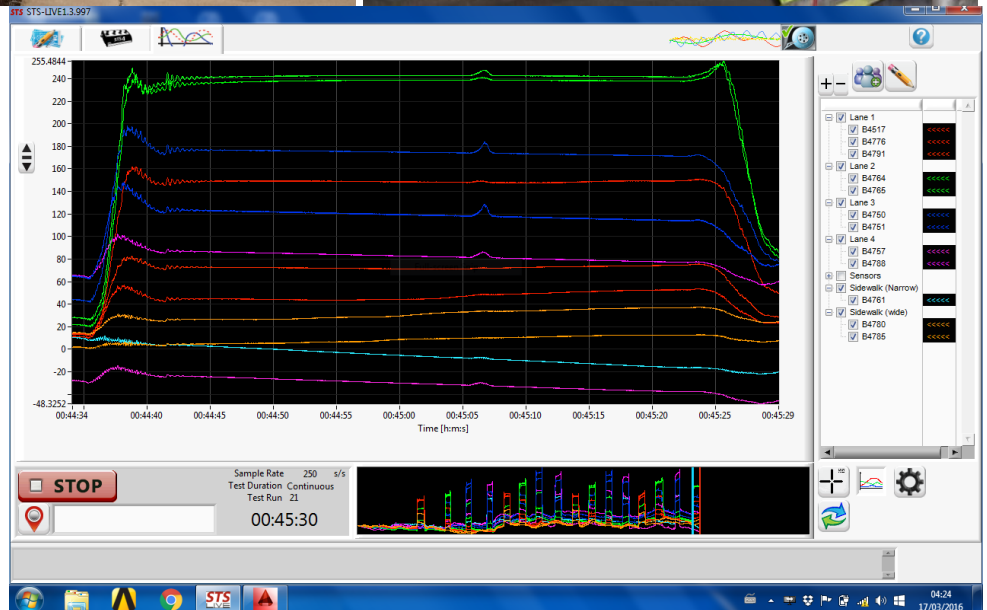



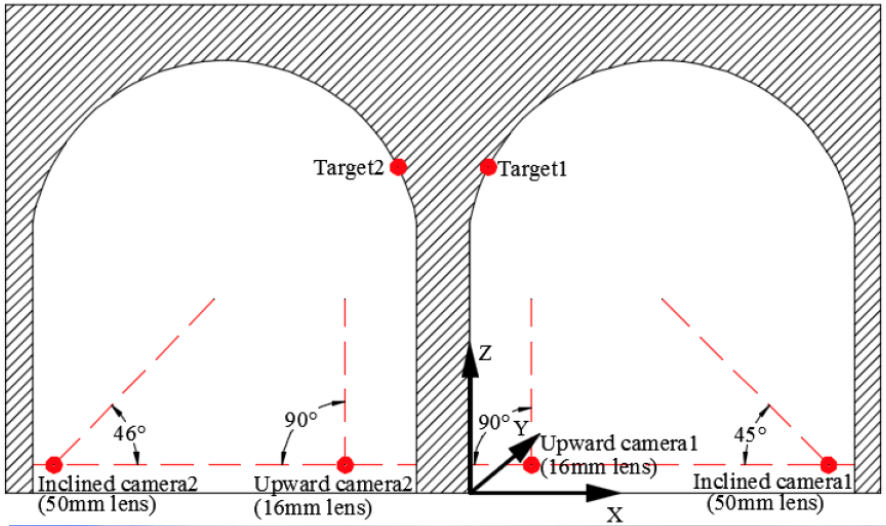
# SHM in short span road bridges:

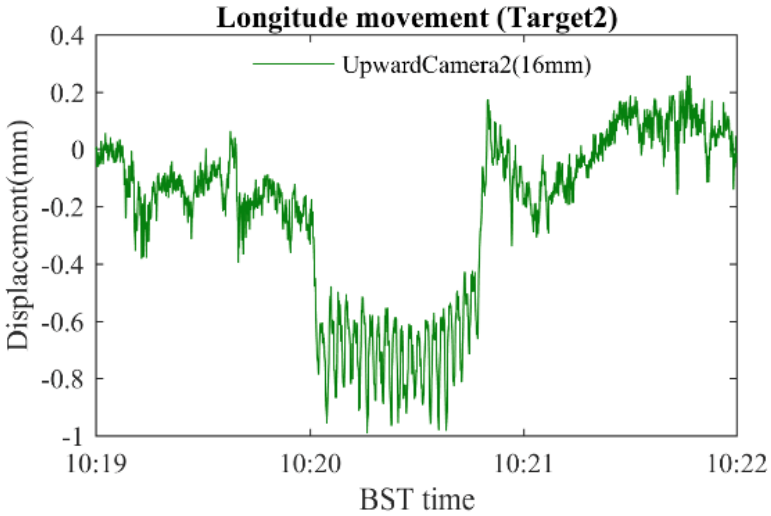
## Load testing, Exe Bridge North, Exeter

# SHM in rail bridges:
## West Somerset Railway

# SHM in rail bridges:
## Harringworth viaduct



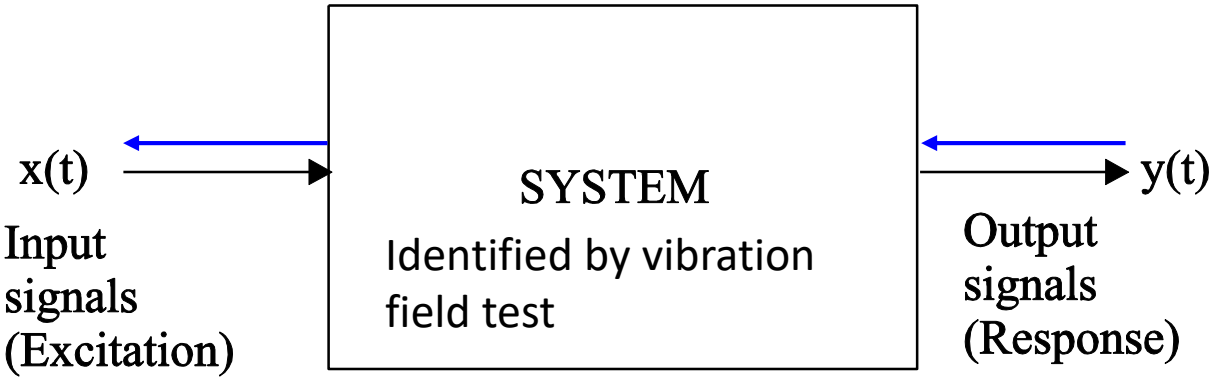

# SHM of lighthouses:

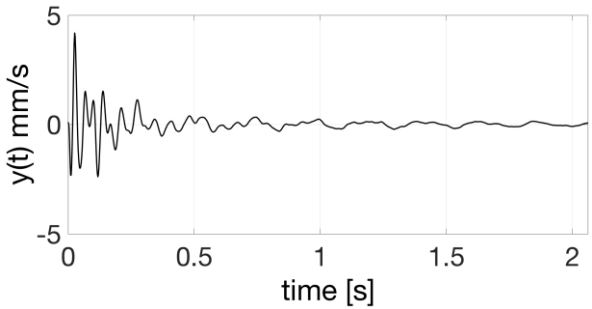
Fastnet lighthouse, Ireland

Dubh-Artach, Scotland

Checking structural integrity

Inverse identification of wave loads




$$y(t)=T\{x(t)\}$$

$$F=kx$$

$$x(t) \Leftarrow T^{-1}\{y(t)\}$$

$$x \Leftarrow k^{-1}F$$

Monitoring response to infer wave impact loads

# Conclusions

- SHM is a real-world commercial proposition, recoginised by UK govt.
- Understanding how structures behave is key to bringing them back on line rapidly due to trauma or discovered degradation.
- We believe measuring deformation in the loing term provides a crucial role in understanding structural behaviour.