Structural Health assessment of Bridges –
Safety Audit, capacity augmentation and Life enhancement

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Transactions of INAE
Journal of Structural Engineering
Editorial Board member:
Structural Engg and Mechanics
Advances in Computational design

- Rating and priority ranking of bridges
- Instrumentation, response measurement and data synthesis
- Performance evaluation and condition assessment
- Response evaluation under fatigue and dynamic loading
- Structural Health Monitoring
- Retrofitting and upgradation for service life enhancement
- Mechanics of materials and structures

Outline of the presentation

- About CSIR and Structural Engineering Research Centre
- What is SHM? Importance and relevance
- Sensors, data transfer, acquisition, acquisition and signal processing
- Structural Health Monitoring and health assessment
- Future trend, challenges and activities

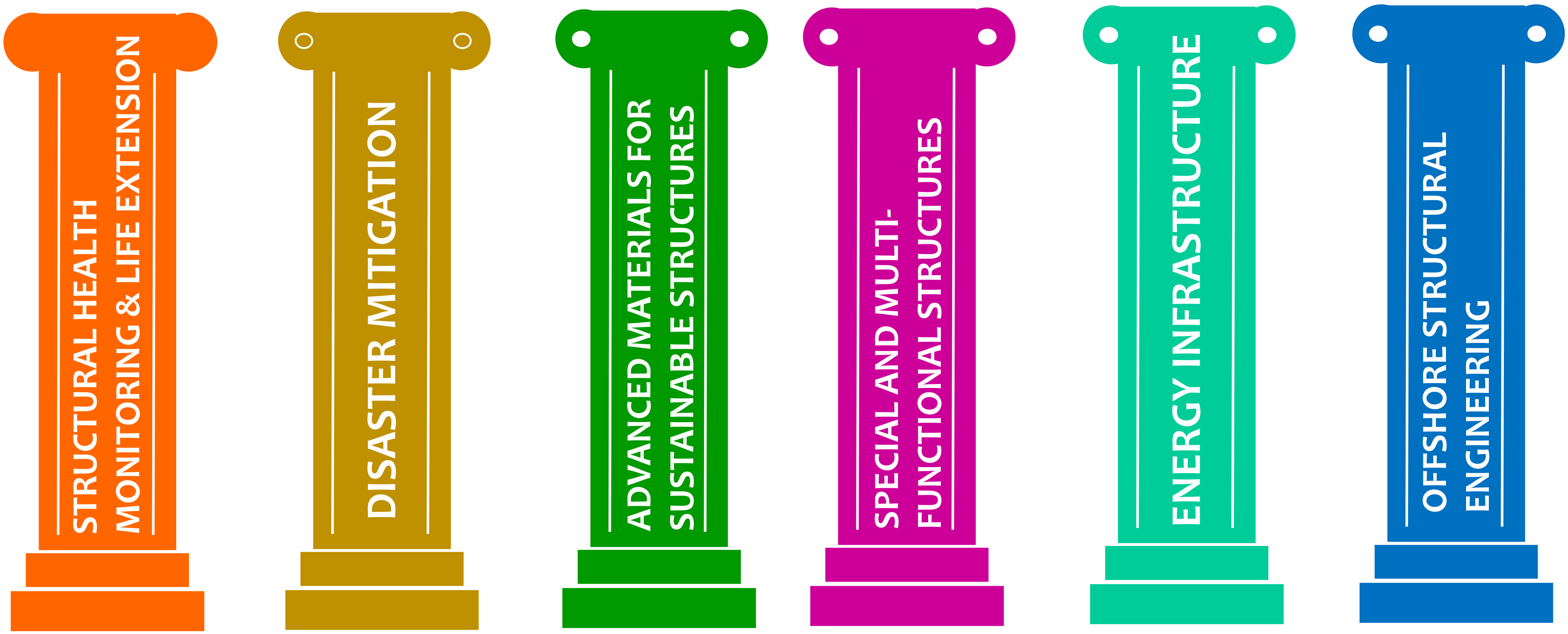
CSIR-Structural Engineering Research Centre

CSIR-Structural Engineering Research Centre is a constituent laboratory and a unit of Council of Scientific & Industrial Research (CSIR) under Department of Scientific and Industrial Research (DSIR) coming under the Ministry of Science and Technology of the Government of India.

Infrastructure Laboratories at CSIR-SERC

- Advanced Concrete Testing and Evaluation Laboratory
- Advanced Materials Laboratory
- Advanced Seismic Testing Laboratory
- Fatigue and fracture laboratory
- **Special- and Multi- functional Structures Laboratory**
- Wind Engineering Laboratory
- Tower Testing Laboratory
- Steel Structures Laboratory
- Structural Health Monitoring Laboratory
- Theoretical and Computational Mechanics Laboratory

Thrust areas of Research – CSIR-SERC



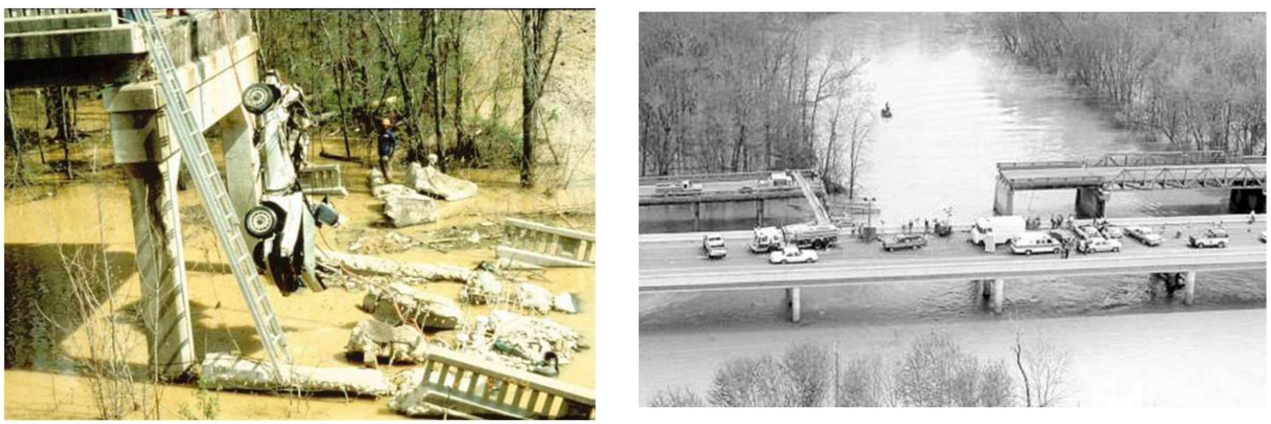
Health monitoring, assessment and prognosis

CSIR-SERC has a world class research laboratory and field testing capabilities/facilities for safety auditing of bridges (of various types, materials and spans) for Railways, Highways, PSUs, State agencies, etc...

- Expertise in carrying out instrumentation, data acquisition, signal processing, field investigations on **condition assessment, distress diagnosis, performance evaluation and health monitoring of bridges**
- **Capacity building for the field engineers** on maintenance and management of bridges
- Expertise in carrying out **experimental investigations** on components or full scale under **static, cyclic, fatigue and dynamic loading**
- Expertise on development of repair/retrofit/upgradation schemes for old and deteriorated bridges for **capacity augmentation** and **service life enhancement**

Failure of critical structures

I-90 Bridge over Schoharie Creek, New York (1987)



US 51 Bridge over Hatchie River, Tennessee (1989)

Failure of critical structures

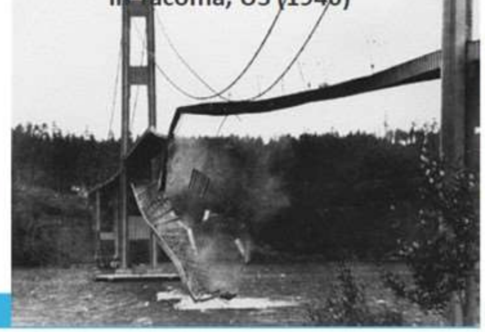
Sampoong Department Store Collapse due to Overload in Seoul, South Korea (1995).

Nicoll Highway Collapse due to Construction Failure and Overload, Singapore (2004)

I-35 Bridge Collapse in Minessota, US (2007)

Historical Archive of the City Collapse due to Ground Deformation in Cologne, Germany (2009)

Tacoma Bridge Collapse due to Wind in Tacoma, US (1940)



Sung-Su Bridge Collapse in Korea (1994)

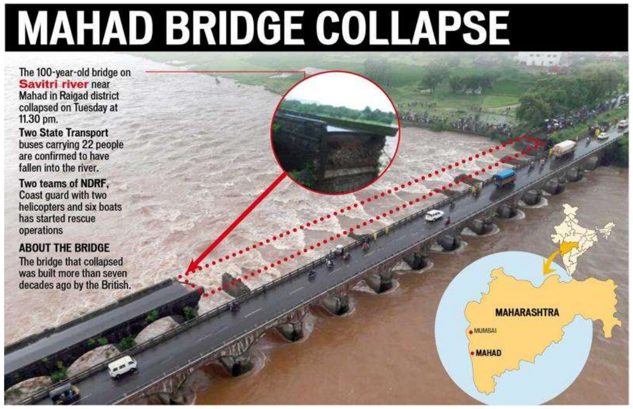
bridge collapse in Goa -2017

bridge collapse near Siliguri

near Calicut, in 2001

Bridge over Alaknanda river near Srinagar

Majerhat bridge in southern Kolkata



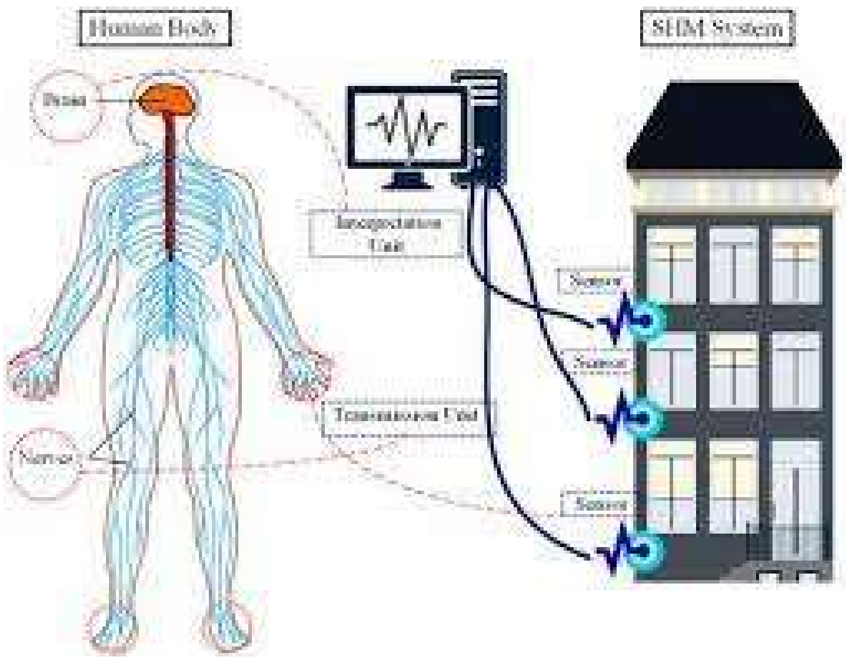
What is SHM?

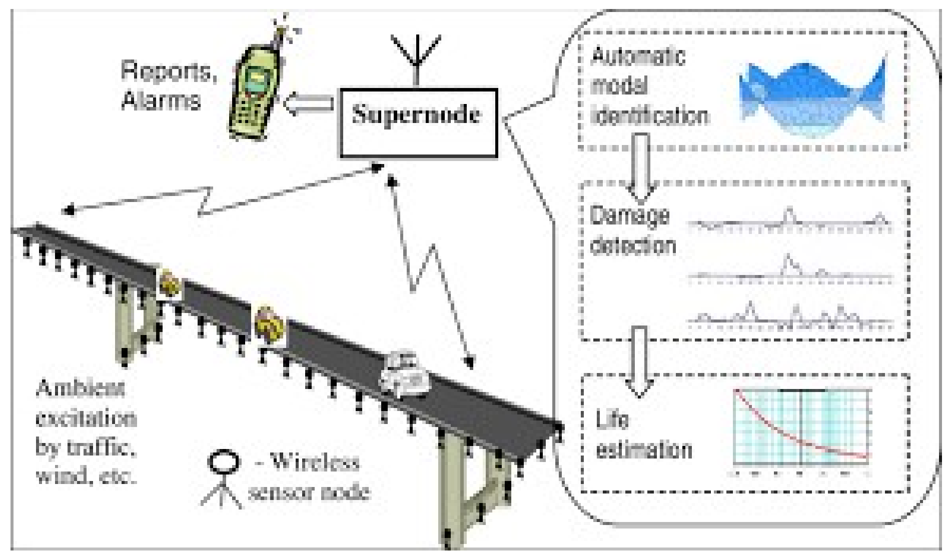
- Conventional NDE ⇨ Schedule based Maintenance: Flaws can be induced and become critical between successive maintenance schedules
- Overwhelming interest pervasive throughout the civil, mechanical and aerospace engineering communities to address the issue
- Need for real-time detection of damage at an early stage – led to the development of the general area of **Structural Health Monitoring**.

Paradigm shift

Regular schedule-driven maintenance ⇨ Condition-based as-needed maintenance regime

Structural Health Monitoring and assessment





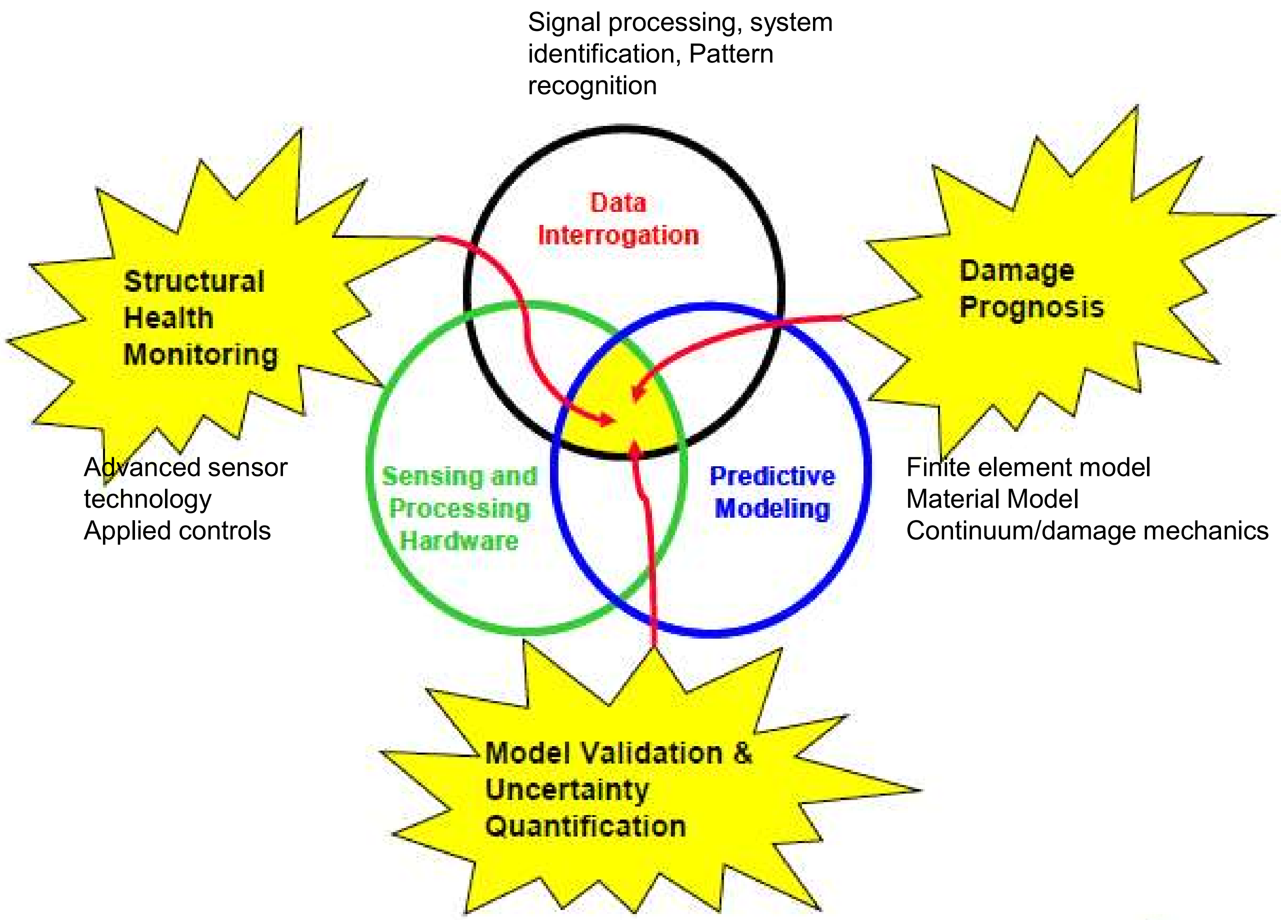
The process of implementing a damage detection and characterization strategy for engineering structures

Advantages of SHM

Advantages of SHM include…

- Increased understanding of in-situ structural behaviour
- Early damage detection
- Assurances of structural strength and serviceability
- Decreased down time for inspection and repair
- Development of rational maintenance / management strategies
- Increased effectiveness in allocation of scarce resources
- Enables and encourages use of new and innovative materials

Schematic of SHM process



Classification of SHM Systems

Level IV

Detect presence, location, severity and consequences of damage

Level III

Detect presence, location and severity of damage

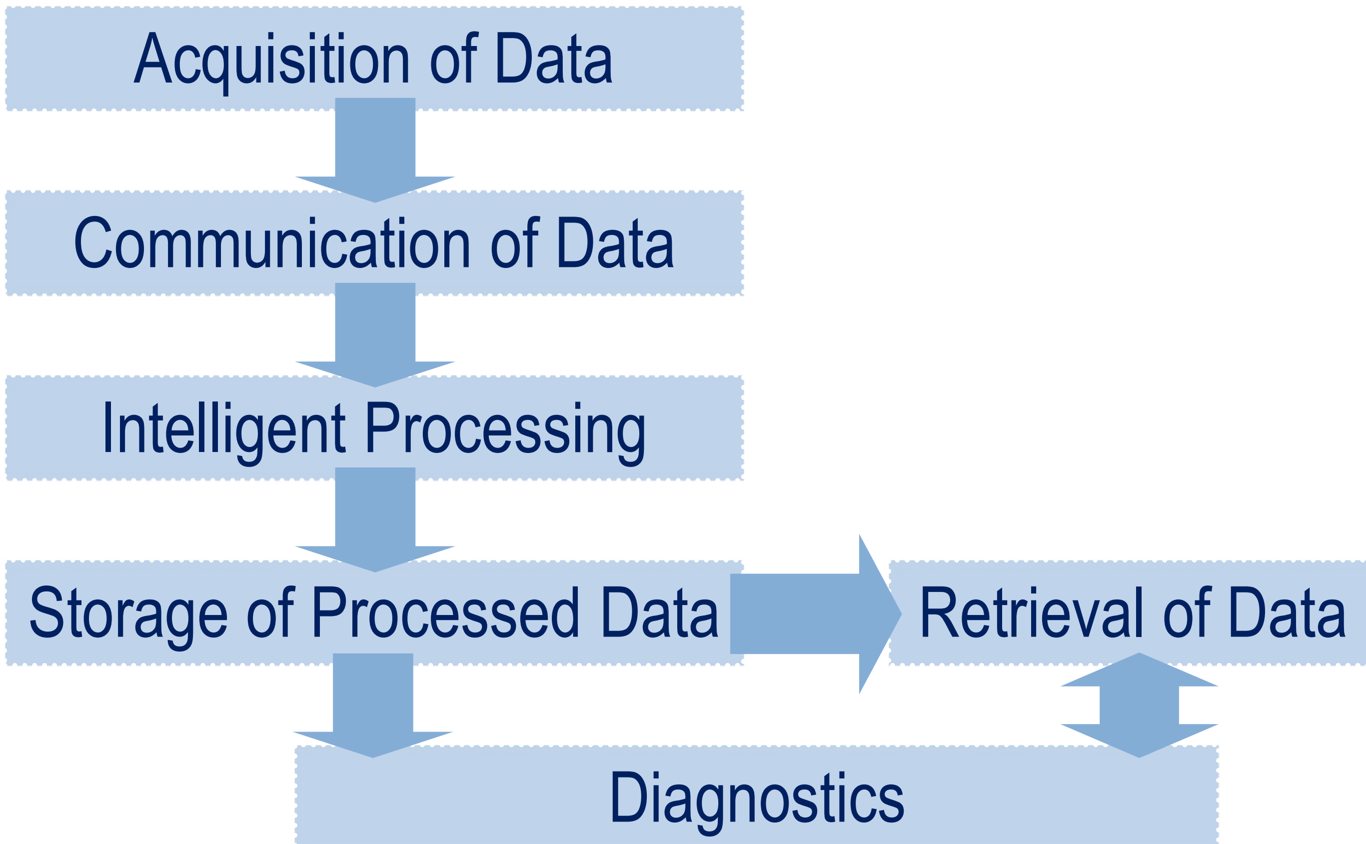
Level II

Detect presence and location of damage

Level I

Detect presence of damage

SHM System Components

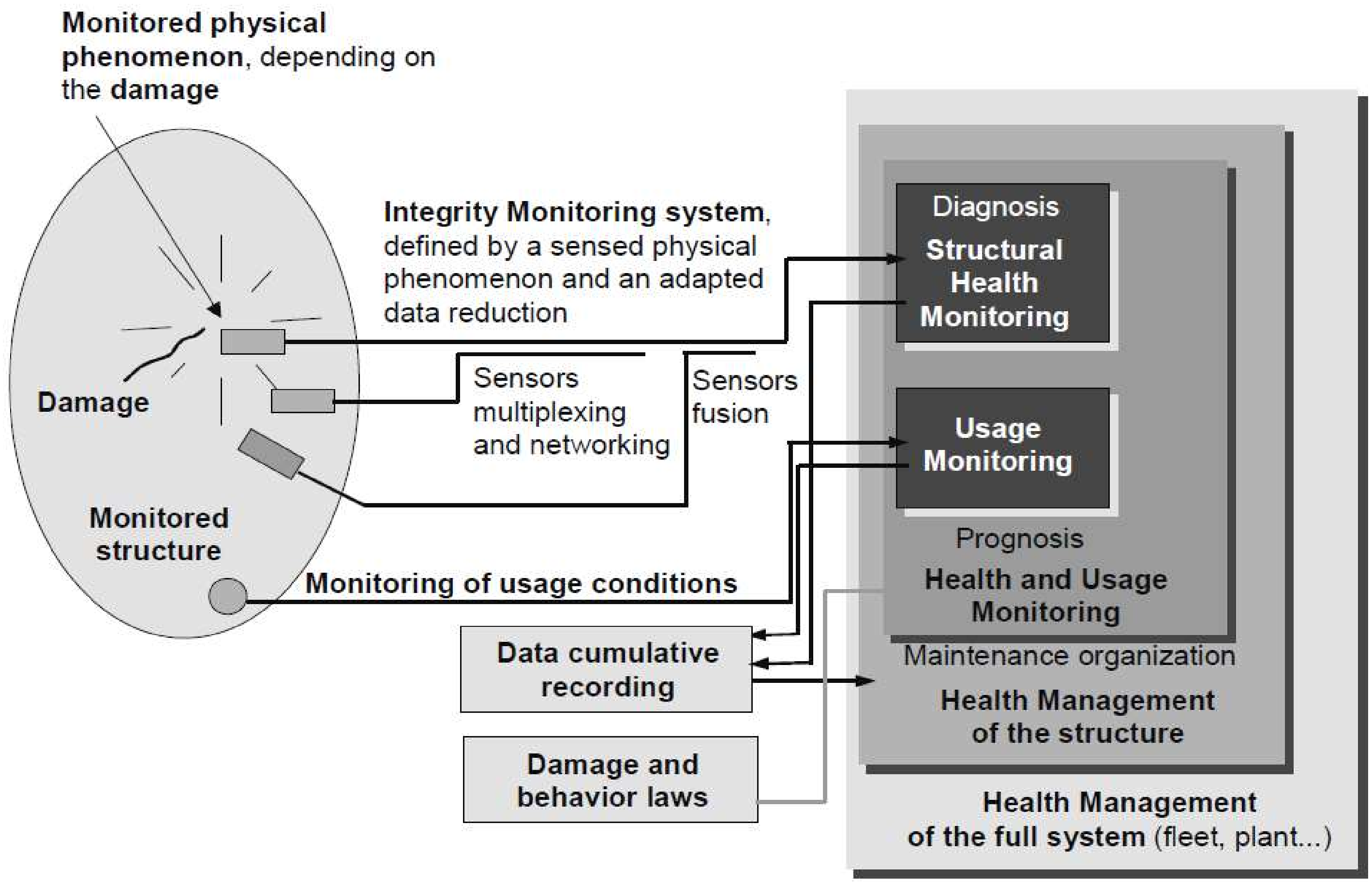


Hierarchical Structure of SHM (Rytter, 1993)

Diagnosis
- Identification
- Localization
- Characterization

Prognosis
- Assessment of severity -Remaining Useful Life

Principle and Organization of a SHM System



Types of Sensors

LOAD	Load cells
DISPLACEMENT	Linear Variable Differential Transformer
	Linear Potentiometer
ACCELERATION	Accelerometers
TEMPERATURE	Thermocouples
	Integrated Temperature Circuits
STRAIN	Vibrating wire strain gauges
	Electrical resistance gauges
	Fiber optic sensors

SHM Categories

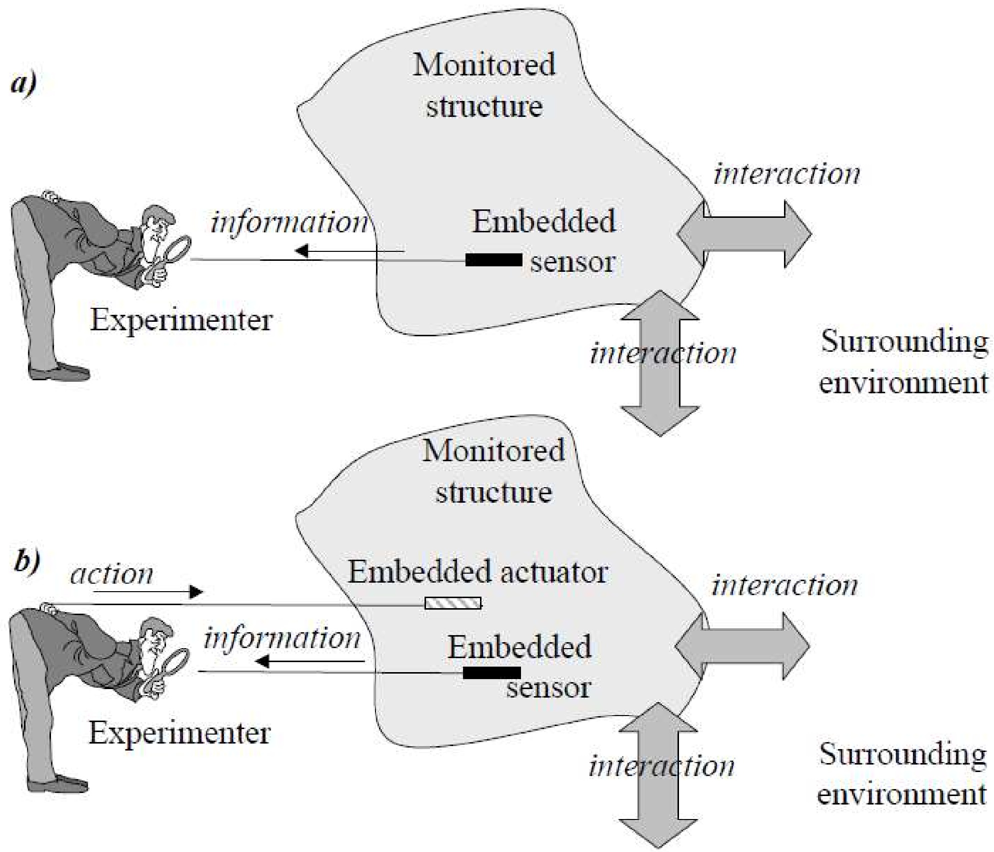
Static Field Testing:
Behaviour tests
Diagnostic tests
Proof tests

Dynamic Field Testing:
Stress history tests
Ambient vibration tests
DLA tests
Pullback tests

Periodic Monitoring:
Includes field testing
Tests to determine changes in structure

Continuous Monitoring:
Active monitoring
Passive monitoring

Passive and Active Monitoring



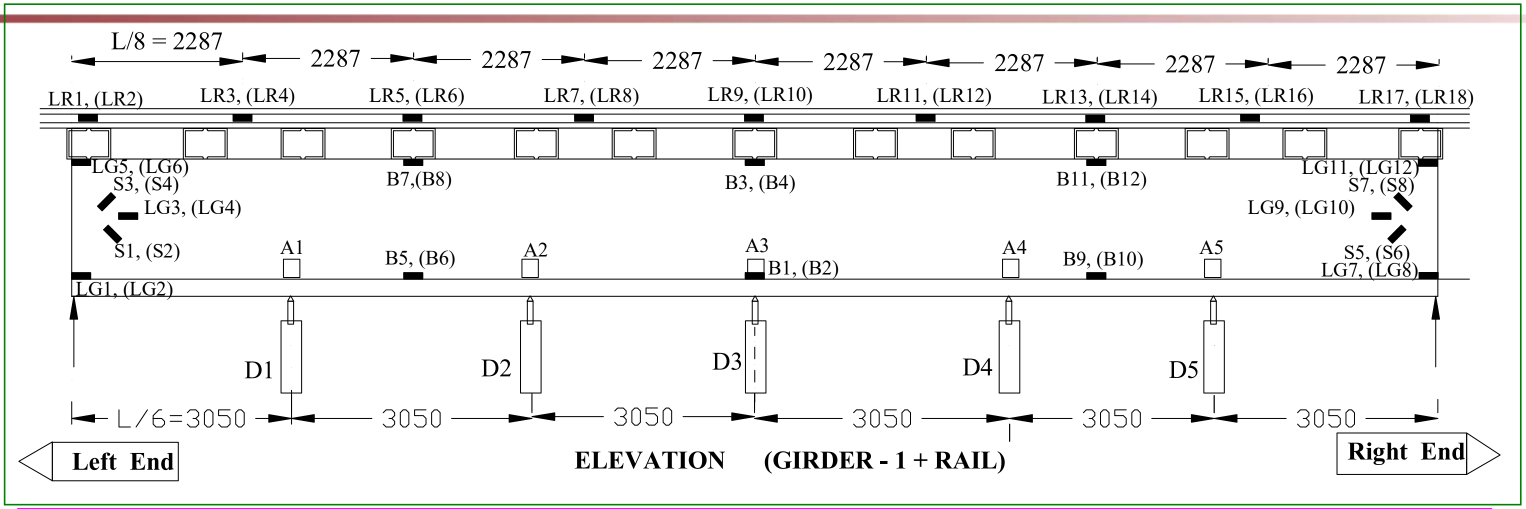
Mobile laboratory and complete instrumentation

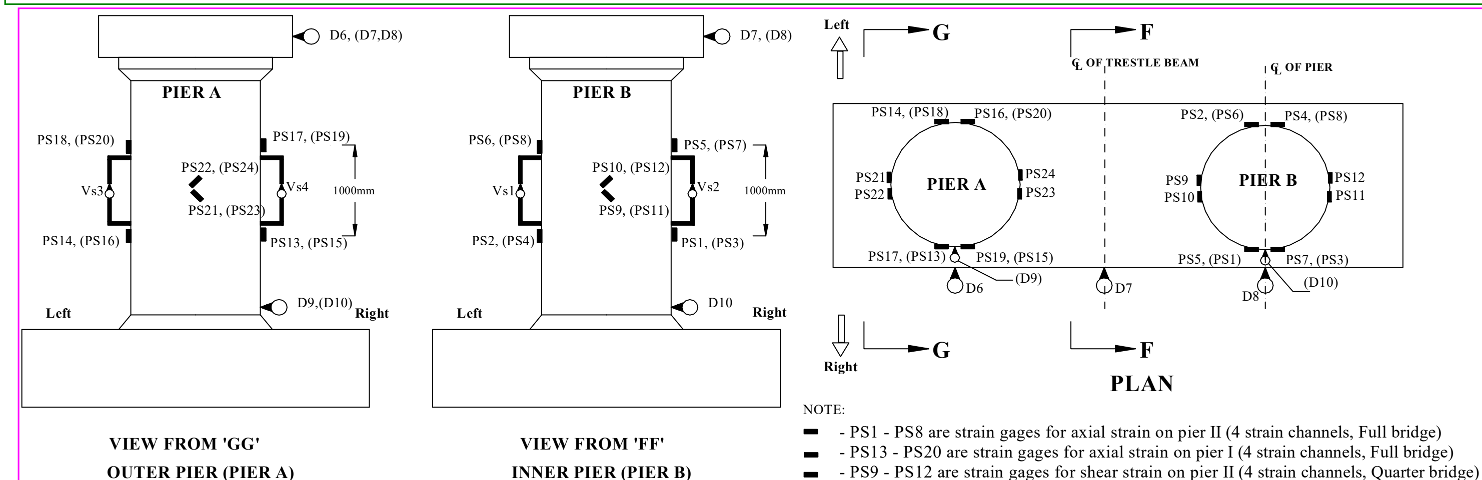
Long stroke electro-dynamic Multi-shaker Excitation System

Performance Evaluation of Railway Bridges

- Electrical Strain Gauges
- Accelerometers
- Linear variable displacement transducers (LVDTs)
- Specially fabricated load cells / Instrumented fixture arrangement
- Data acquisition systems
- Dynamic strain conditioner/amplifier

Instrumentation scheme adopted

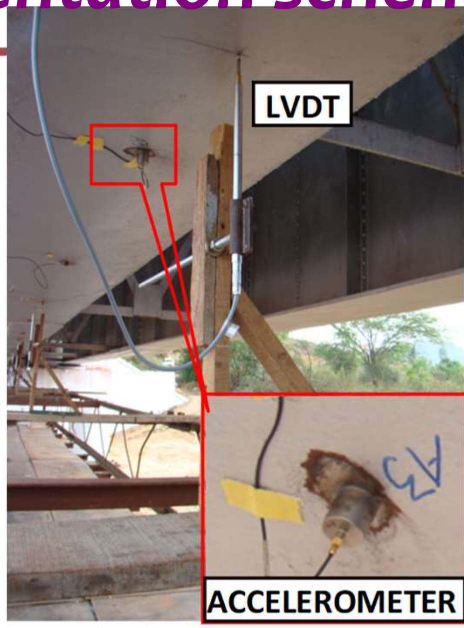




All dimensions are in mm

NOTE:
- PS1 - PS8 are strain gages for axial strain on pier II (4 strain channels, Full bridge)
- PS13 - PS20 are strain gages for axial strain on pier I (4 strain channels, Full bridge)
- PS9 - PS12 are strain gages for shear strain on pier II (4 strain channels, Quarter bridge)
- PS21 - PS24 are strain gages for shear strain on pier I (4 strain channels, Quarter bridge)
- Vs1 - Vs2 are LVDTs for strain measurement on pier I and pier II
- D6 - D10 are LVDTs for tilt & rotattion measurement (5 channels)

Instrumentation scheme adopted



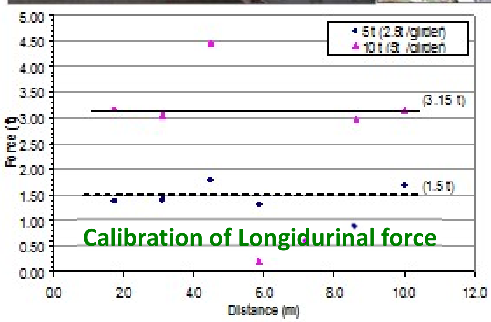
LVDT and accelerometers

Strain gage on rail

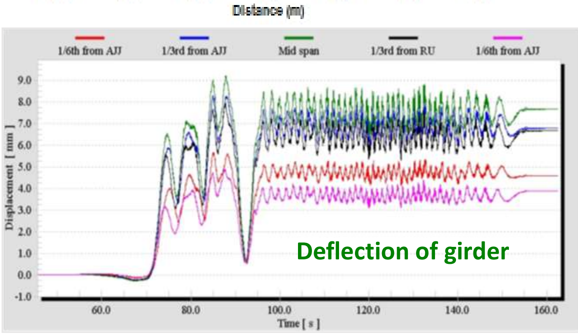
LVDT and strain gaging on piers

Realtime longitudinal force measurement

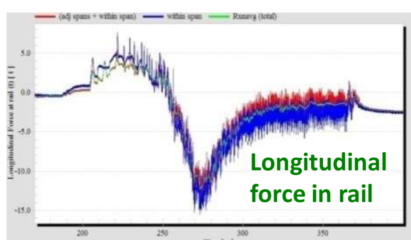
Special fixture arrangements for evaluation of longitudinal force



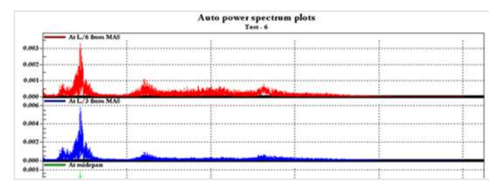
Calibration of Longidurinal force



Deflection of girder



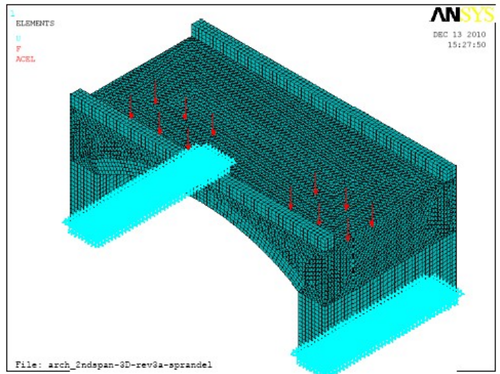
Longitudinal force in rail

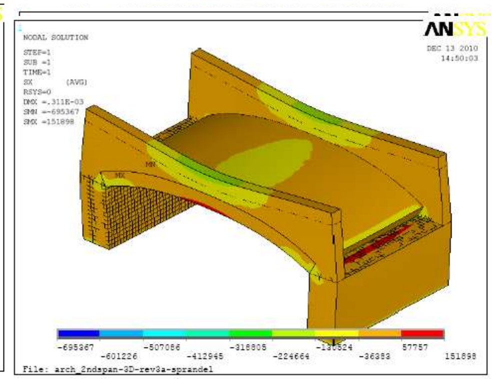


Frequency spectra

Vibration based health assessment

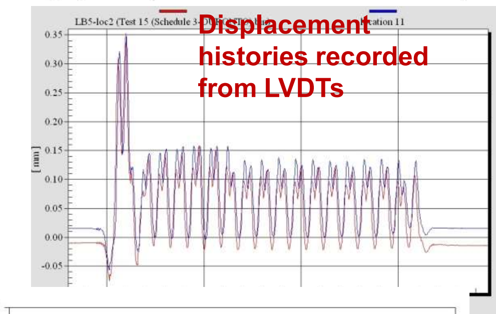
Live load stress monitoring in masonry arch bridge



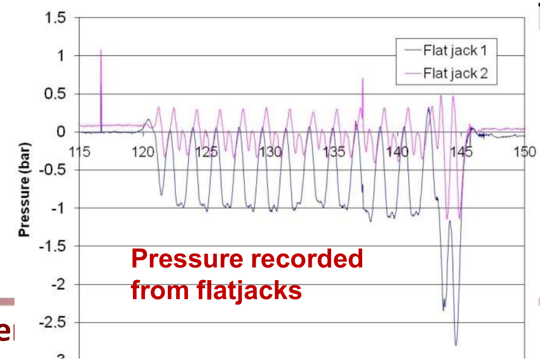


Flat jack installation

LVDT and accelerometers

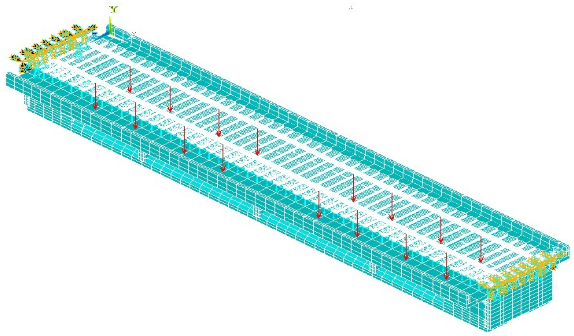


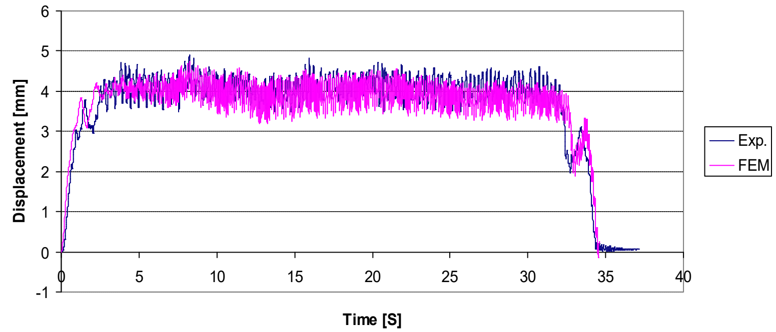
Displacement histories recorded from LVDTs

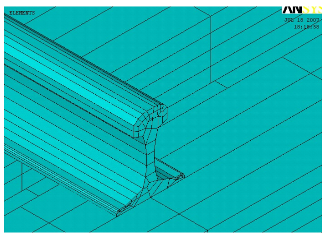


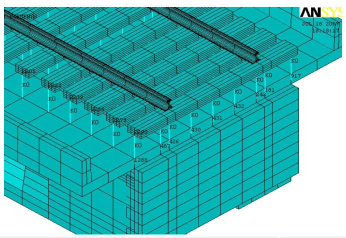
Pressure recorded from flatjacks

Numerical simulations for response prediction







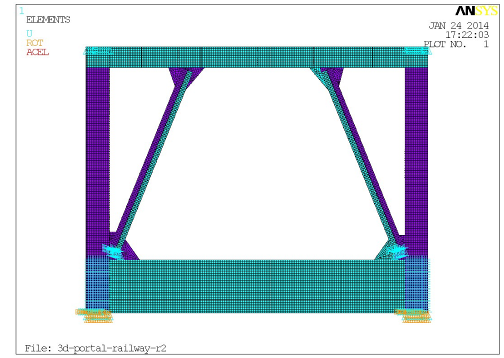


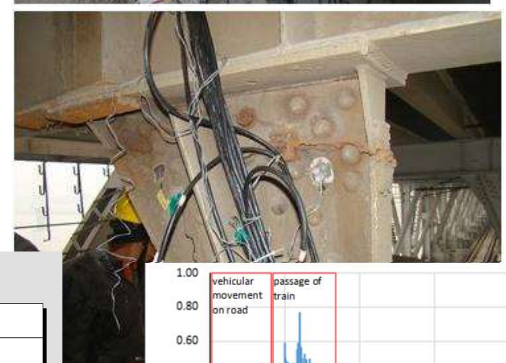
LOADING CONDITION	Displacement at centre of the span, mm		
	Field Measurement	ANSYS Result	Percentage of Difference
Loco placed centrally on the span	2.876	3.0375	5.615
Loco placed for Maximum Bending Moment	2.744	2.9385	7.088
Wagons placed centrally on the span	4.579	4.7870	4.5424
Wagons placed for Maximum Bending Moment	4.357	4.5487	4.3998

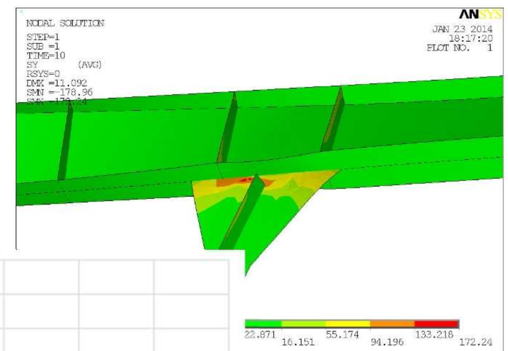
Distress diagnosis and restoration

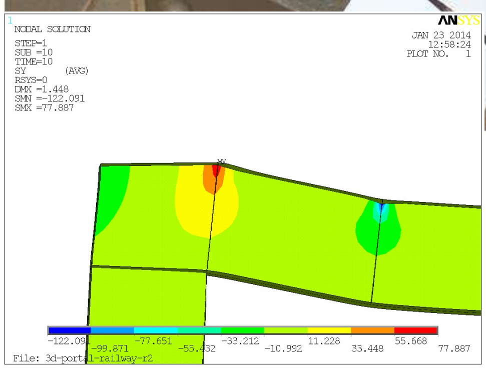


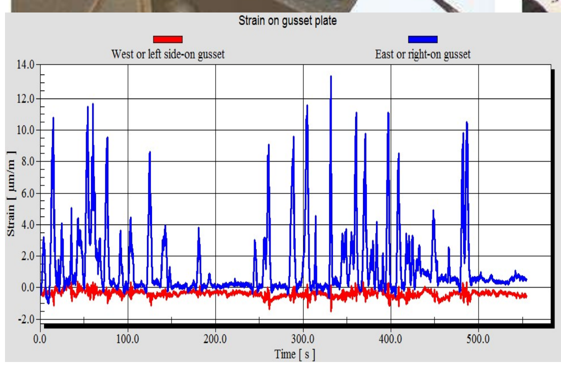


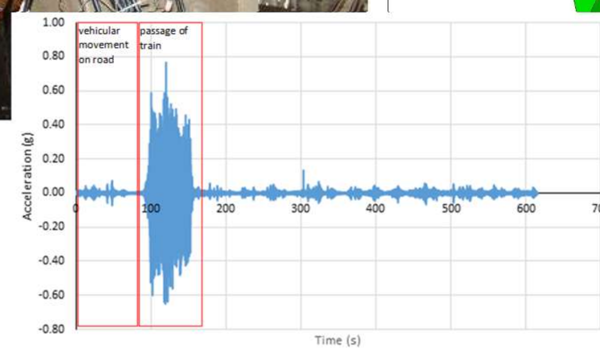


ELEMENTS
ANSYS
JAN 24 2014
17:22:03
PLOT NO. 1
File: 3d-portal-railway-r2




NODAL SOLUTION
STEP=1
SUB =1
TIME=10
SY (AVG)
RSYS=0
DMX =11.092
SMN =-178.96
ANSYS
JAN 23 2014
18:17:20
PLOT NO. 1
22.871
16.151
55.174
94.196
133.218
172.24


NODAL SOLUTION
STEP=1
SUB =10
TIME=10
SY (AVG)
RSYS=0
DMX =1.448
SMN =-122.091
SMX =77.887
ANSYS
JAN 23 2014
12:58:24
PLOT NO. 1
-122.091
-99.871
-77.651
-55.432
-33.212
-10.992
11.228
33.448
55.668
77.887
File: 3d-portal-railway-r2


Strain on gusset plate
West or left side-on gusset
East or right-on gusset
Strain [μm/m]
Time [s]
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
0.0
100.0
200.0
300.0
400.0
500.0


vehicular movement on road
passage of train
Acceleration (g)
Time (s)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
100
200
300
400
500
600
700

External prestressing –shear in anchor zone

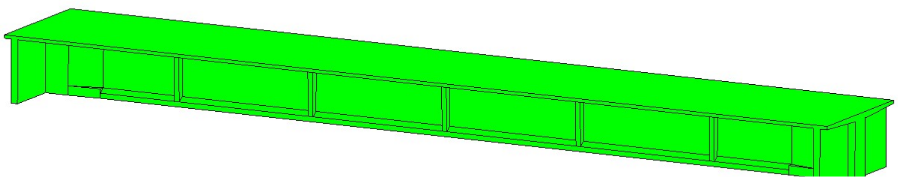
- Rehabilitation of distressed PSC structures is usually carried out by adopting external prestressing.
- There is a need to rehabilitate structures in the fast track mode, but adopting the scheme which would ensure performance of the retrofitted structure to its desired level.
- Complicated three-dimensional reaction at the anchor zone in conventional external prestressing scheme has been replaced by simple shear in longitudinal direction in the case of proposed external prestressing scheme.

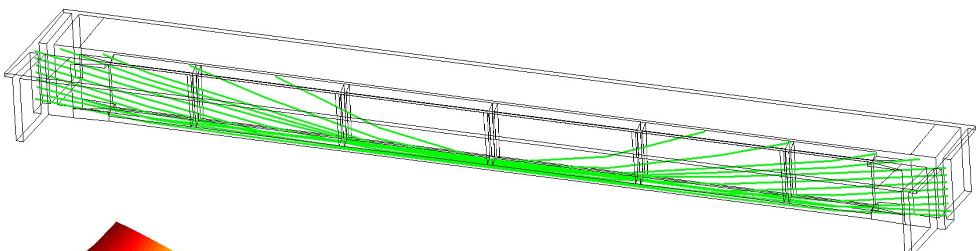
Re-engineering of Pamban bridge

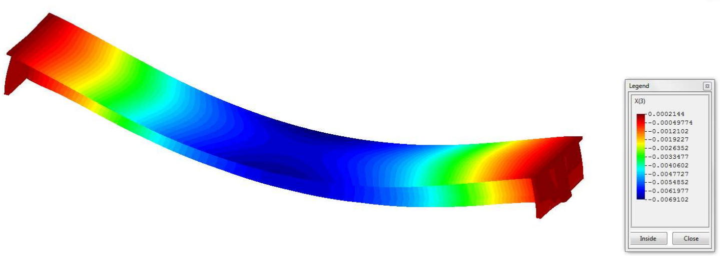


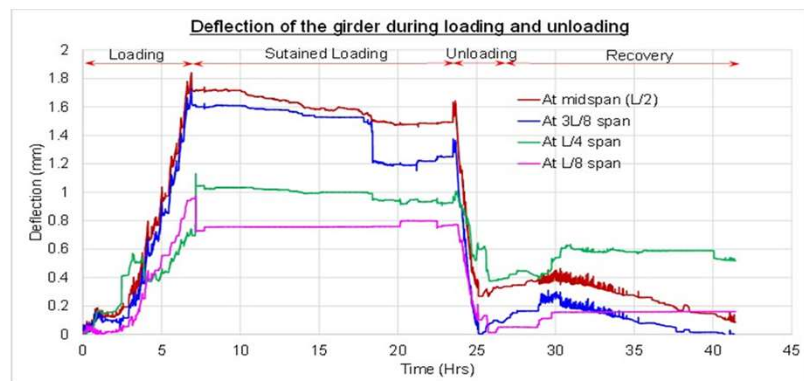



Health assessment of prestressed ash pipe bridge

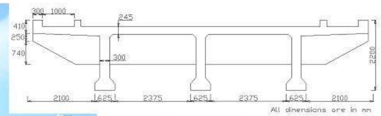




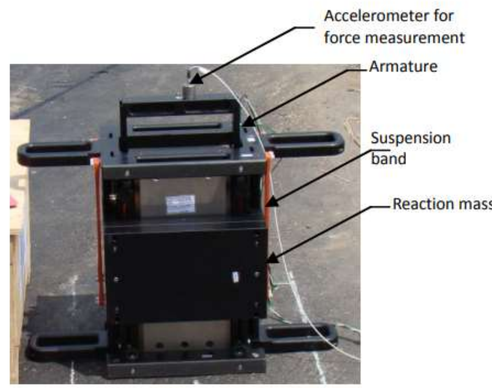


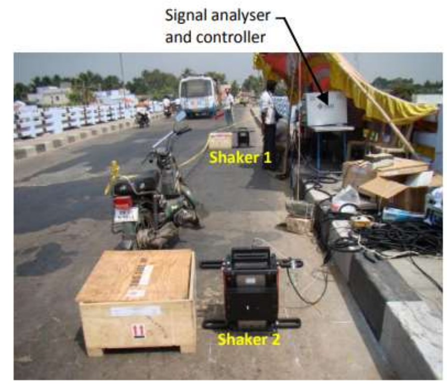


Induced vibration – road bridge assessment



Cross-sectional details





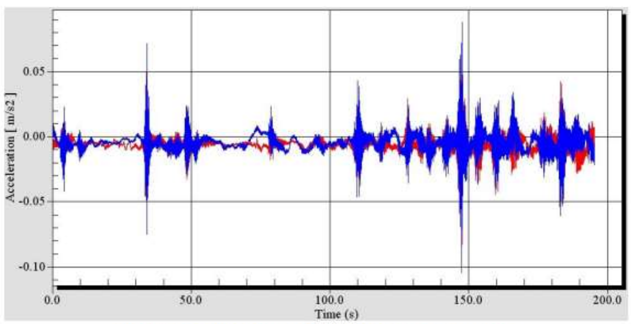


Fig.6 Acceleration time history response

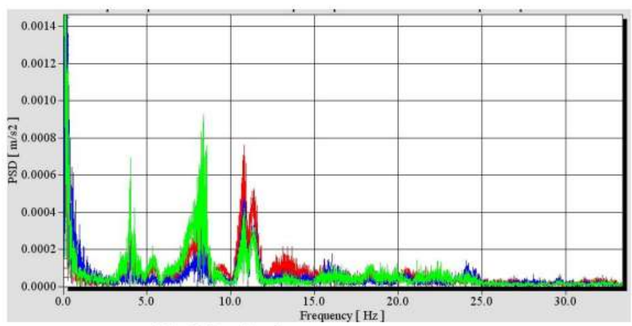
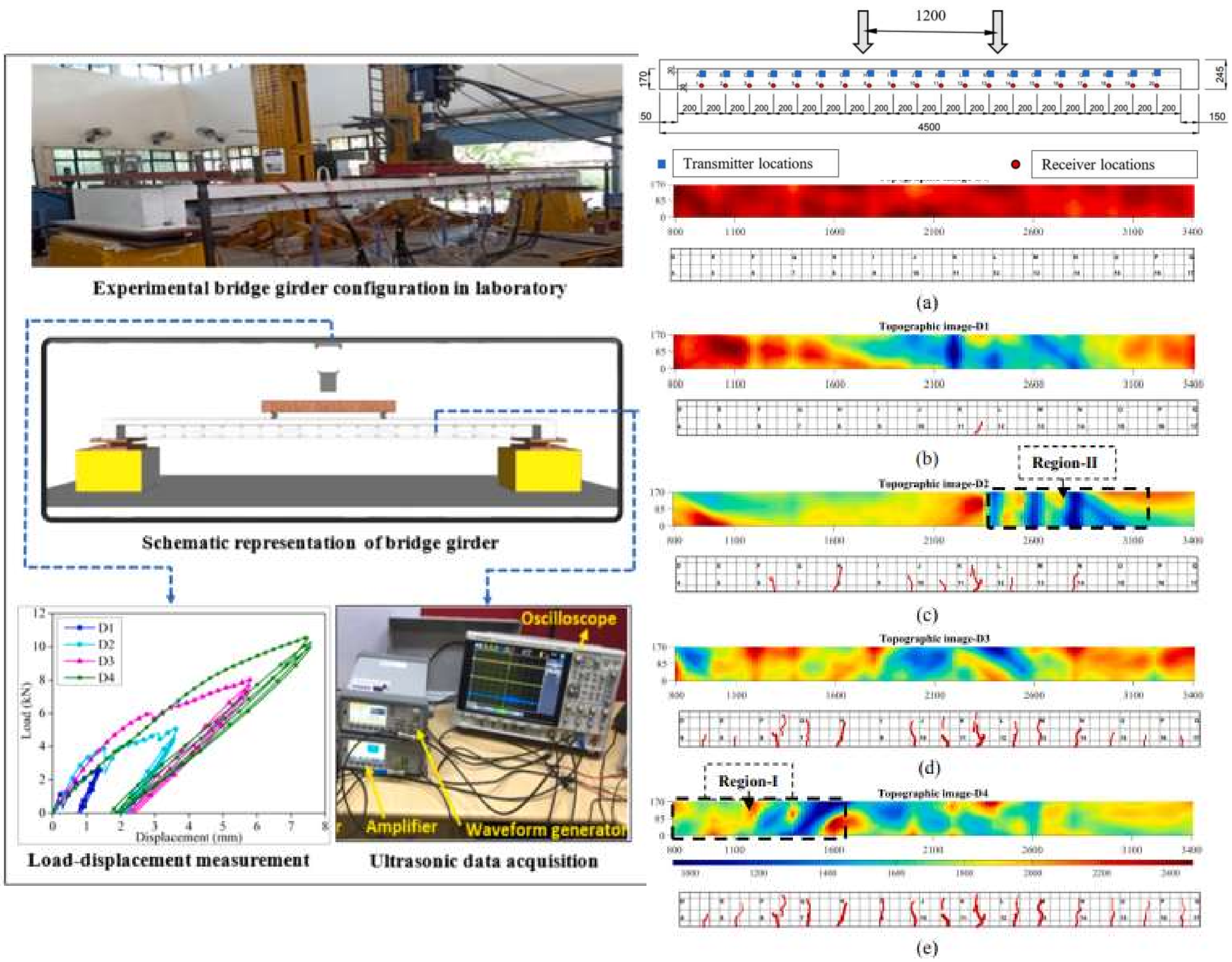


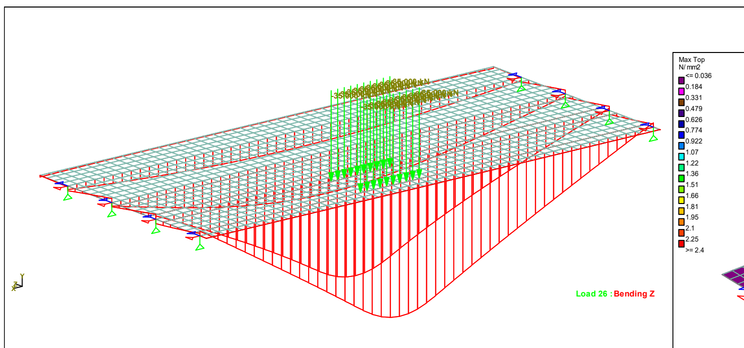
Fig.7 Typical auto power spectra

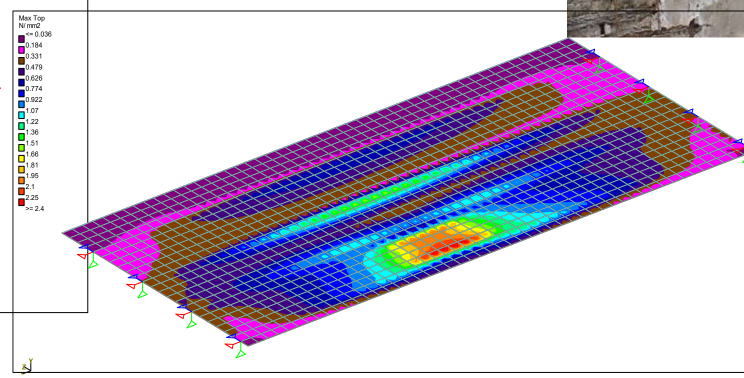
Damage mapping using ultrasonic tomography

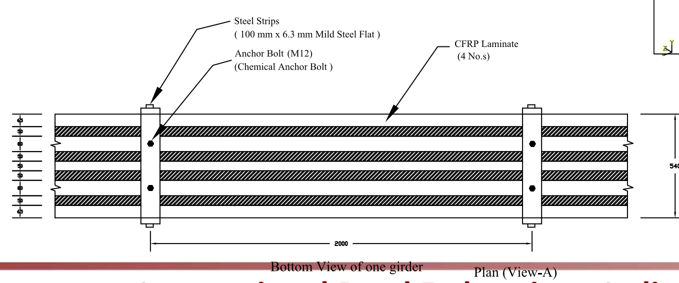


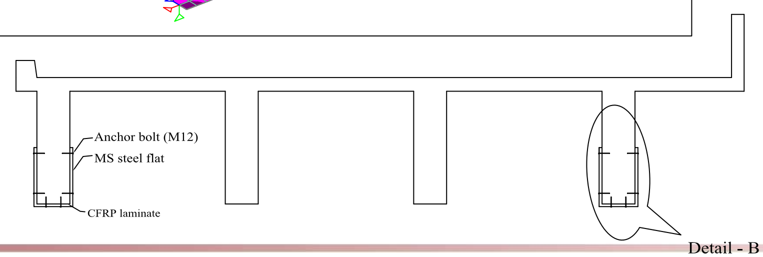
Tomographic imaging results and the corresponding experimentally observed crack pattern (schematic sketch) for different damage levels, (a) D0; (b) D1; (c) D2; (d) D3; (e) D4.

Retrofit of corrosion damaged exterior girders of bridge



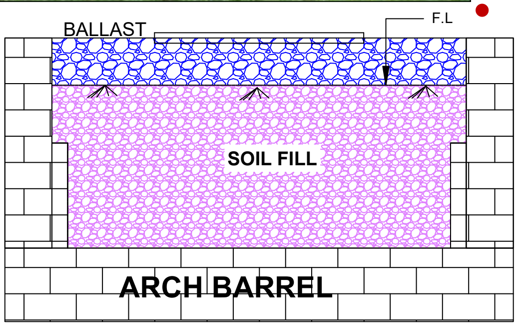


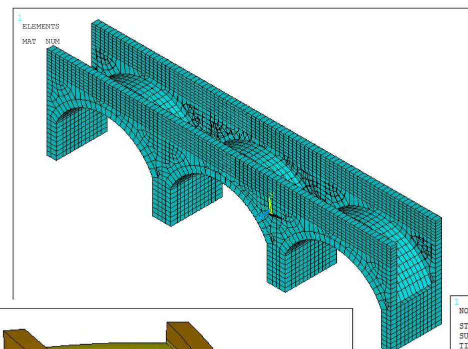


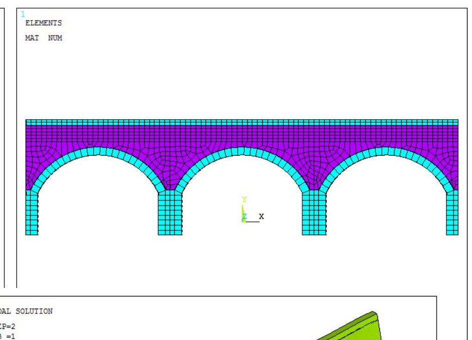


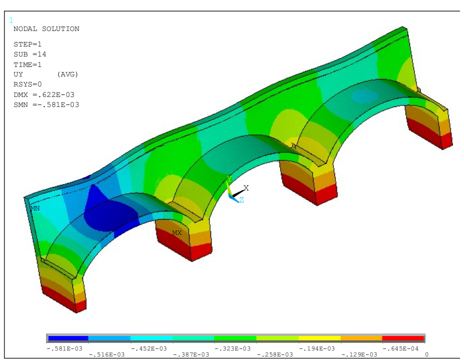
Numerical simulation of masonry arch railway bridge

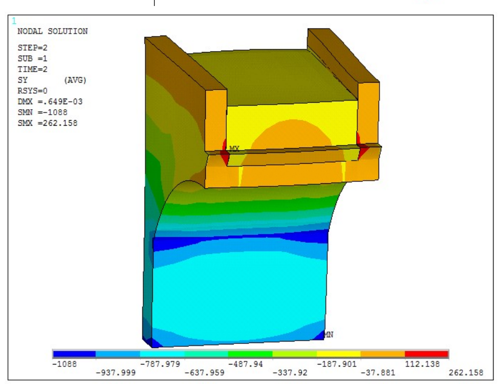
- Solid 65 employed for masonry material- uses a smeared crack model to allow the formation of cracks
- Overlaid on the arch barrel and contained within the spandrel walls, 3D solid elements to model the fill
- To facilitate movement of the fill material over the barrel without generating significant tensile stresses, 3D frictional contact surfaces included
- Drucker-Prager material law used for fill material (cohesion, angle of internal friction and angle of dilation)
- William-Warnke material model used for arch masonry

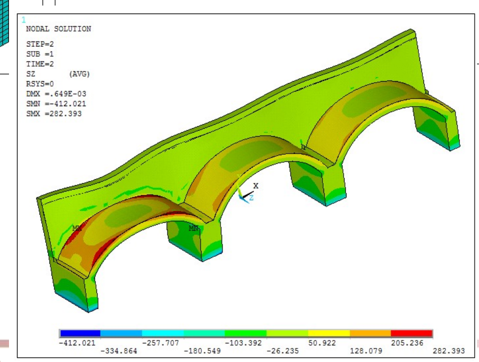




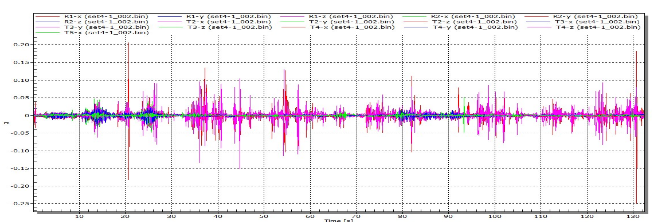




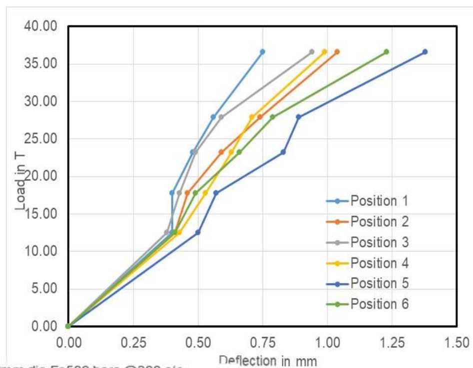


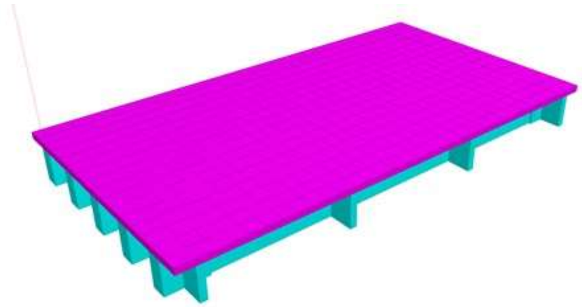


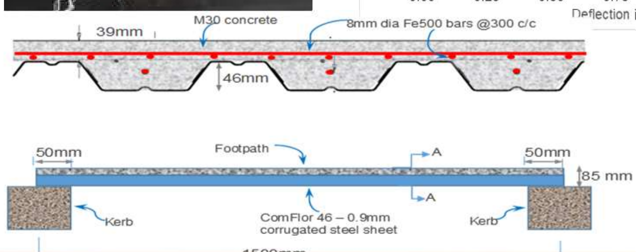
Instrumentation and performance evaluation

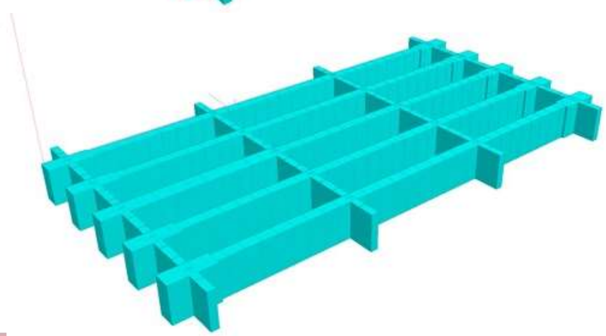


Performance evaluation –Post bridge









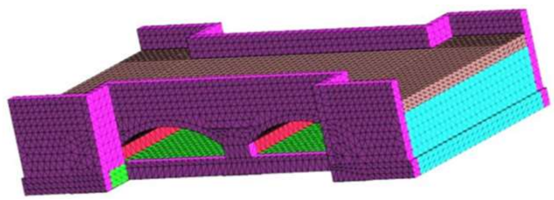
French era brick masonry arch bridge – life enhancement

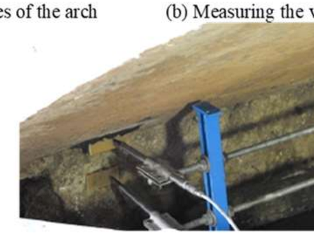

(a) Measuring the responses of the arch


(b) Measuring the vertical deflection of the arch

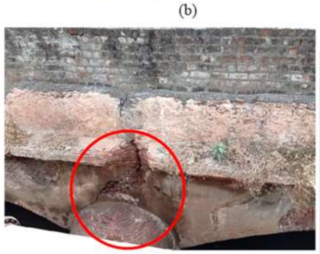

(a)

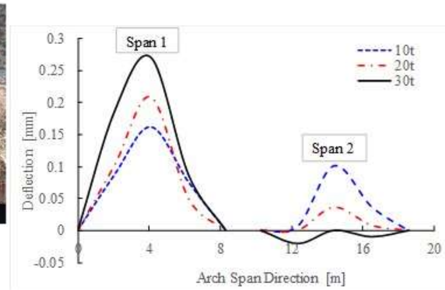

(b)




(c) Measuring the arch spread

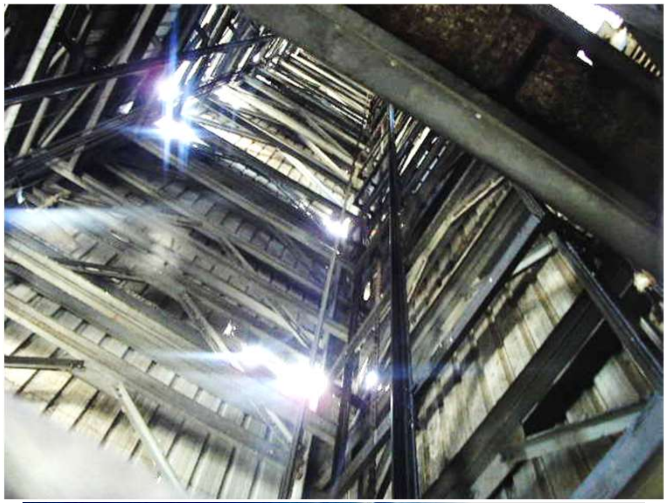

(c)

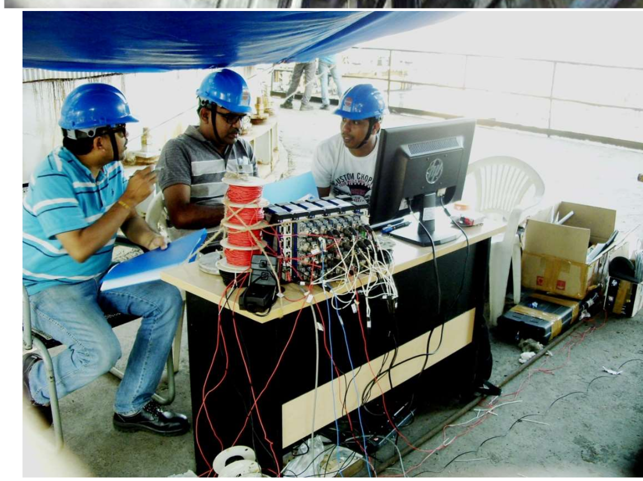

(d)

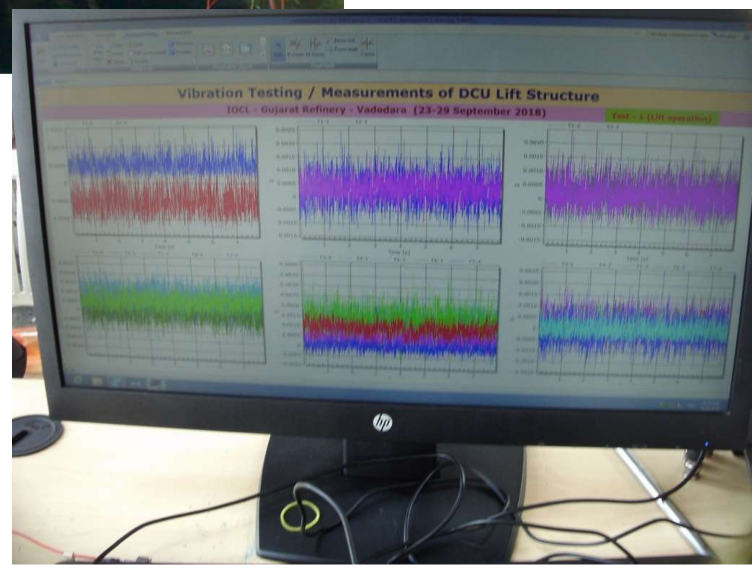



(d) Measuring the widening of existing cracks on the arch

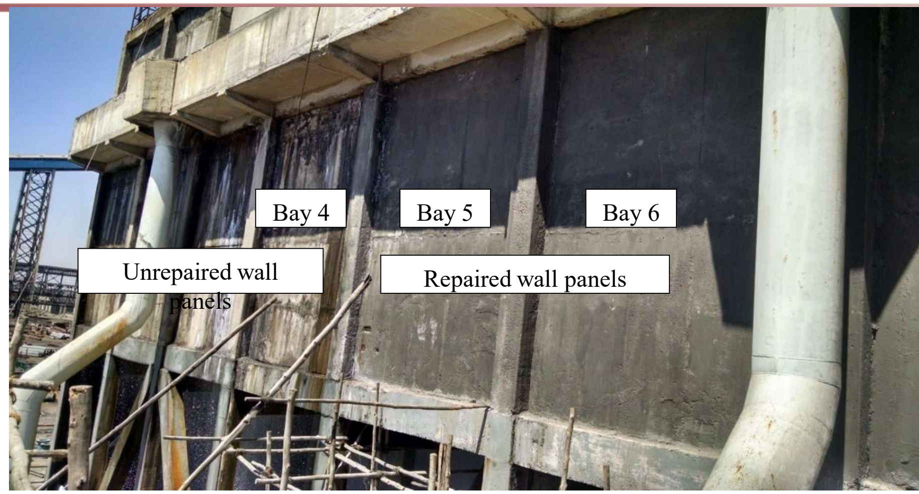
French era brick masonry arch bridge - assessment

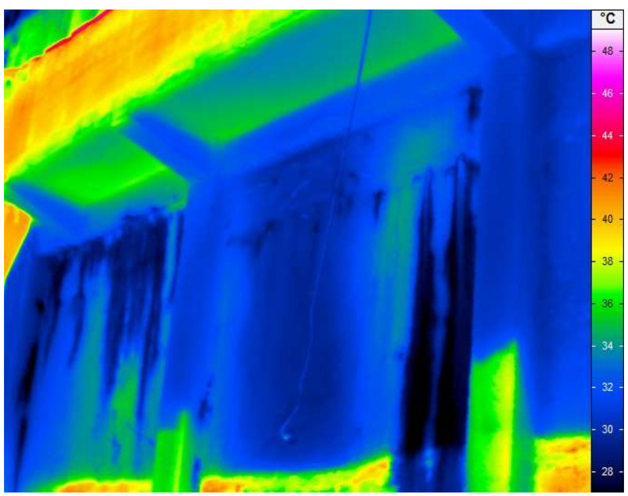


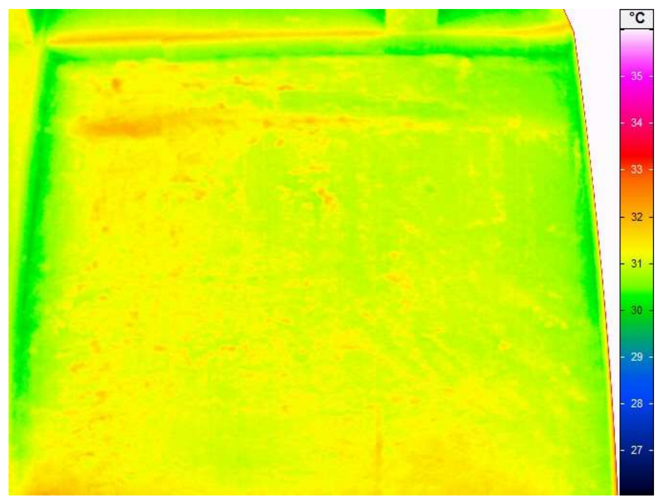




Infrared Thermography for integrity assessment







IR Thermographic image of the unrepaired wall panel with lot of seepage

IR Thermographic image of the repaired wall panel

Monitoring of Polavaram dam -Acoustic Emission

CSIR-SERC
ENGINEERING SUSTAINABLE STRUCTURES

Integrity assessment of Polavaram dam through Acoustic Emission (AE) and advanced non-destructive evaluation (NDE) Techniques

Challenge: Due to the presence of huge concrete, dense reinforcement and bi-directional prestress conventional NDT&E is not suitable.

Outcomes: An innovative multi-sensor based three-dimensional instrumentation strategy for assessing microcracks deep inside the structure

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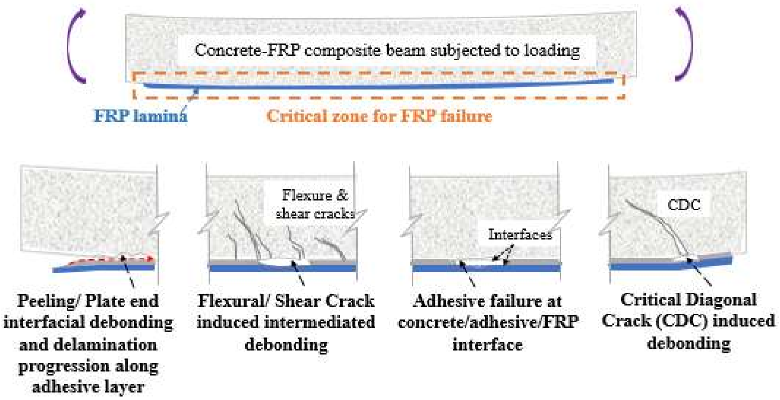
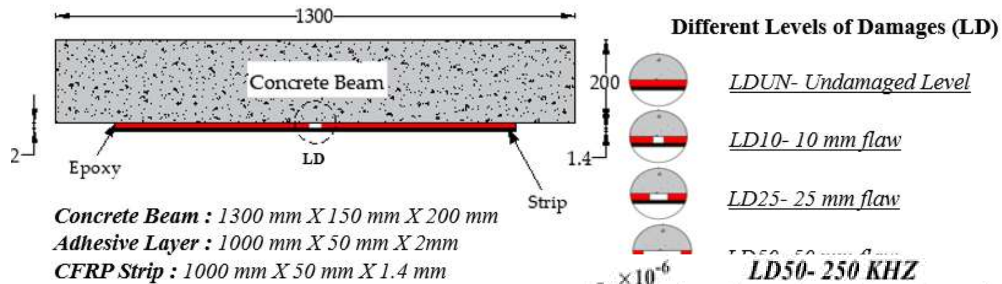
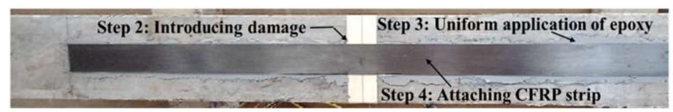
POWER
7 AFFORDABLE AND CLEAN ENERGY

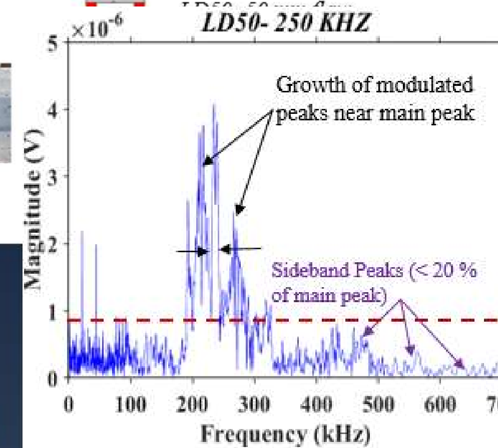
Prestressed trunnion beams in Polavaram Dam

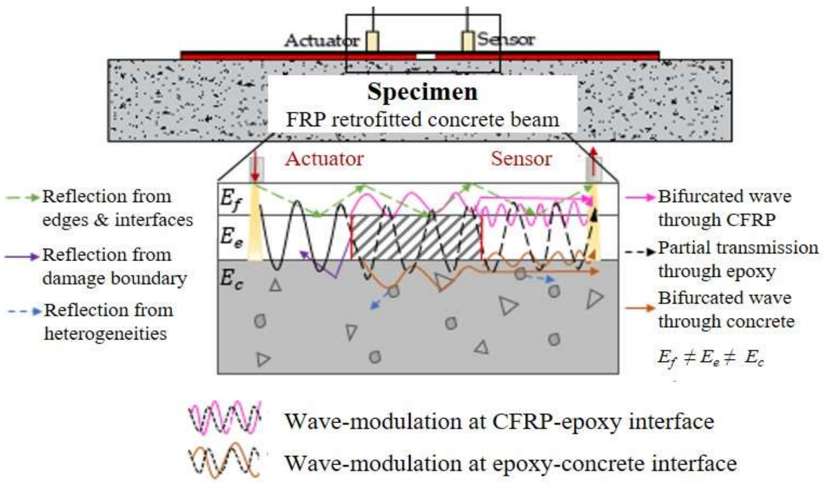
FRP applications- need understanding, mechanics and skill

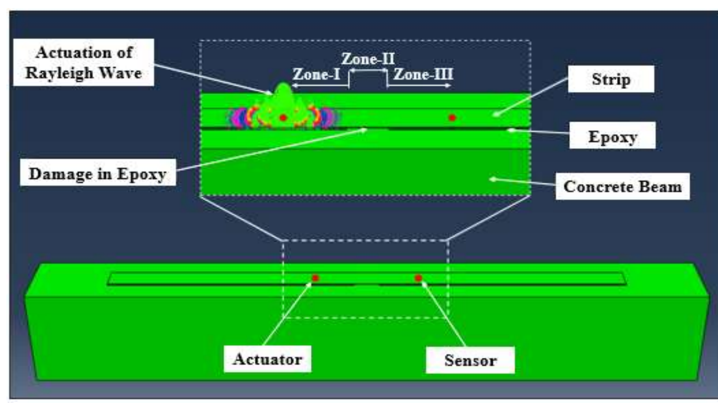


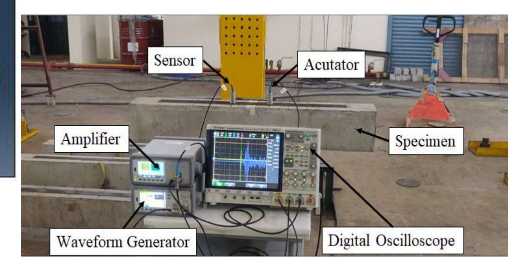




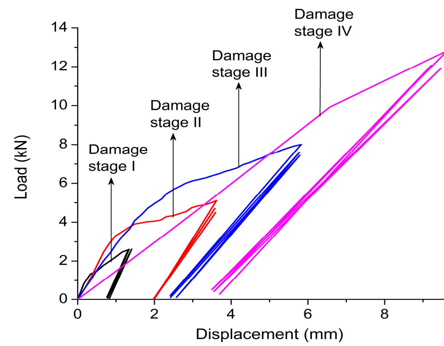


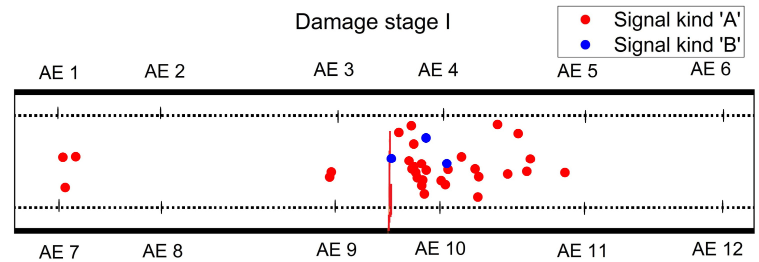


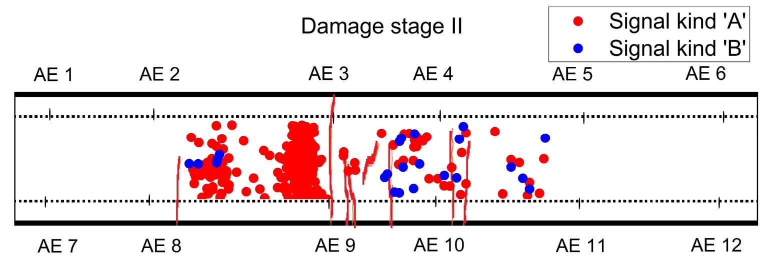


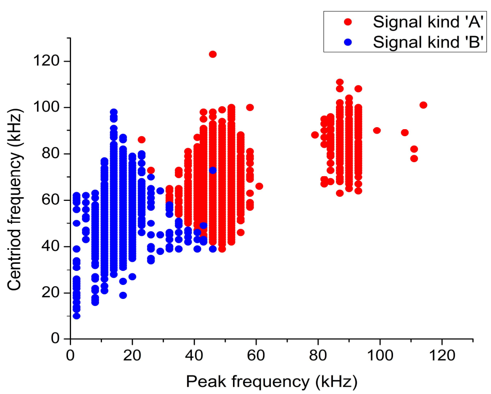


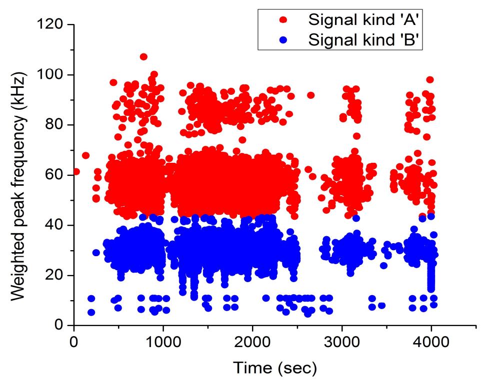
AI-ML for damage classification

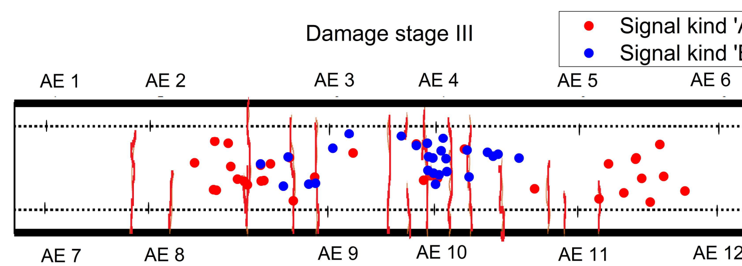




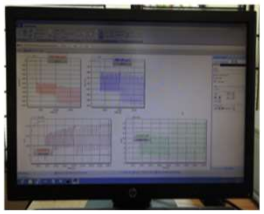


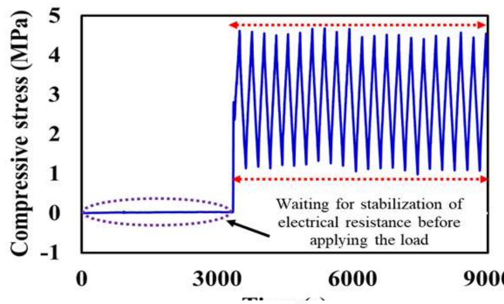


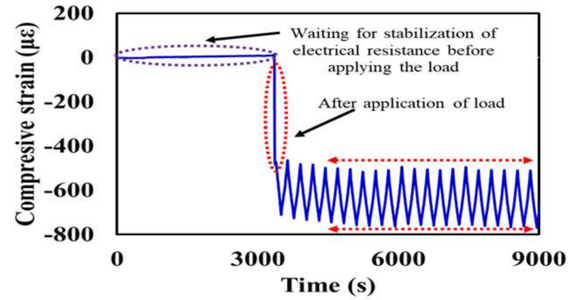


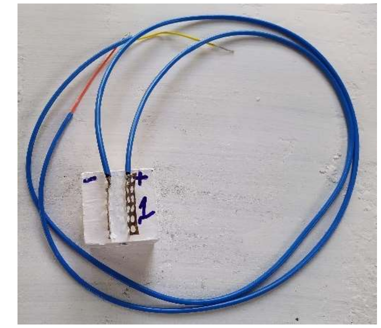


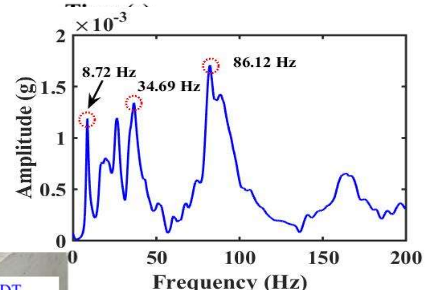
Indigenously developed smart embedded sensor

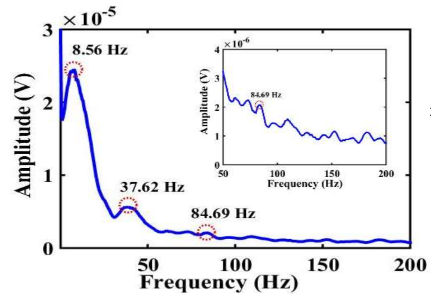


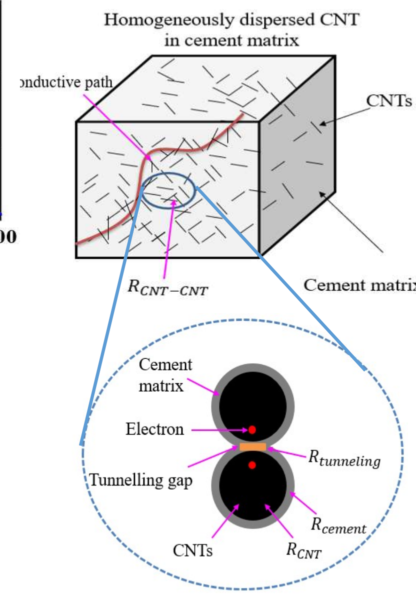


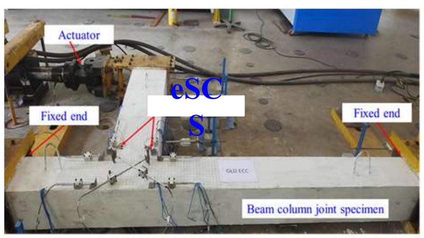


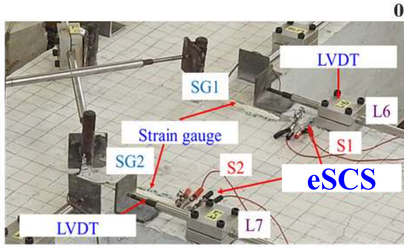


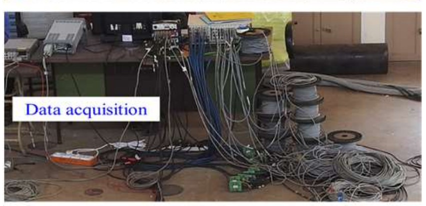


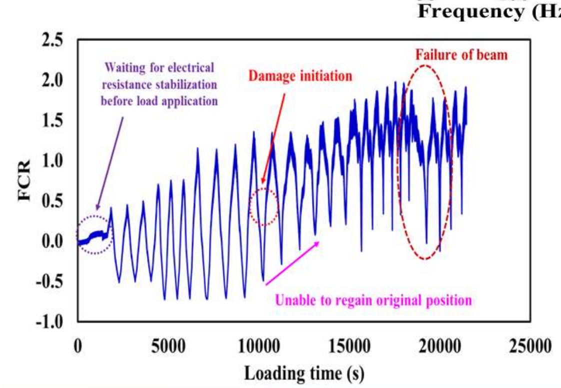








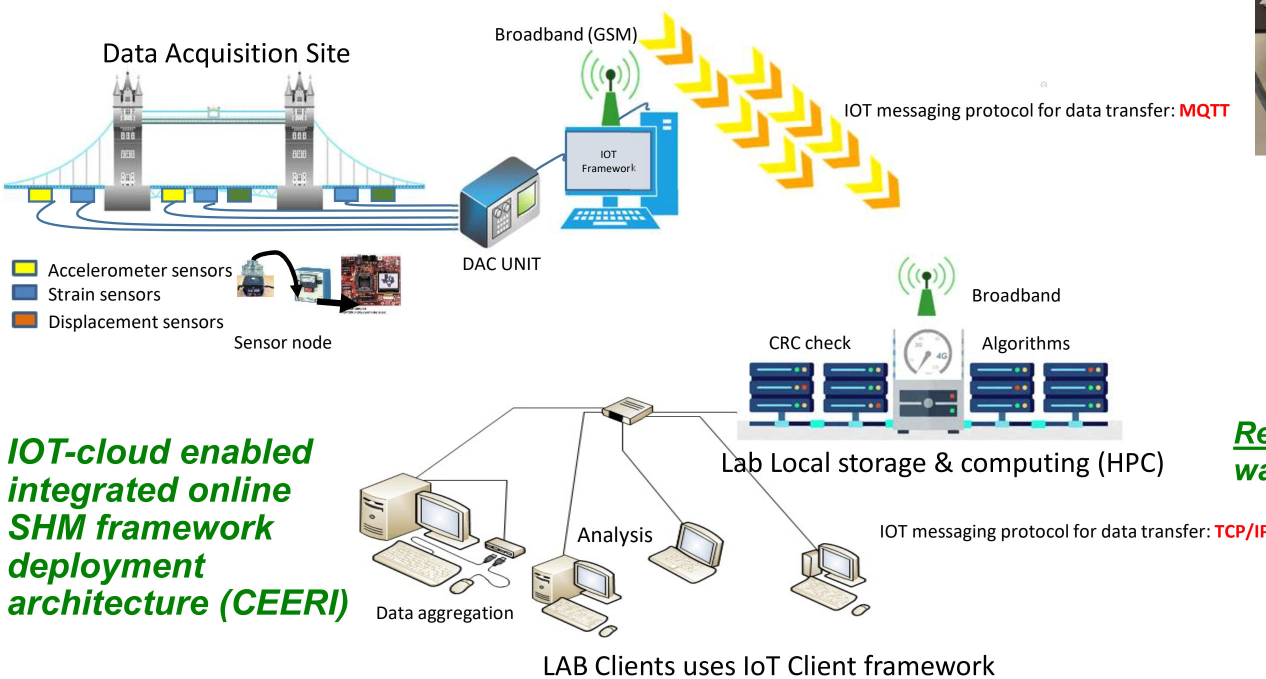




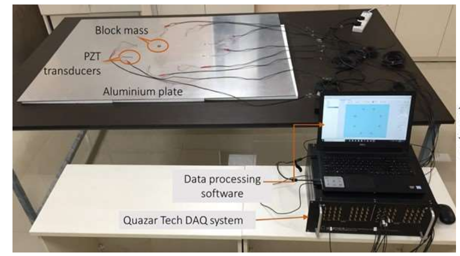
Future trend and challenges in SHM

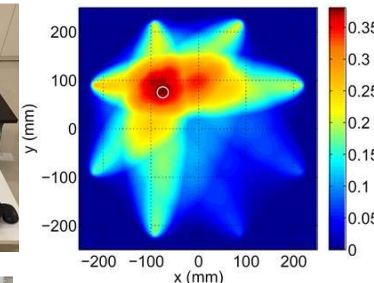
- Output-only methods
- Population based methods
- Data driven models - Machine learning algorithms
- Distributed fibre optics sensing for long structures
- Stretchable sensors/bioinspired design
- Vision based sensing
- Optimal sensor placement
- Sensor fault detection
- Model based techniques - Efficient and accurate computational models
- Material models to predict strength based on current microstructure
- Use of IOT platforms for wireless sensing and data transfer

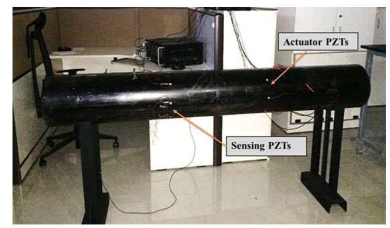
Mission Mode Project : Structural Health Monitoring



IOT-cloud enabled integrated online SHM framework deployment architecture (CEERI)

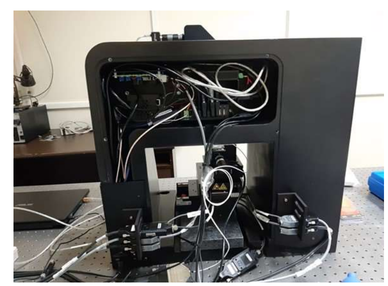






RTRM at extended mode DI

Refined baseline-free damage identification in thin walled structures using Lamb wave propagation (SERC)



Development of Femto-second laser based FBG inscription for application in SHM (CGCRI)

Participating Labs

CSIR- SERC, CSIR- CBRI, CSIR-CEERI, CSIR- CGCRI, CSIR- NAL

Way forward

- Baseline-free SHM techniques for detection, localization and characterization of damages in varied types of infrastructure
- Data-driven damage localization and quantification methods for SHM using AI techniques
- Development of **Digital Twin for critical structures** (for example: bridges)
- **Indigenous, low cost durable sensors (point and distributed)**

***Establishment of Centre of Innovation** & Manufacturing Eco-system for Sensors (CIMES)*

2022-2027

Funded by

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MINISTRY OF **ELECTRONICS AND INFORMATION TECHNOLOGY**

THANK YOU

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CSIR-SERC can significantly contribute towards safety auditing, capacity augmentation and service life enhancement of bridges.

- **Full scale field testing** of the bridges
- Condition assessment and **non-destructive testing** of bridges
- **Complete instrumentation** of super- and sub- structure, response measurements of in-service bridges under vehicular traffic
- **Performance evaluation** of bridges under service load conditions as well for increased vehicular load demands
- **Distress diagnosis and damage assessment** of bridges to identify weak zones in the bridge structures based on static and dynamic measurements
- **Capacity augmentation** of bridges due to the increased demand
- **Life enhancement** (repair, rehabilitation, retrofitting, and strengthening) of bridges
- Complete and long term **structural health monitoring** of bridges (SHM)
- **Overall design and proof checking** of all types of bridges

Imparting training to the engineers on inspection, maintenance and management of bridges