Managing Civil Infrastructure on the Basis of Structural Health Monitoring

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Built forever!?

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B52 – Built to fly 100 years?

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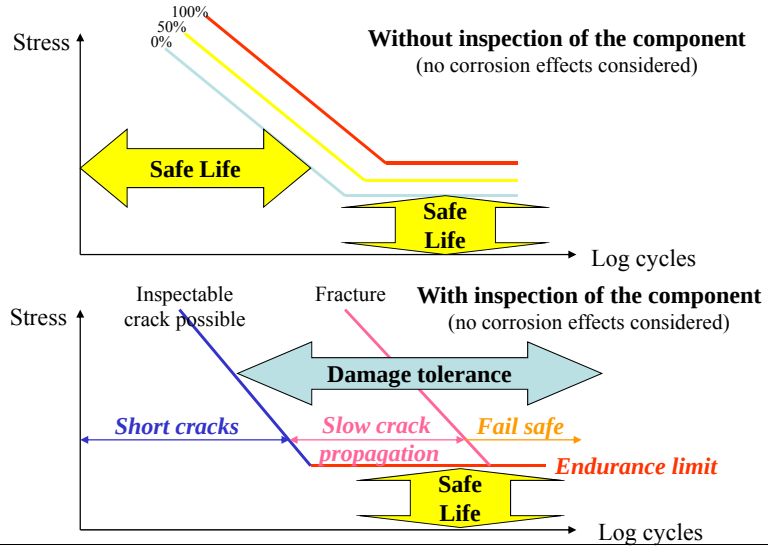
Design Principles for Structures



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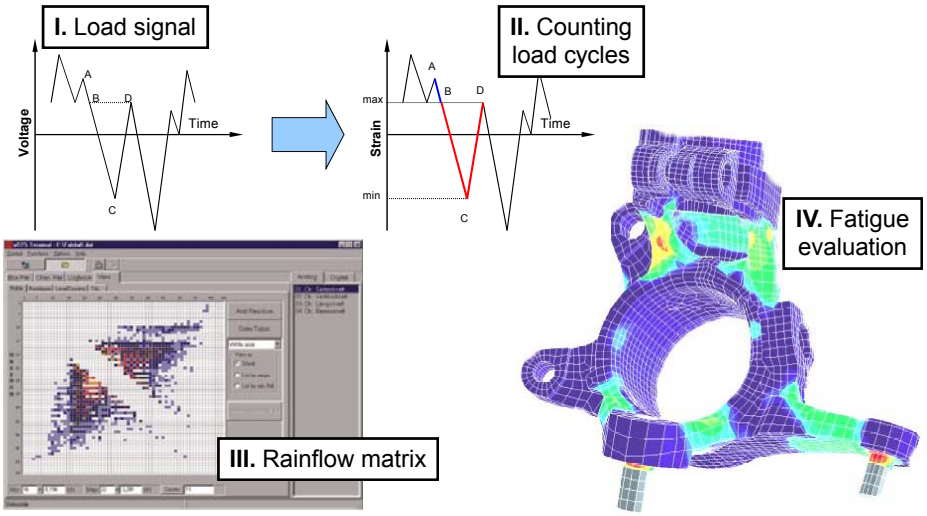
Estimation of damage accumulation



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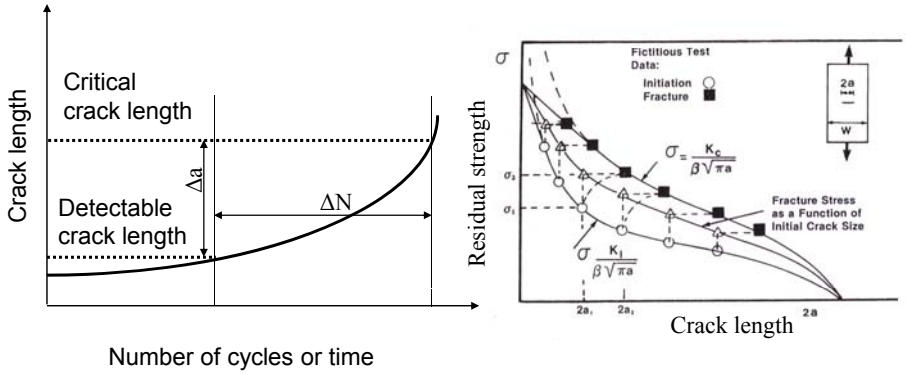
$$\Delta N = f\,(\text{Residual Strength})$$



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Steps to be considered for crack propagation calculation

1. Initial crack length a_0
2. Y factor
3. Load (stress)
4. K value
5. Crack propagation equation (i.e. Forman)
6. Crack extension Δa
7. $a = a_0 + \Delta a$ & back to step 1 with $a_0 = a$

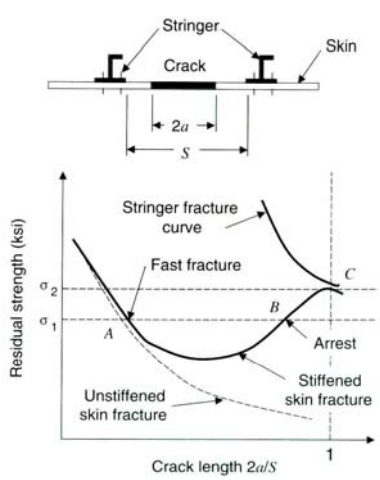
For example:

$$Y = \sqrt{\sec \frac{\pi a}{w}}$$

$$K_I = Y \sigma \sqrt{\pi a}$$

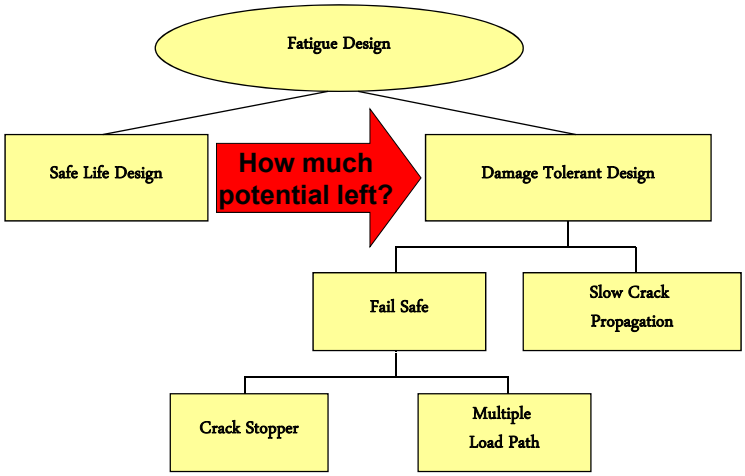
$$\frac{da}{dN} = C_F \frac{\Delta K^{m_F}}{(1-R)K_c - \Delta K}$$

Influence of Stringers on Fracture



Source: A. Grant: Fundamentals of Structural Integrity

Airframe Fatigue Design Principles



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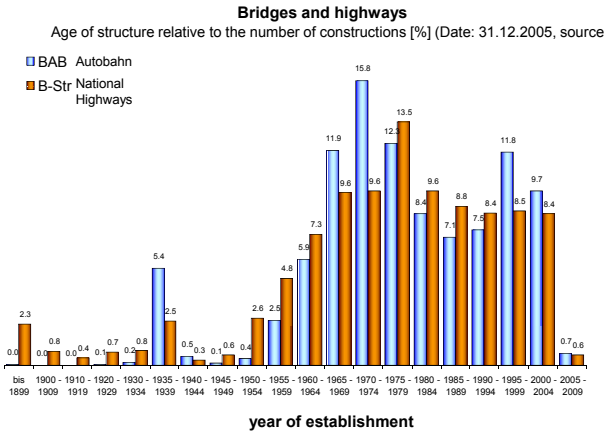
Ageing bridge infrastructure in Germany

Ageing bridge infrastructure in Germany over the last century



World changed:

- More traffic
- Environment
- etc.

BUT

2008 Civil infrastructure remained

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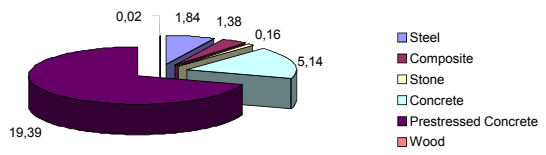
Civil infrastructure - An issue for monitoring

- Bridges
- Pipelines and processing industry
- Power supply (e. g. supply lines, wind energy plants)
- Dams
- Buildings of the early ages of reinforced concrete
- Tunnels
- Waste refilling
- Cultural heritage
- Others

Example: bridge area in 10^6 m^2 in Germany sorted by type of construction:



Date 31.12.2005, source BASt

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Options and challenges for life cycle management

Options:

- Sensors and miniaturisation
- Robotics
- Enhanced computation power
- Internet
- Wireless data communication
- CAE simulation
- Prognostics
- Risk assessment
- Life cycle cost analysis

Challenges:

- New materials
- Higher loads
- Global warming
- Criminal threats and security policies
- Regulations
- Possibly others

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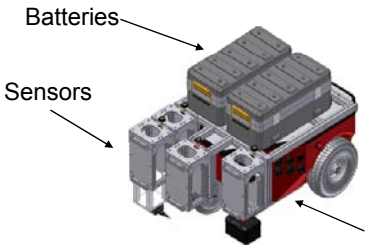
BetoScan

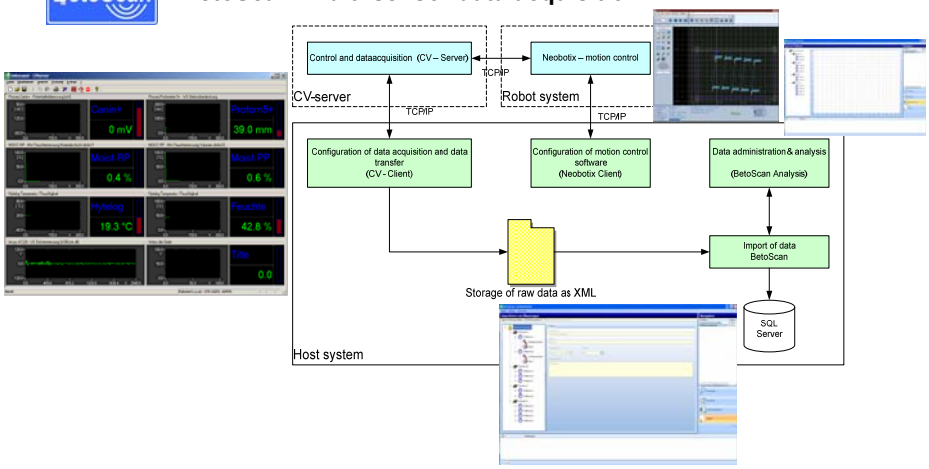
BetoScan: self navigating mobile robot



Air temperature and humidity	Concrete humidity (surface)	Concrete humidity (volume)	Concrete coverage	Geometry information	Reinforcement information	Corrosion risk
Hytelog	Hf MOIST RP, microwave	Hf MOIST PP, microwave	Profometer, eddy current	Acsys A1220, ultrasound	Mala ProEx, radar	Canin, potential (resistivity)

BetoScan

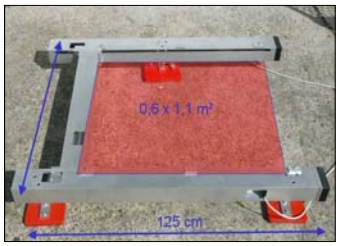
BetoScan: multi-sensor data acquisition



OSSCAR

OSSCAR bauwerkscanner

OnSite SCAnneR



www.vdivde-it.de/innonet

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OSSCAR

OSSCAR bauwerkscanner

OnSite SCAnneR

Reinforcement information	Geometry information	Concrete coverage
Mala ProEx, radar	Acsys A1220, ultrasound	Profometer, eddy current

Data cube also called OLAP (Online Analytical Processing) cube data format

Generalized data concept

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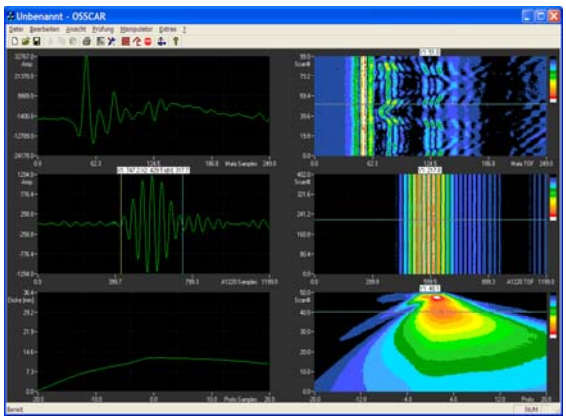
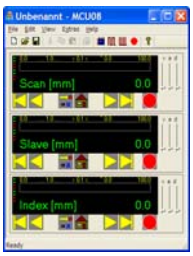
OSSCAR

OnSite SCAnneR





Data acquisition and motion control

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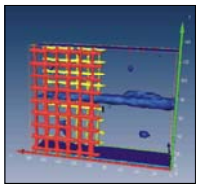
Outlook data analysis

Data analysis: comparison, fusion, joint-inversion

Data fusion: combination of multiple source data to achieve inferences

Test specimen before placing of concrete



Fused image of NDT data measured at specimen on the left

Source: BAM Berlin

Joint inversion or multi-objective optimization: finding model that explains several data sets at once

Data cube

Function container

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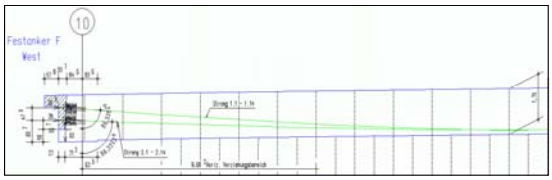
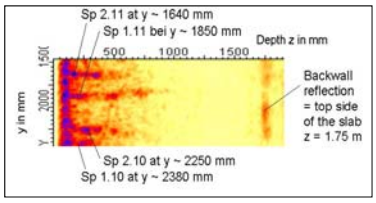
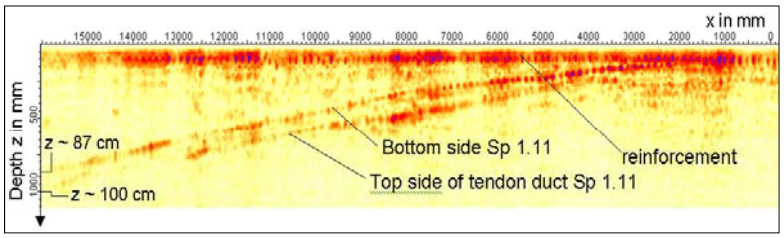
Visualisation of inner parts of constructions

Ultrasound measurements on a concrete deck







Source: Alexander Taffe, BAM Berlin

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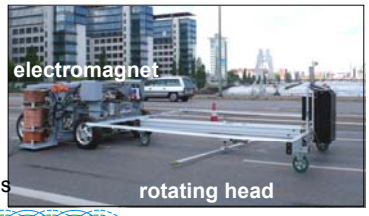
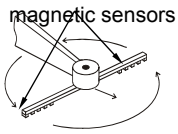
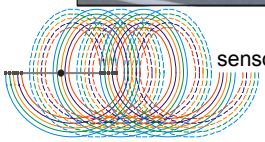
Diagnosis of prestressed tendons

Magnetic rotating head scanner

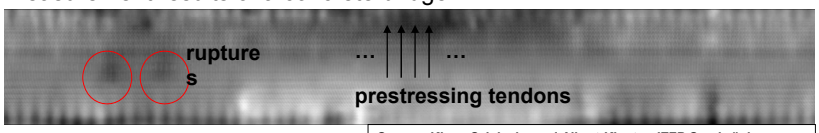
Rotating speed: 2Hz
Linear speed: 720m/h
Rotor diameter: 3.5m
Application: prestressed steel rupture detection in concrete plates







measurement results of a concrete bridge



Source: Klaus Szielasko and Albert Kloster, IZFP Saarbrücken

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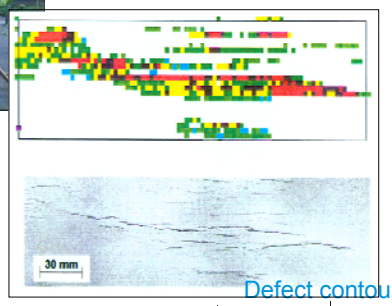
Crack and flaw detection in pipelines

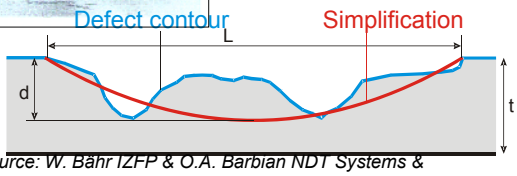
Inspection of pipelines using pigs



Crack and flaw detection by ultrasound pigs

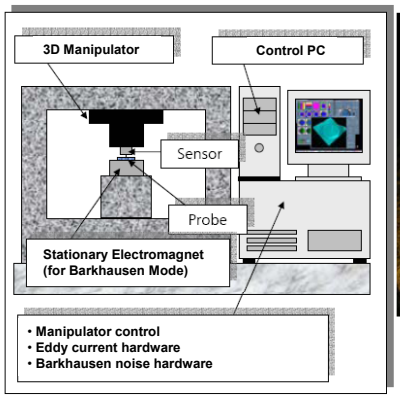
Correlation of data from mearuemnts and geometry models of cracks for assessment

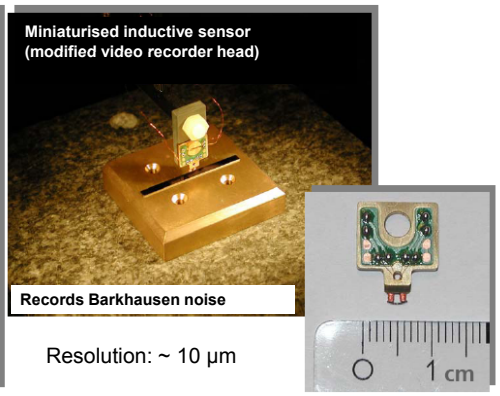
- Up to 300 km of pipelines have to be inspected in one run
- Signals from up to 1000 sensors have to analysed for each segment



Source: W. Bähr IZFP & O.A. Barbian NDT Systems & Services

Barkhausen noise and Eddy current MIcroscope (BEMI)

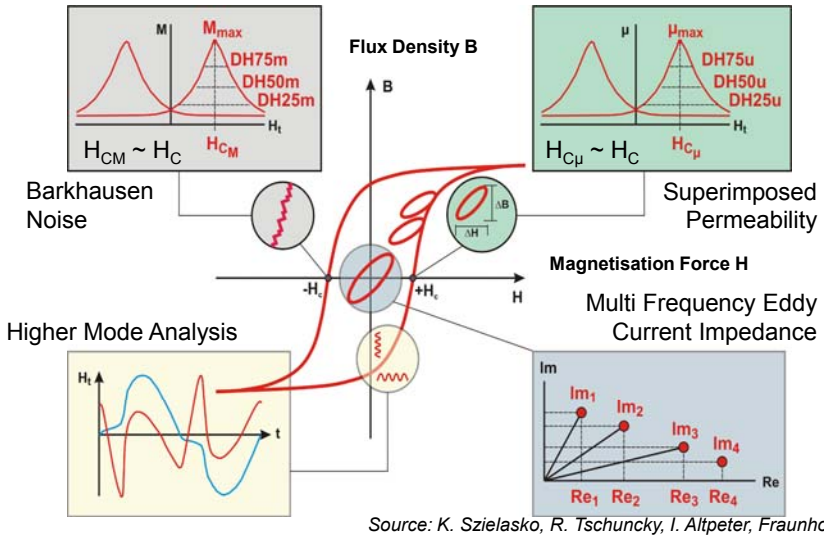




Resolution: ~ 10 µm

Source: M. Rabung, U. Rabe, S. Hirsekorn, I. Altpeter, Fraunhofer IZFP

Monitoring Technique



Source: K. Szielasko, R. Tschuncky, I. Altpeter, Fraunhofer IZFP

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Quantitative NDT / Calibration

Data Base
(NDT Recorded Data + Reference Data)

↓

Computation
(Regression Analysis, Pattern Recognition, …)

↓

(Approximation Function, Similarities, …) **Hardness**	(Approximation Function, Similarities, …) **Residual Austenite**	(Approximation Function, Similarities, …) **Residual Stresses**
QNDT Hardness	**QNDT Residual Austenite**	**QNDT Stress**

Source: K. Szielasko, R. Tschuncky, I. Altpeter, Fraunhofer IZFP

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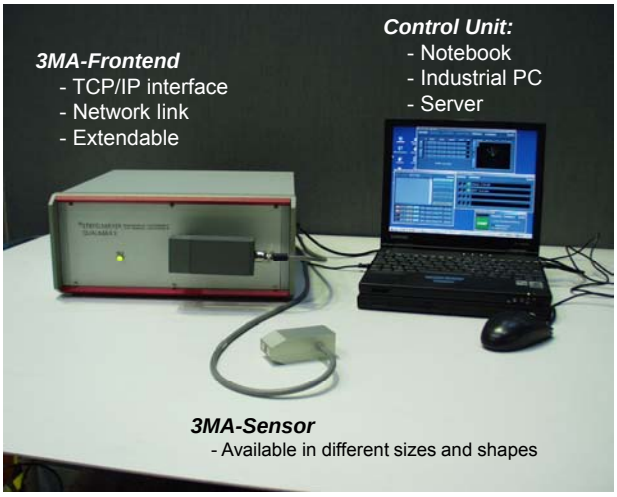
3MA Test System

Modular Hardware

- Components linked via a TCP/IP interface
- Expandable through additional components (i.e. magnetostriction, US)
- Easily upgradable with new components



Source: K. Szielasko, R. Tschuncky, I. Altpeter, Fraunhofer IZFP

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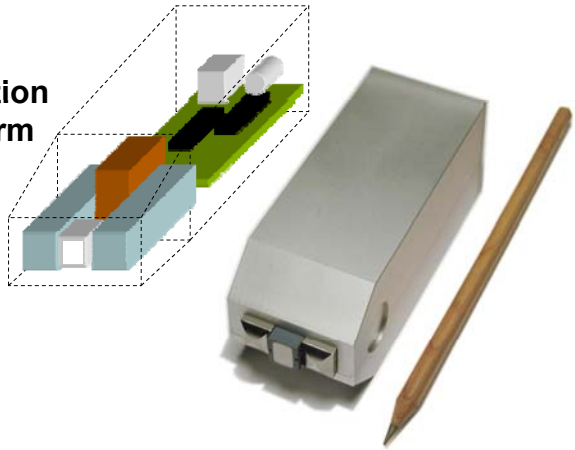
MikroMach Test System

Mikromagnetic Materials charakterisation in its most compact form

Sensor = Test Equipment

Link control PC via Standardised USB link



Source: K. Szielasko, I. Altpeter, Fraunhofer IZFP

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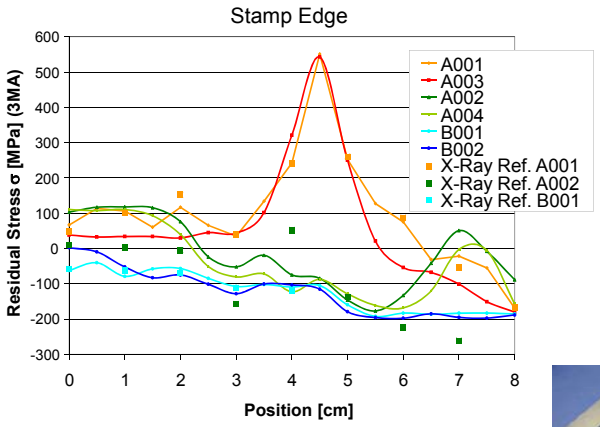
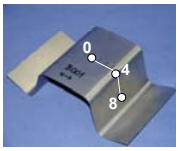
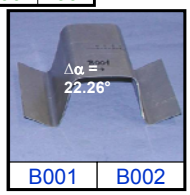
Quantitative Determination of Residual Stresses







Source: B. Wolter, K. Szielasko, I. Altpeter, Fraunhofer IZFP

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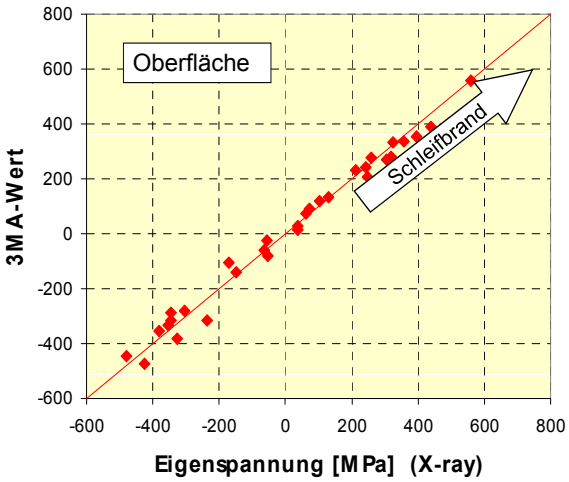
QNDT of Residual Stresses due to Machining

17 CrNiMo 6 residual stress maeasurement in gear wheels



Source: B. Wolter, K. Szielasko, I. Altpeter, Fraunhofer IZFP

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Residual Austenite Determination on Anchor Bolts using 3MA

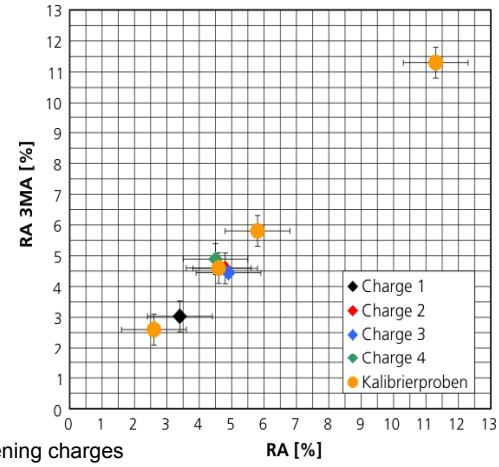
Results:

Calibaration Probes:

44 Anchor bolts with a RA of 2,6%
43 Anchor bolts with a RA of 2,6%
44 Anchor bolts with a RA of 4,6%
43 Anchor bolts with a RA of 11,3%
15 Anchor bolts with a RA of 5,8%

Validation Probes:

Charge 1 with a RA of 3,4%
Charge 2 with a RA of 4,8%
Charge 3 with a RA of 4,9%
Charge 4 with a RA of 4,5%
25 anchor bolts each from different hardening charges



Source: K. Szielasko, R. Tschuncky, I. Altpeter, Fraunhofer IZFP

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Inspection of Sheet Steel using the 3MA System

Trolley with integrated 3MA System
for inspection of milled sheets during rolling

Unit for remote control of trolley
with 3MA system

Source: B. Wolter, K. Szielasko, I. Altpeter, Fraunhofer IZFP

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The Central Question

Without compromising safety, could we make our structures:

- Better available?
- Lighter weight?
- More cost efficient?
- More reliable?

by making sensors (and possibly also actuators) to become an integral part of the structure?

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What about …

- Looking at advanced cheap sensors, which are continuously becoming
  - Smaller,
  - Lighter,
  - Cheaper?
- Making the sensors an integral part of the structural component?
- Combining the sensors through advanced microelectronics and possibly
  - Wireless technology with
  - Advanced microprocessors and
  - Advanced signal processing?

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Structural Health Monitoring (SHM)

… is the integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of a structure to be recorded, analysed, localised and predicted in a way that non-destructive testing becomes an integral part of the structure. SHM is **not** an additional NDT application, nor QNDT, a fatigue analysis, vibration analysis, signal processing, material science or any other single technological area but rather lateral integration of all those in terms of a structure's life cycle management.

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What We Need to Know

- Structural Behaviour and Performance
- Loads
- Design Principles
- Maintenance
- Systems for Structural Assessment
- Emerging Technologies

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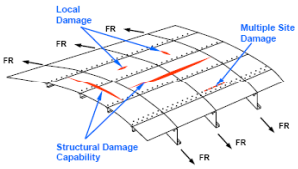
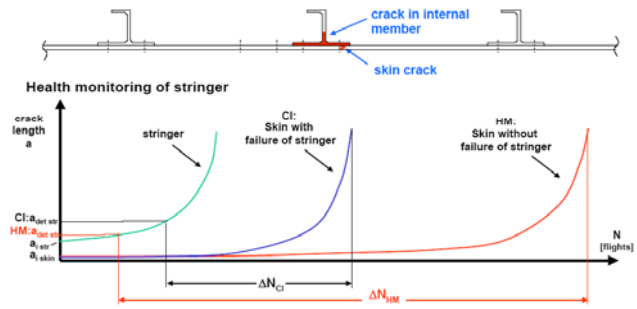
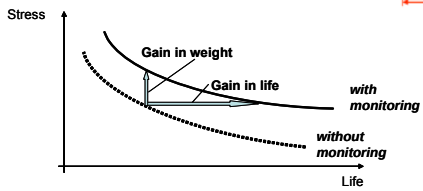
Enhancing Damage Tolerance through SHM







Source: H.-J. Schmidt, Airbus

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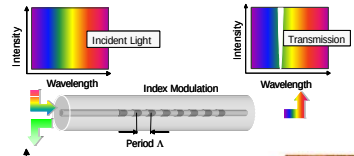
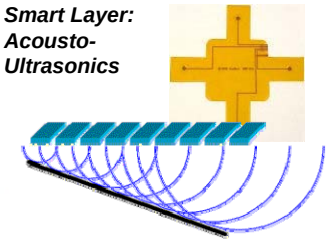
Technologies Beyond State-of-the-Art in Aircraft NDT

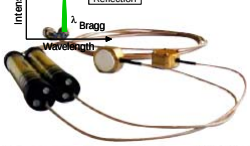
Optical Fibre Bragg Grating Sensor:
- ***Strain***
- ***Pressure***
- ***Temperature***

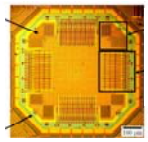


Smart Layer: Acousto-Ultrasonics



Acoustic Emission

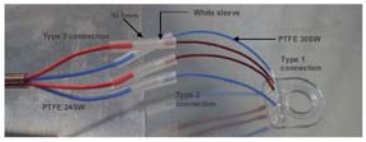




Phased Array

MEMS

Comparative Vacuum Monitoring:
- ***Crack***



Electro Magnetic Layer

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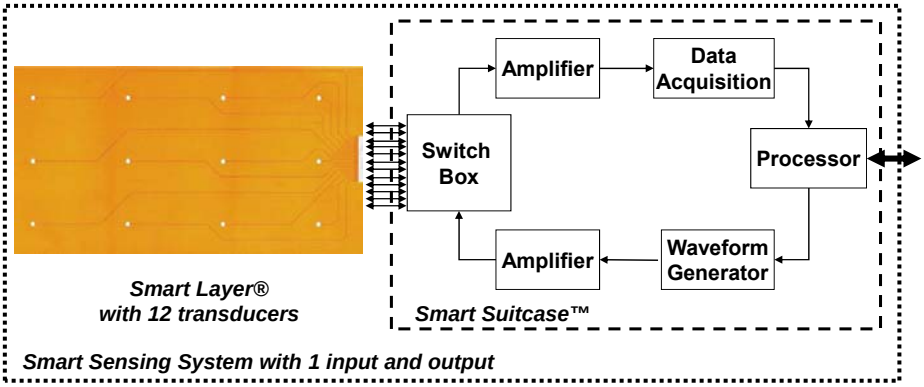
What is a Sensor?



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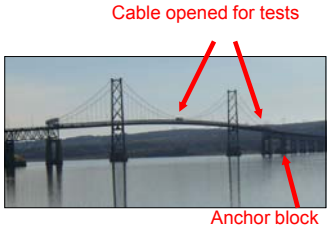
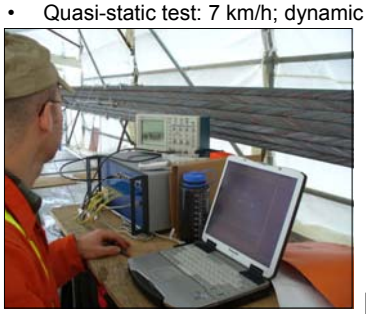
Stress measurements of a suspension bridge

Fibre optic sensors for loads monitoring

- Six strands on center-east and anchorage chamber measured
- SOFO Dynamic fiber optic sensing system used
- Two 12-wheels trucks, ~30 tons each
- Quasi-static test: 7 km/h; dynamic test: 72 km/h





Source: Smartec SA, Lugano Switzerland

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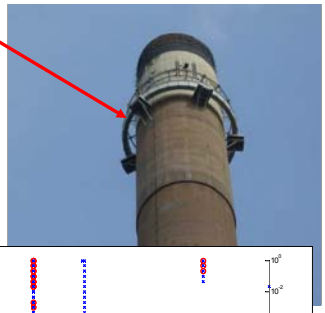
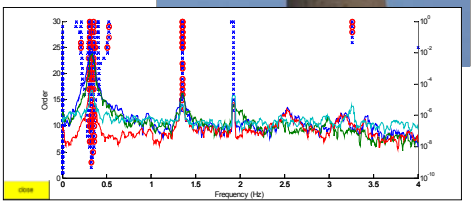
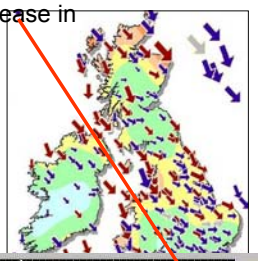
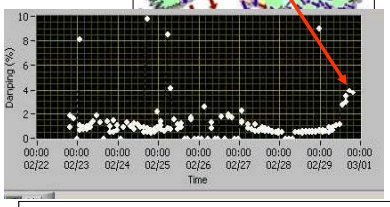
Remote dynamic loads monitoring

SSI implemented in Labview VI operates in real-time and confirms operation of TMD during strong winds via eight-times increase in damping









Source: James Brownjohn, The University of Sheffield

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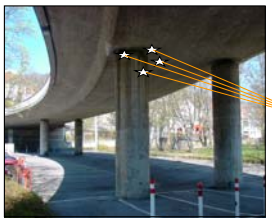
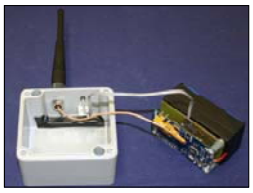
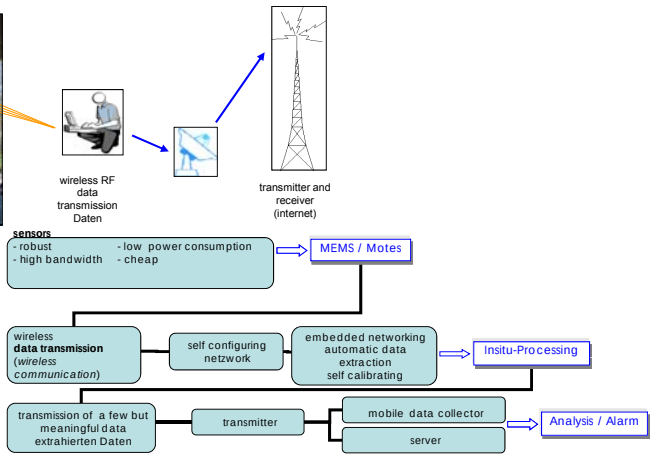
Structural health monitoring using wireless sensor networks







Source: Christian Grosse MPA University of Stuttgart

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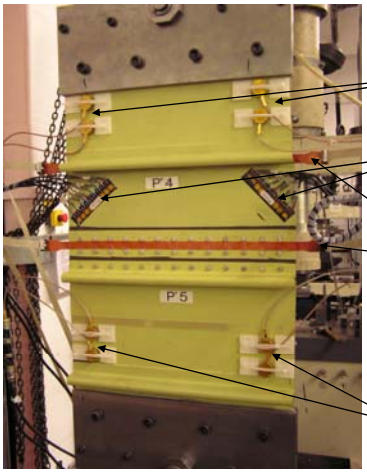
Specimen Sensor Attachment



Acoustic emission sensors

Phased array transducers

Smart Layer transducers

Acoustic emission sensors

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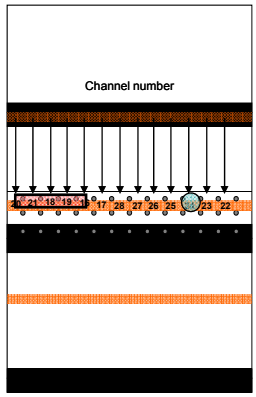
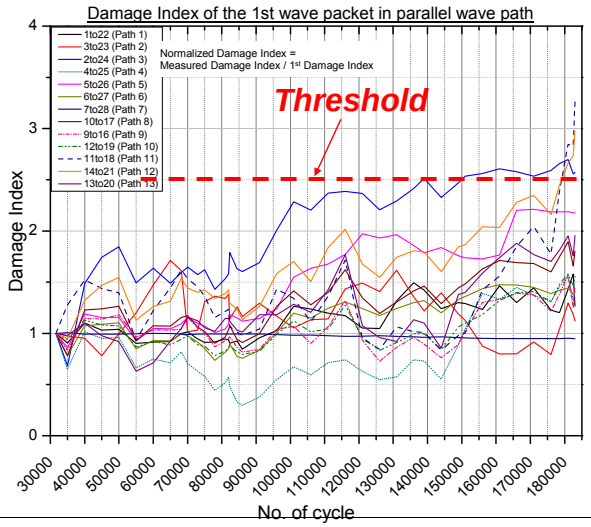
Data Processing Results





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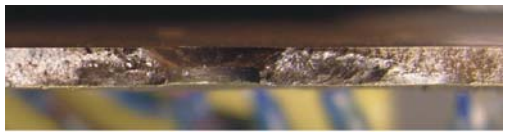
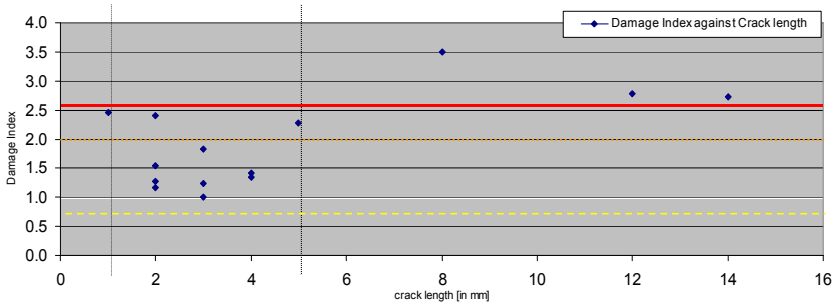
Argumentation of Threshold Setting



Damage Index against the estimation of the crack length from the parallel paths at 183kcycle



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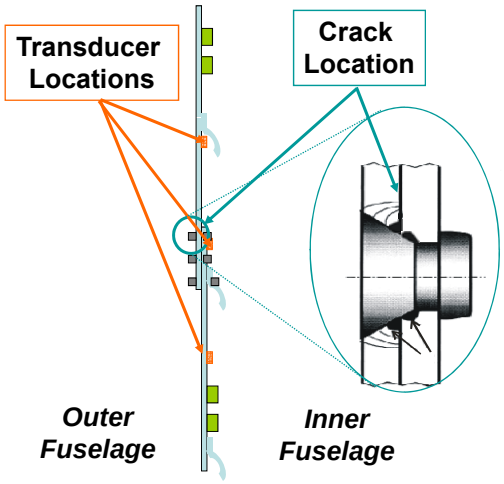
Crack Initiation at Countersunk Rivet Holes



Constraints:

- Transducers only to be placed inside the fuselage
- Acoustic signals passing a lap can reduce up to a factor of 4
- Area around riveted lap allows for a multitude of acoustic wave reflections

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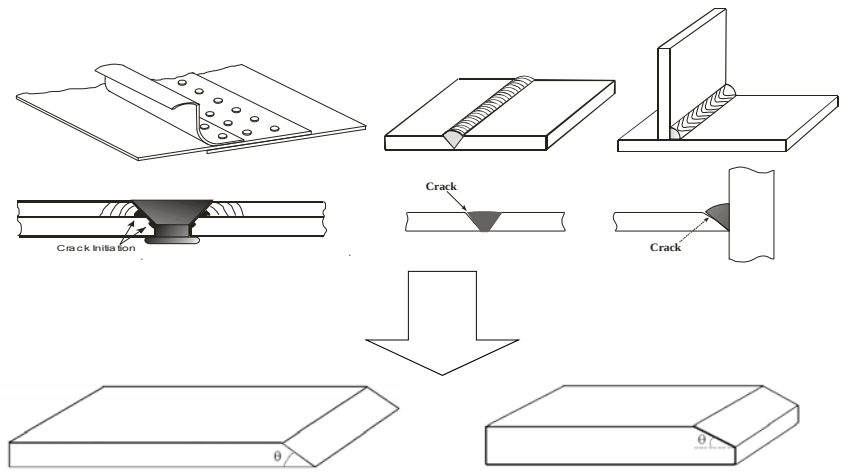
Wave Modulation at Tapered Surfaces



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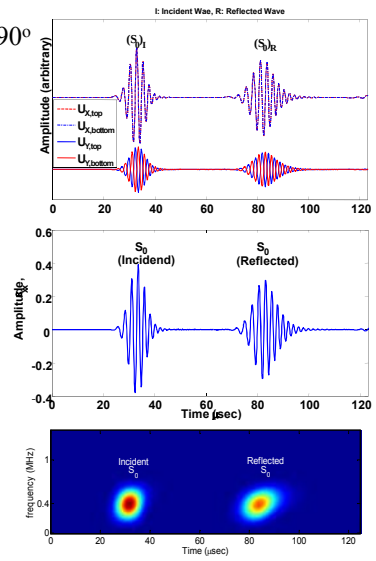
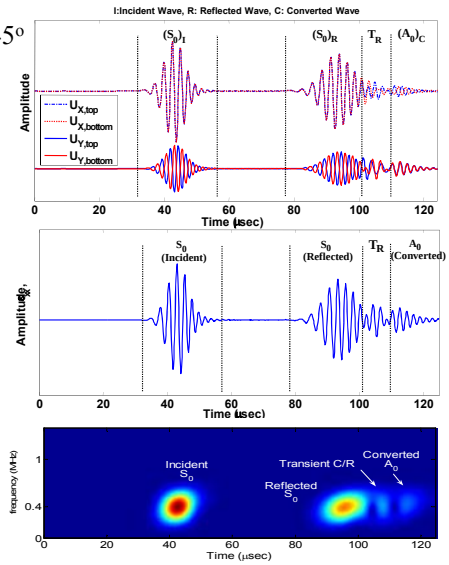
Mode Conversion at Tapered Surfaces

θ=90°



θ=45°



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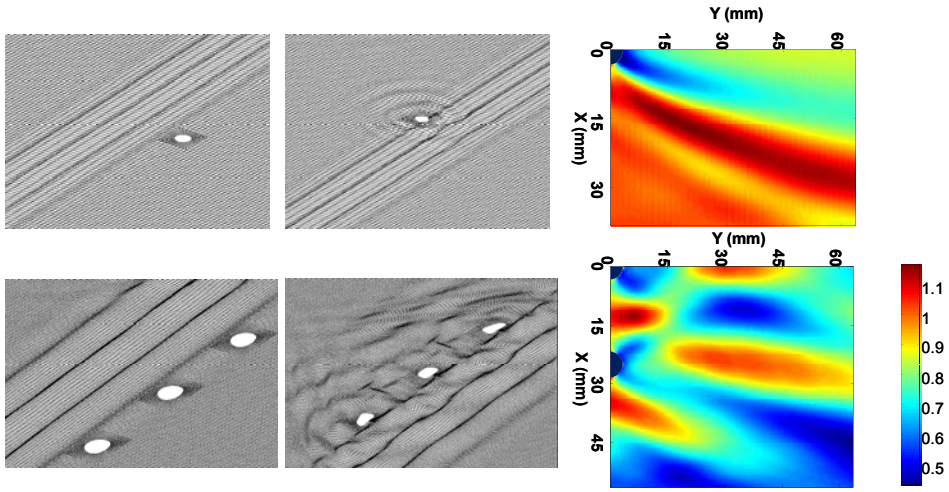
Effect of Holes on Scattered Wave Distribution



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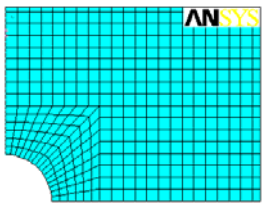
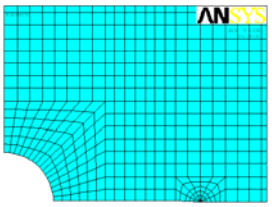
Meshing for Cracks around Holes



Without Crack



With Crack

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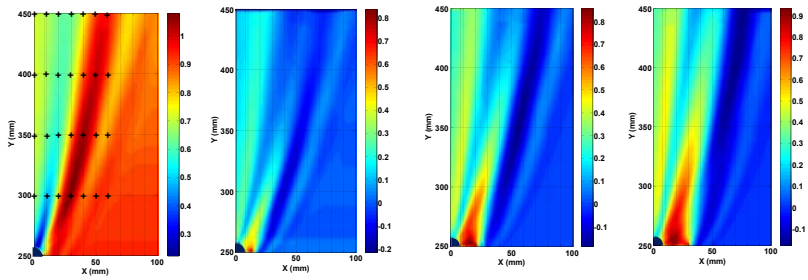
Effect of Cracks on Scattered Wave Differentials



Reference 10 mm Crack 15 mm Crack 20 mm Crack

Crack length 2.5 x rivet diameter needs to be monitored no further away than 12.5 x rivet diameter

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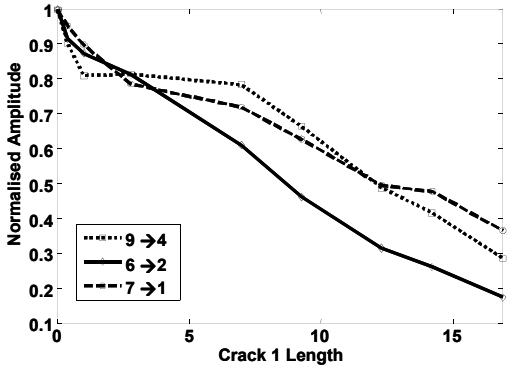
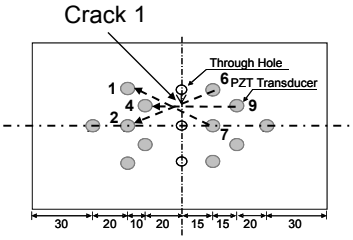
Multiple Path Monitoring for Confidence Enhancement





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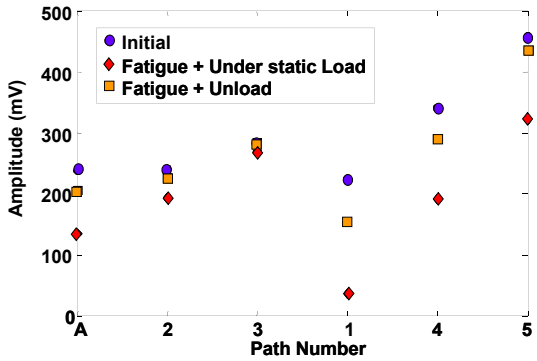
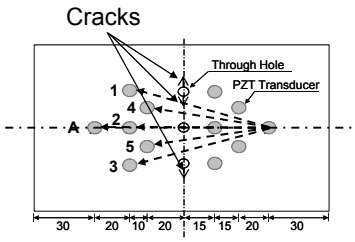
Loading Condition Influence on Damage Monitoring





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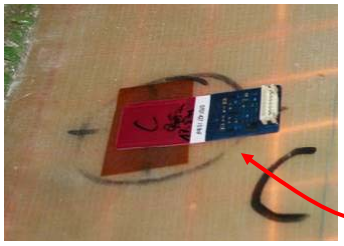
Monitoring of Windmill Rotor Blades

high frequency

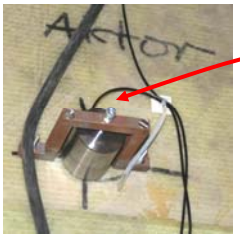
- Acoustic Emission (passive)
- Acousto Ultrasonic (active)



36 HF piezo fibre transducer

Sensor/actor elements

- piezo fibre patches (HF) as sensors (and low range actors)
- pzt stacks for lamb wave generation (large range actuators)



6 HF pzt stacks

Source: B. Frankenstein et al., Fraunhofer IZFP

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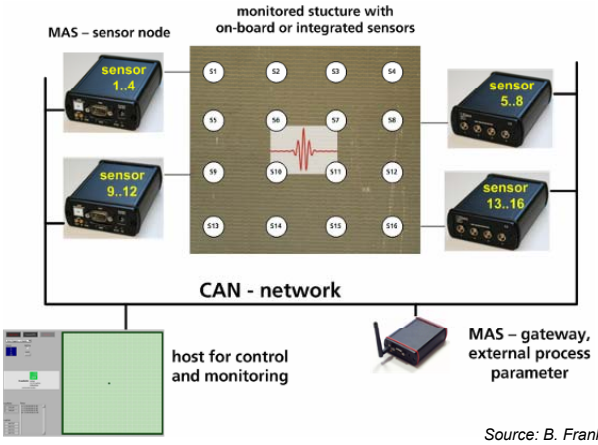
SHM Systems



- structure independent application for SHM
- online reconfiguration
- online and offline analysis, documentation of structural damage
- realization of structure dependent data base
- development and test of online SHM algorithms

Source: B. Frankenstein et al., Fraunhofer IZFP

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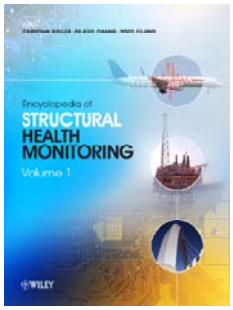
SHM in Publication

- Internat., European and Asia-Pacific Workshop on SHM
- Encyclopedia of SHM; John Wiley & Sons, 5. Vols., ca. 3,000 pages, 01/2009
- Structural Health Monitoring – An International Journal; SAGE Publ.
- Int. Journal on Structural Control and Monitoring; John Wiley & Sons
- Smart Materials and Structures; Inst. of Physics Publ.
- Intelligent Material Systems and Structures; SAGE Publ.
- Staszewski W.J., C. Boller and G.R. Tomlinson (Ed.s), 2003: Health Monitoring of Aircraft Structures; J. Wiley & Sons
- Balageas D., C.-P. Fritzen and A. Güemes, 2005: Structural Health Monitoring; ISTE Ltd.
- …



- Introduction and Definitions
- Physical Monitoring Principles
- Signal Processing
- Simulation
- Sensors
- Systems and System Design
- Principles of SHM-Based Structural Monitoring, Design and Maintenance
- Aerospace Applications
- Civil Engineering Applications
- Other Applications
- Standardization and Specification
- Glossary

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Conclusions

- Ageing structures must have a damage tolerance if they should be managed
- Structural design principles and geometry must be understood
- Operational loads need to be known
- Digital model of the structure is helpful for damage accumulation evaluation
- NDT methods available for in situ structural and materials characterisation
- Different sensing system principles to be ready for structural integration
- NDT phenomena around the areas to be monitored have to be known
- SHM technologies considered provide sufficient maturity and reliability
- A lot of technology around for SHM based ageing infrastructure management

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