Materials & Structural Health Monitoring

Engineering Mechanics Symposium – Workshop Introduction

Richard Loendersloot[1] Eliz-Mari Lourens[2] Johan Hoefnagels[3]

[1]University of Twente, [2]Delft University of Technology, [3]Eindhoven Technical University

26th of October 2022

Table of Contents

Introduction

Organisers of the Workshop "Materials & Structural Health Monitoring"

University of Twente

Delft University of Technology

Eindhoven University of Technology

What is SHM?

Wikipedia

Structural health monitoring (SHM) involves the observation and analysis of a system over time using periodically sampled response measurements to monitor changes to the material and geometric properties of engineering structures such as bridges and buildings.

The Constructor – Building Ideas

Structural health monitoring (SHM) is the process of using damage detection and characterization techniques for critical structures like bridges, wind turbines, and tunnels. It is a non-destructive in-situ structural evaluation method that employs several types of sensors embedded or attached to the structure.

What is SHM?

IGI-Global

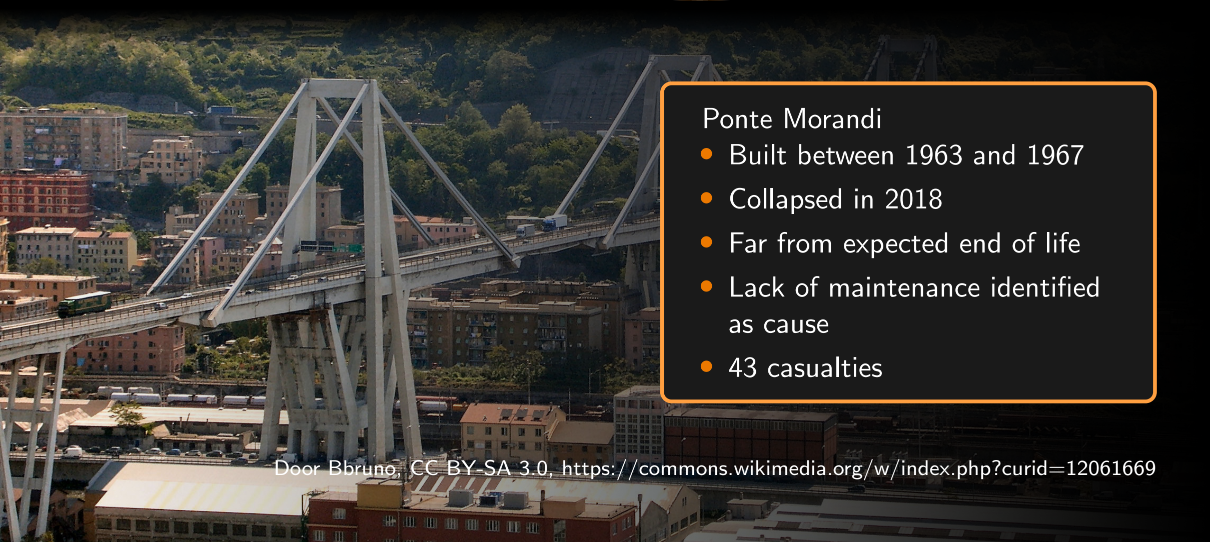
1. Systematic procedure used to evaluate the damage of engineering structures such as bridges.
2. The integration of sensors and actuators in a material or structure in order to perform load monitoring, damage detection, damage diagnosis and damage prognosis so that nondestructive testing becomes online and in situ.
3. Process of implementing a damage detection and characterization strategy for engineering structures.
4. Structural Health Monitoring (SHM) is the process of detecting and characterizing damages in engineering structures to ensure structural integrity and safety of buildings, bridges and all kinds of engineering structures. The monitoring is automated and can continuously monitor and detect state (such as strain, stress, and temperature) and damages (such as cracks, holes, and ruptures) of structures with minimum human intervention. Using SHM we can optimize the maintenance of the structures maximizing the service life of the structure and the safety of its usage.

What is SHM?

Summarizing, Structural Health Monitoring (SHM):

- is process / method with several aspects:
  - Data acquisition through embedded sensor systems
  - Processing of acquired data
  - Analysis of processed data
- is applied to various fields of engineering
- focusses on detection and characterization (optional) of damage

Why is SHM needed?



Ponte Morandi

- Built between 1963 and 1967
- Collapsed in 2018
- Far from expected end of life
- Lack of maintenance identified as cause
- 43 casualties

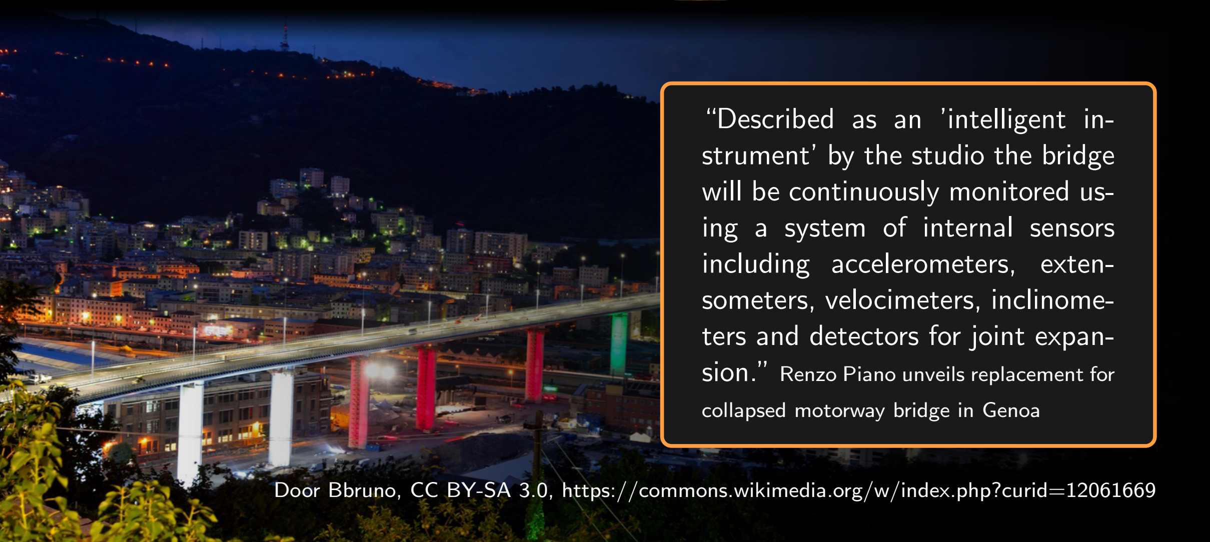
Why is SHM needed?

Ponte Morandi

- Built between 1963 and 1967
- Collapsed in 2018
- Far from expected end of life
- Lack of maintenance identified as cause
- 43 casualties

Engineering.com – The Rise, Fall and Rebuild of the Doomed Morandi Bridge

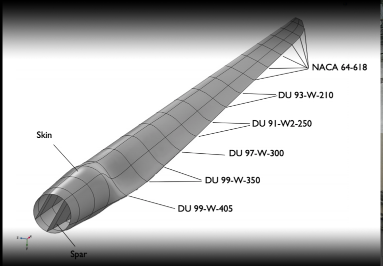
Why is SHM needed?



"Described as an 'intelligent instrument' by the studio the bridge will be continuously monitored using a system of internal sensors including accelerometers, extensometers, velocimeters, inclinometers and detectors for joint expansion." Renzo Piano unveils replacement for collapsed motorway bridge in Genoa

Why is SHM needed?

Design Process



Source: Comsol

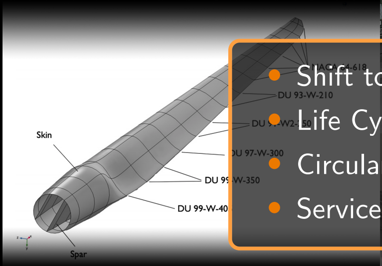
Manufacturing Process

Source: LM Wind

Operation

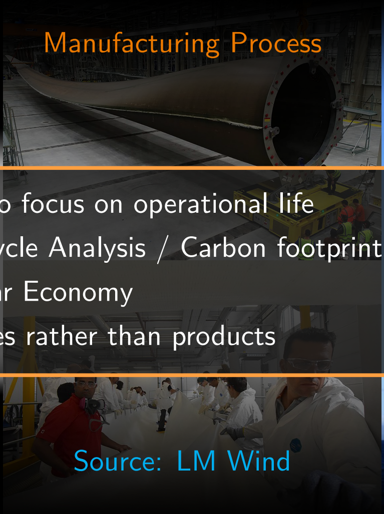
Why is SHM needed?

Design Process



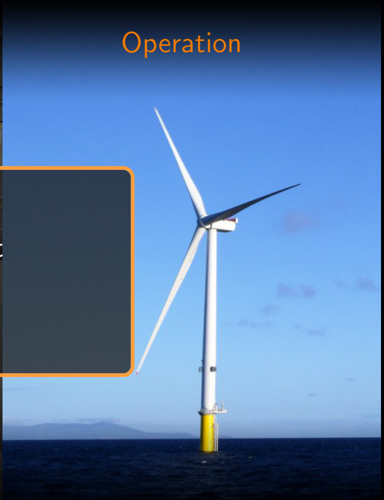
Source: Comsol

Manufacturing Process



Source: LM Wind

Operation



- Shift to focus on operational life
- Life Cycle Analysis / Carbon footprint
- Circular Economy
- Services rather than products

Why is SHM needed?

Summarizing, Structural Health Monitoring is needed to guarantee safe operation of systems throughout their operational life, while:

- Accounting for changes and variability in operational conditions
- Designing less conservative, use less material, optimizing performance, reducing CO2 emissions
- Optimizing maintenance planning, avoiding unnecessary waste of materials

Seven Axioms of SHM

I. All materials have inherent flaws or defects
II. The assessment of damage requires a comparison between two systems states
III. Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage and the damage severity can generally only be done in a supervised learning mode
IV. a. Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information
    b. Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions
V. The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system
VI. There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability
VII. The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation

K. Worden, et al., The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A*, (2007)**463**, 1639–1664

Seven Axioms of SHM

I. All materials have inherent flaws or defects
II. The assessment of damage requires a comparison between two systems states
III. Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage and the damage severity can generally only be done in a supervised learning mode
IV.
  a. Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information
  b. Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions
V. The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system
VI. There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability
VII. The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation

K. Worden, et al., The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A*, (2007)**463**, 1639–1664

Seven Axioms of SHM

- I All materials have inherent flaws or defects
- II The assessment of damage requires a comparison between two systems states
- III Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage and the damage severity can generally only be done in a supervised learning mode
- IV
  - a Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information
  - b Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions
- V The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system
- VI There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability
- VII The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation

K. Worden, et al., The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A*, (2007)**463**, 1639–1664

Seven Axioms of SHM

I. All materials have inherent flaws or defects
II. The assessment of damage requires a comparison between two systems states
III. Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage and the damage severity can generally only be done in a supervised learning mode
IV.
   a. Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information
   b. Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions
V. The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system
VI. There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability
VII. The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation

K. Worden, et al., The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A*, (2007)**463**, 1639–1664

Seven Axioms of SHM

I. All **materials** have inherent **flaws or defects**

II. The assessment of damage requires a **comparison between two systems states**

III. Identifying the existence and location of damage can be done in an **unsupervised** learning mode, but identifying the type of damage and the damage severity can generally only be done in a **supervised learning mode**

IV.
   a. Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information
   b. Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions

V. The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system

VI. There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability

VII. The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation

K. Worden, et al., The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A*, (2007)**463**, 1639–1664

Seven Axioms of SHM

- I All **materials** have inherent **flaws or defects**
- II The assessment of damage requires a **comparison between two systems states**
- III Identifying the existence and location of damage can be done in an **unsupervised** learning mode, but identifying the type of damage and the damage severity can generally only be done in a **supervised learning mode**
- IV
  - a Sensors cannot measure damage. Feature extraction through **signal processing and statistical classification** is necessary to convert sensor data into damage information
  - b Without **intelligent feature extraction**, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions
- V The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system
- VI There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability
- VII The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation

K. Worden, et al., The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A*, (2007)**463**, 1639–1664

Seven Axioms of SHM

- I. All materials have inherent flaws or defects
- II. The assessment of damage requires a comparison between two systems states
- III. Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage and the damage severity can generally only be done in a supervised learning mode
- IV.
  - a. Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information
  - b. Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions
- V. The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system
- VI. There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability
- VII. The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation

K. Worden, et al., The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A*, (2007)**463**, 1639–1664

Disciplines Linked to SHM

Disciplines Linked to SHM

Sensor Technology

- Development new sensor technologies: PZT, optical fibres, MEMS, ...
- Autonomous, distributed, wireless sensor networks: local processing, data transfer, power management, ...

Disciplines Linked to SHM

Sensor Technology

- Development new sensor technologies: PZT, optical fibres, MEMS, ...
- Autonomous, distributed, wireless sensor networks: local processing, data transfer, power management, ...

Physical Modelling

- Dynamics: Modal characteristics, nonlinear dynamics (contact, damping), wave propagation, acoustic emission, ...
- Material Science: Wear, fatigue, fracture, degradation, corrosion, ...

Disciplines Linked to SHM

Sensor Technology

- Development new sensor technologies: PZT, optical fibres, MEMS, ...
- Autonomous, distributed, wireless sensor networks: local processing, data transfer, power management, ...

Signal Processing

- Filtering, denoising, ...
- Domain transformations: time, time-frequency, frequency, ...

Physical Modelling

- Dynamics: Modal characteristics, nonlinear dynamics (contact, damping), wave propagation, acoustic emission, ...
- Material Science: Wear, fatigue, fracture, degradation, corrosion, ...

Disciplines Linked to SHM

Sensor Technology

- Development new sensor technologies: PZT, optical fibres, MEMS, ...
- Autonomous, distributed, wireless sensor networks: local processing, data transfer, power management, ...

Physical Modelling

- Dynamics: Modal characteristics, nonlinear dynamics (contact, damping), wave propagation, acoustic emission, ...
- Material Science: Wear, fatigue, fracture, degradation, corrosion, ...

Signal Processing

- Filtering, denoising, ...
- Domain transformations: time, time-frequency, frequency, ...

Data Analysis

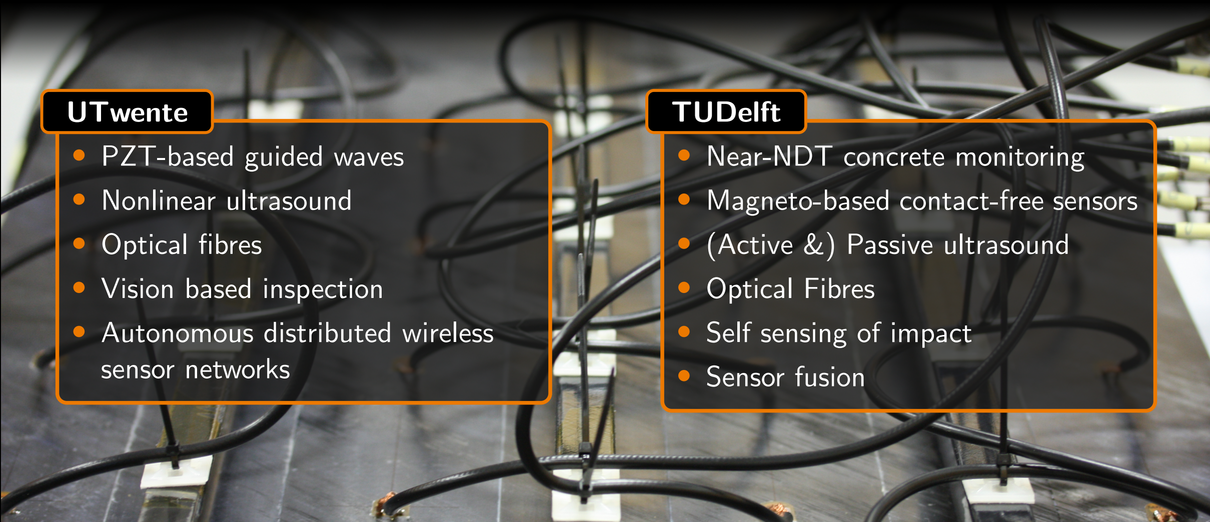
- Statistical pattern recognition
- Machine Learning & Artificial Intelligence

Disciplines Linked to SHM

Digital Twins & Cyber Physical Spaces

- Virtual representation of physical objects and/or behaviour
- One-way or two-way interaction between virtual and physical space
- Sensor & Actuation technologies for interaction
- Scenario projection

Sensor Technology



UTwente

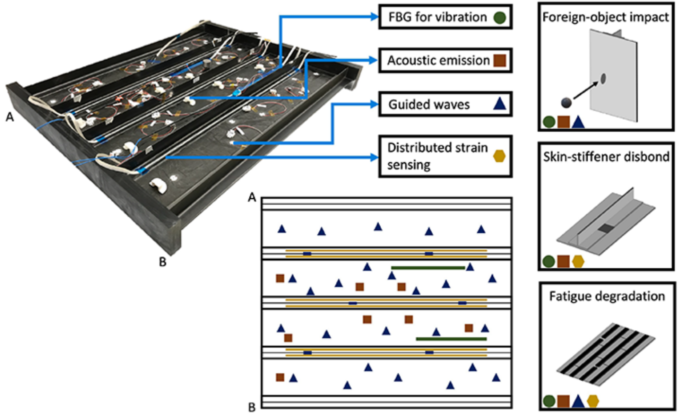
- PZT-based guided waves
- Nonlinear ultrasound
- Optical fibres
- Vision based inspection
- Autonomous distributed wireless sensor networks

TUDelft

- Near-NDT concrete monitoring
- Magneto-based contact-free sensors
- (Active &) Passive ultrasound
- Optical Fibres
- Self sensing of impact
- Sensor fusion

Sensor Technology

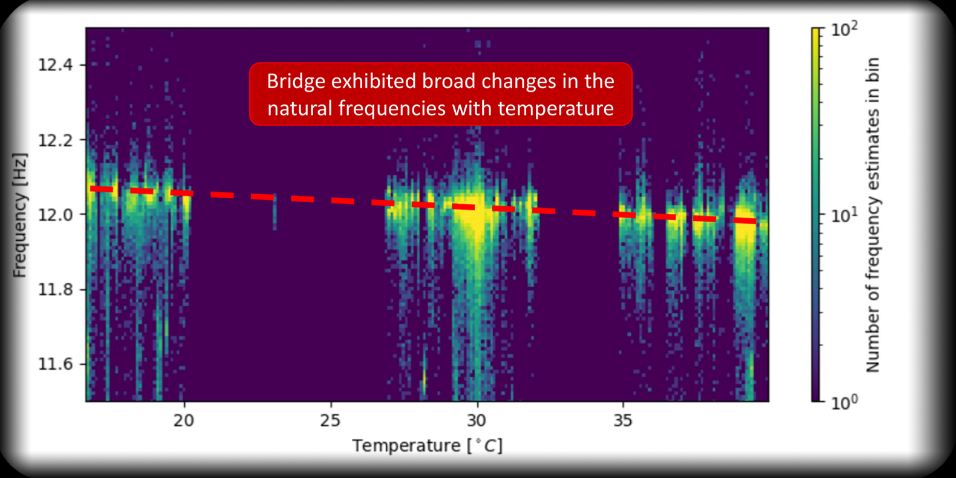
Sensor Technology



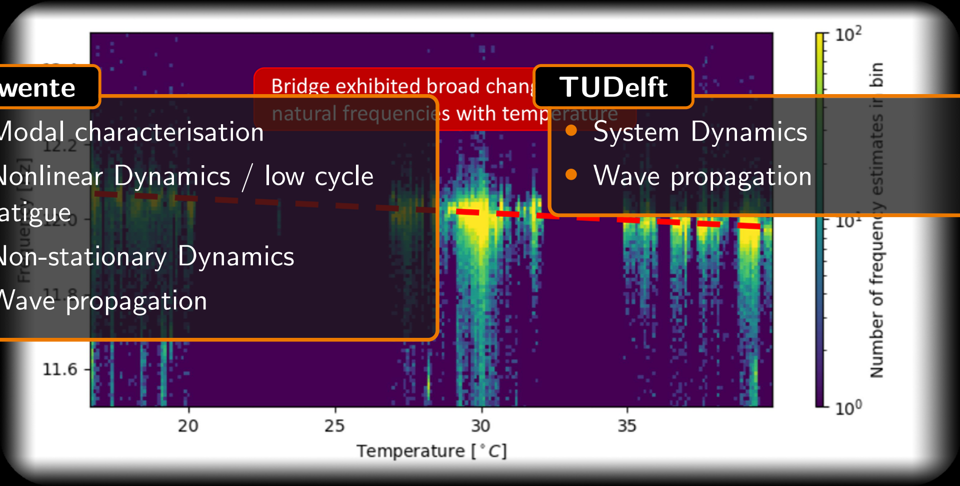
Physical Modelling – Dynamics

Physical Modelling – Dynamics

Physical Modelling – Dynamics



Physical Modelling – Dynamics



UTwente

- Modal characterisation
- Nonlinear Dynamics / low cycle fatigue
- Non-stationary Dynamics
- Wave propagation

TUDelft

- System Dynamics
- Wave propagation

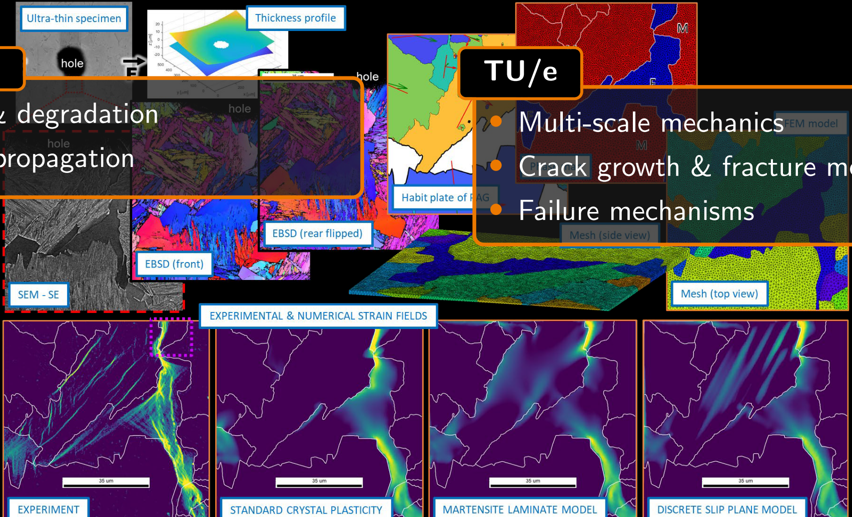
Physical Modelling – Materials

UTwente

- Wear & degradation
- Crack propagation

TU/e

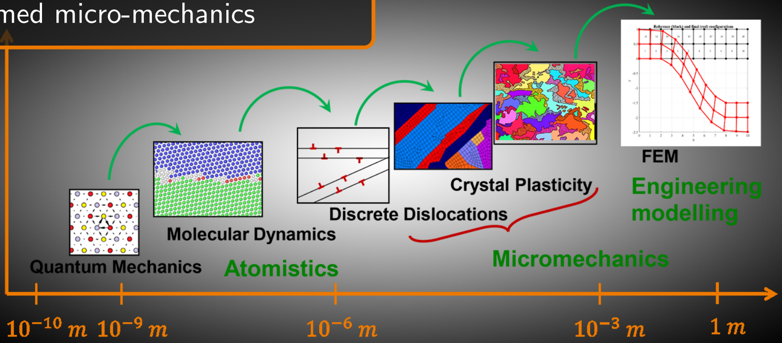
- Multi-scale mechanics
- Crack growth & fracture mechanics
- Failure mechanisms



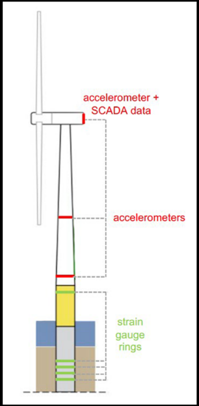
Physical Modelling – Materials

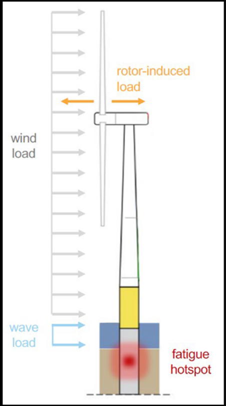
RUG

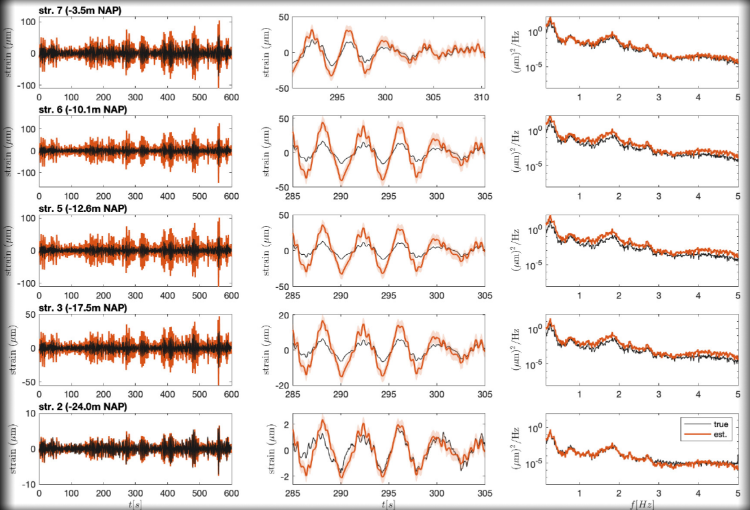
- Atomistic-informed micro-mechanics



Data Analysis







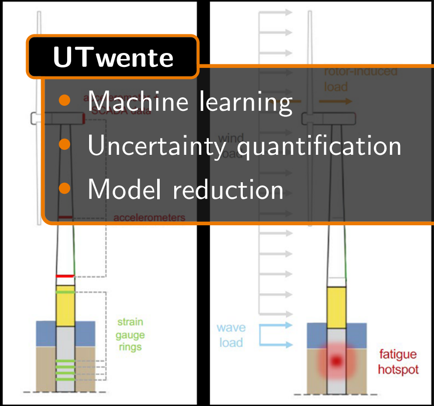
Data Analysis

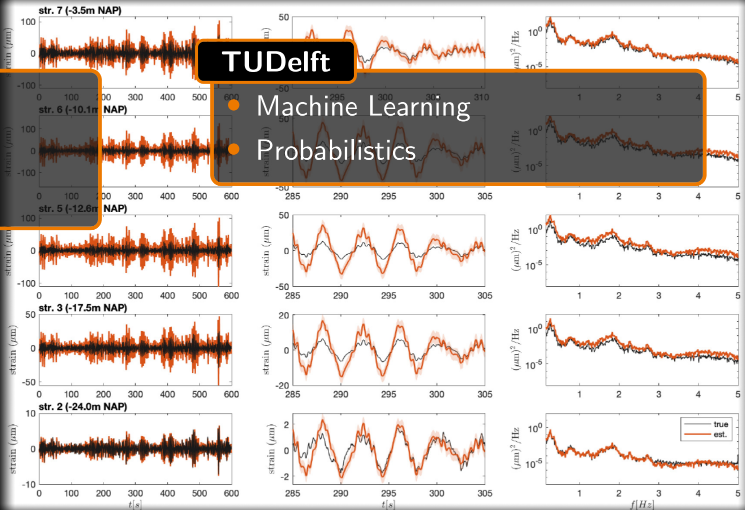
UTwente

- Machine learning
- Uncertainty quantification
- Model reduction

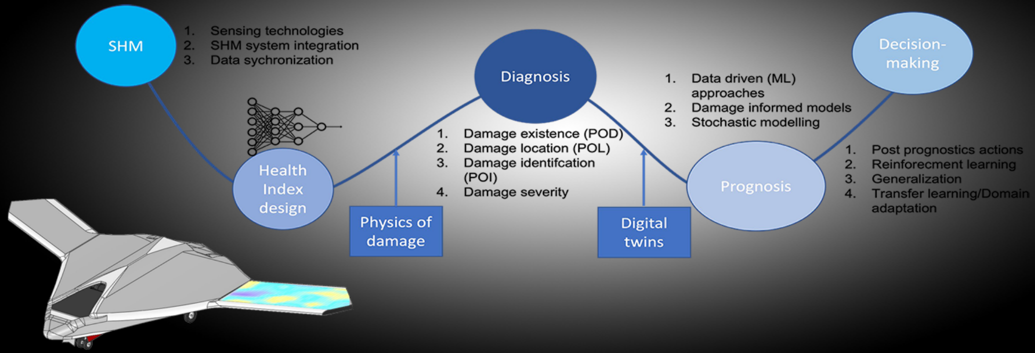
TUDelft

- Machine Learning
- Probabilistics





Data Analysis



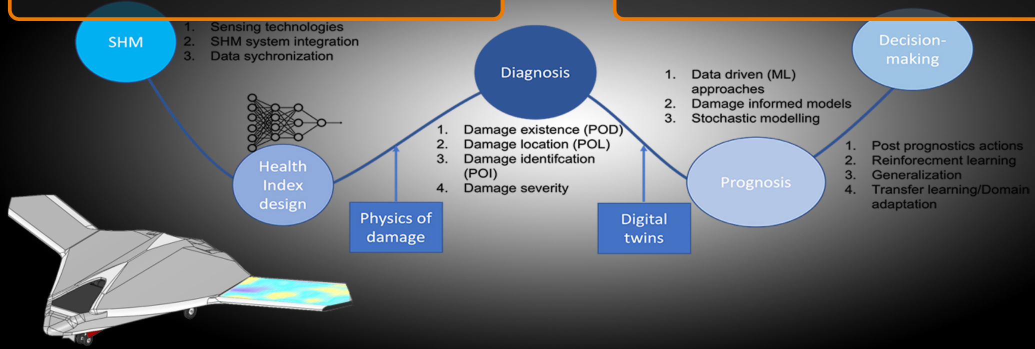
Signal Processing

UTwente

- Non-stationary dynamics

TUDelft

- Real-time processing



SHM Application Fields

Naval

Railway
- Infrastructure
- Rolling Stock

Large infrastructure
- Static
- Moveable

Buildings

Wind Energy

Process Industry

Aerospace

Rotating Systems
- Engines
- Bearings

Water Distribution
- Drink water
- Waste water

Smart Industry

SHM Application Fields

Naval

Railway
- Infrastructure
- Rolling Stock

Large infrastructure
- Static
- Moveable

Buildings

Wind Energy

NEW Energy Systems & Storage

Process Industry

Aerospace

Rotating Systems
- Engines
- Bearings

Water Distribution
- Drink water
- Waste water

Smart Industry

SHM Application Fields

UT
Naval

UT
Ra
- Infrastructure
- Rolling Stock

Large infrastru
UT
- Static
- Moveable

Buildings

Wind Energy

NEW Energy Systems & Storage

Process Industry

Aerospace
UT

Rotating Systems
- Engines
- ngs

UT

Water Distribution
- Drink water
- Waste wate

UT

Smart Ind stry
UT

SHM Application Fields

- UT TUD Naval
- UT TUD Ra…
  - Infrastructure
  - Rolling Stock
- TUD UT Large …tru…
  - Static
  - Moveable
- TUD Build…
- TUD …nd Energy
- NEW Energy Systems & Storage
- Process Industry
- UT TUD Aerospace
- Rotating Systems
  - Engines
  - UT …ngs
- Water Distribution
  - Drink water
  - Waste water UT
- Smart Industry UT

SHM Application Fields

UT TUD
Naval

UT TUD
Ra
- Infrastructure
- Rolling Stock

TUD UT
Large
- Static
- Moveable

TUD
Build

TUD nd Energy

NEW Energy Systems & Storage

Process Industry

TUe
Aerospace
UT TUD

Rotating Systems
- Engines
- ngs

UT

Water Distribution
- Drink water
- Was

TUe UT

Smart Industry
UT

SHM Application Fields

- UT TUD Naval
- UT TUD Ra…
  - Infrastructure
  - Rolling Stock
- TUD UT Large …tru…
  - Static
  - Moveable
- TUD Build…
- TUD …nd Energy
- NEW Energy Systems & Storage
- Process Industry
- TUe UT TUD Aerospace
- UT Rotating Systems
  - Engines
  - …ngs
- TUe UT Water Distribution
  - Drink water
  - Was… …te…
- UT Smart Industry
- RUG Fundamental Materal Science TUe

Main Challenges

Summarizing, main challenges are found in:

Main Challenges

Summarizing, main challenges are found in:

- Complex, non-isotropic and/or nonlinear material behaviour

Main Challenges

Summarizing, main challenges are found in:

- Complex, non-isotropic and/or nonlinear material behaviour
- Integration of sensors & sensor technologies

Main Challenges

Summarizing, main challenges are found in:

- Complex, non-isotropic and/or nonlinear material behaviour
- Integration of sensors & sensor technologies
- Fusion of sensors and data sources

Main Challenges

Summarizing, main challenges are found in:

- Complex, non-isotropic and/or nonlinear material behaviour
- Integration of sensors & sensor technologies
- Fusion of sensors and data sources
- Management of data and conversion to information

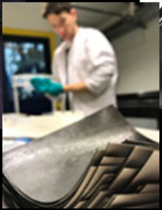
Main Challenges

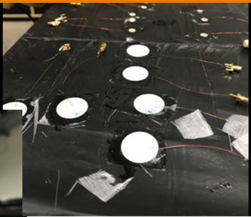
Summarizing, main challenges are found in:

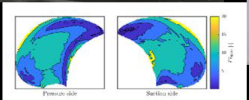
- Complex, non-isotropic and/or nonlinear material behaviour
- Integration of sensors & sensor technologies
- Fusion of sensors and data sources
- Management of data and conversion to information
- Providing meaningful information in a meaningful way to end-users

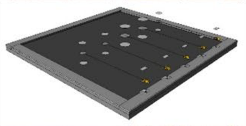
Arno Huijer

Monitoring of dynamic loads and acoustic emissions in composite marine propellers using embedded piezoelectric sensors

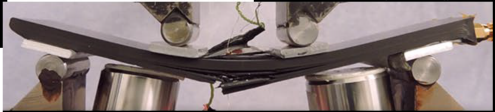






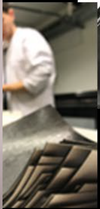


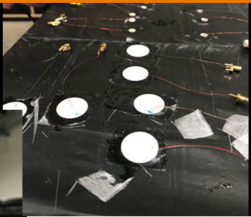
4p bending tests

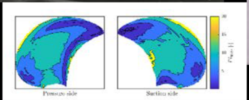


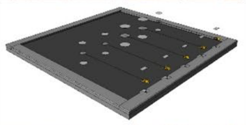
Arno Huijer

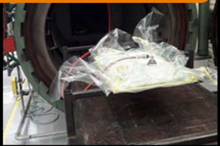
Monitoring of dynamic loads and acoustic emissions in composite marine propellers using embedded piezoelectric sensors



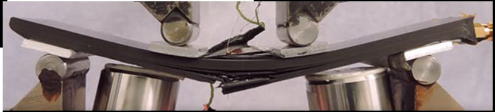






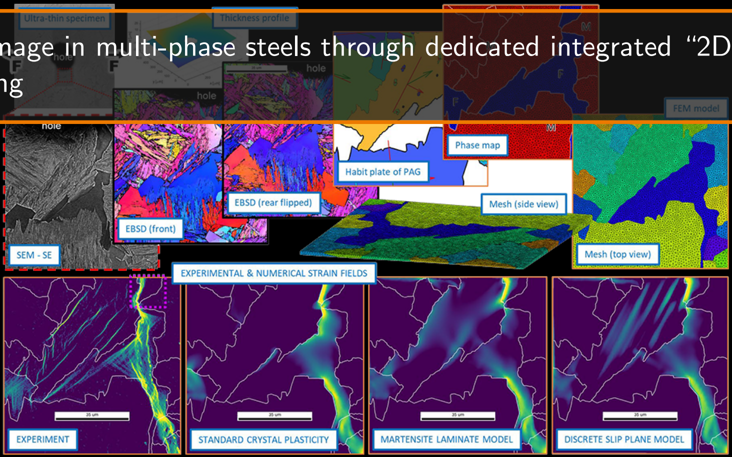


4p bending tests



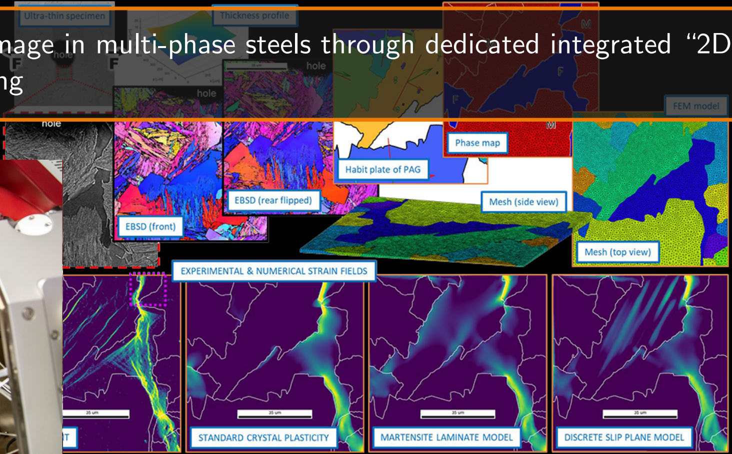
Tijmen Vermeij

Unraveling plasticity and damage in multi-phase steels through dedicated integrated “2D” experimental-numerical testing



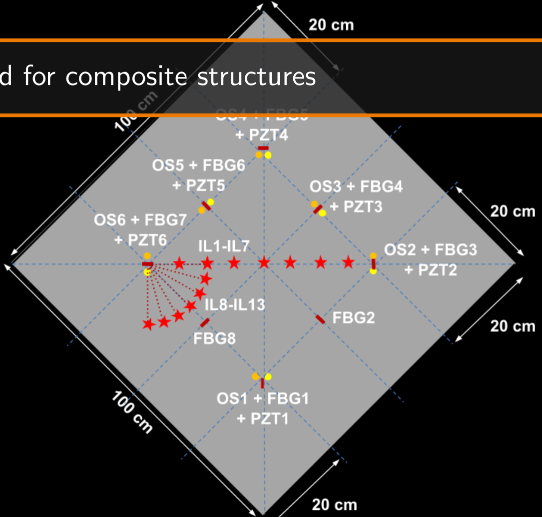
Tijmen Vermeij

Unraveling plasticity and damage in multi-phase steels through dedicated integrated "2D" experimental-numerical testing



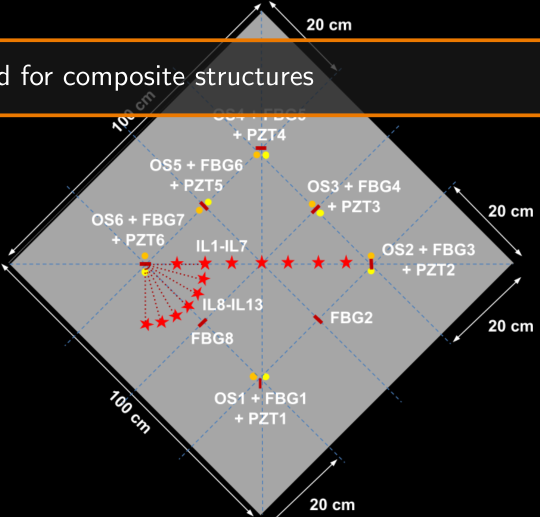
Natália Ribeiro Marinho

Dynamics-based impact identification method for composite structures



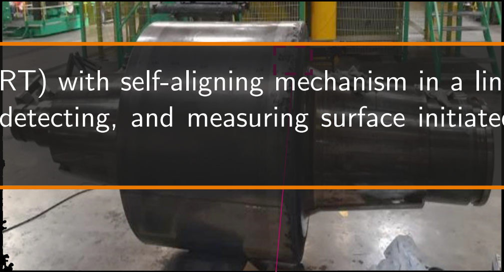
Natália Ribeiro Marinho

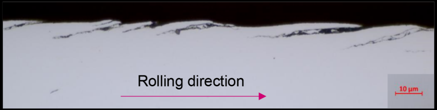
Dynamics-based impact identification method for composite structures



Aleks Vrček

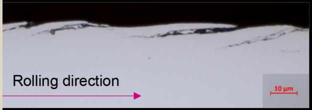
Newly developed Cam-Roller follower Tester (CRT) with self-aligning mechanism in a line contact configuration and ways of simulating, detecting, and measuring surface initiated RCF cracks

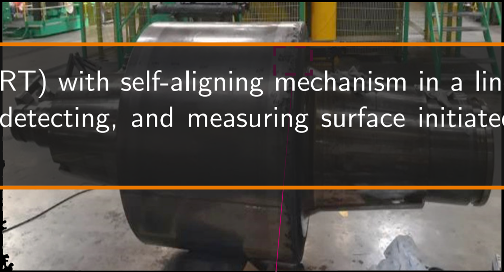




Aleks Vrček

Newly developed Cam-Roller follower Tester (CRT) with self-aligning mechanism in a line contact configuration and ways of simulating, detecting, and measuring surface initiated RCF cracks





Bibliography I

[1] Wikipedia, *Structural Health Monitoring*, https://en.wikipedia.org/wiki/Structural_health_monitoring

[2] The Constructor – Building Ideas, *What is Structural Health Monitoring in Civil Engineering?*, https://theconstructor.org/digital-construction/structural-health-monitoring-civil-engineering/554160/

[3] IGI-Global, *What is Structural Health Monitoring*, https://www.igi-global.com/dictionary/structural-health-monitoring/42149

[4] LM Wind, LM Wind Power manufactures the world's first wind turbine blade beyond 100 meters!, www.lmwindpower.com/.../lm-wind-power-manufactures-the-worlds-first-wind-turbine-blade-beyond-100-meters

[5] Comsol, Anayising Wind Turbine Blades with the Composite Materials Module, www.comsol.com/blogs/analyzing-wind-turbine-blades-with-the-composite-materials-module/

[6] K. Worden, C.R. Farrar, G. Manson, G. Park, The fundamental axioms of structural health monitoring, *Proceedings of the Royal Society A* (2007) **463**, 1639-1664

Materials & Structural Health Monitoring

Engineering Mechanics Symposium – Workshop Introduction

Richard Loendersloot[1] Eliz-Mari Lourens[2] Johan Hoefnagels[3]

[1]University of Twente, [2]Delft University of Technology, [3]Eindhoven Technical University

26th of October 2022