Air Force Institute of Technology

Health Monitoring implementation to aerial platforms for structural integrity monitoring - need or necessity ?

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AFIT MISSION

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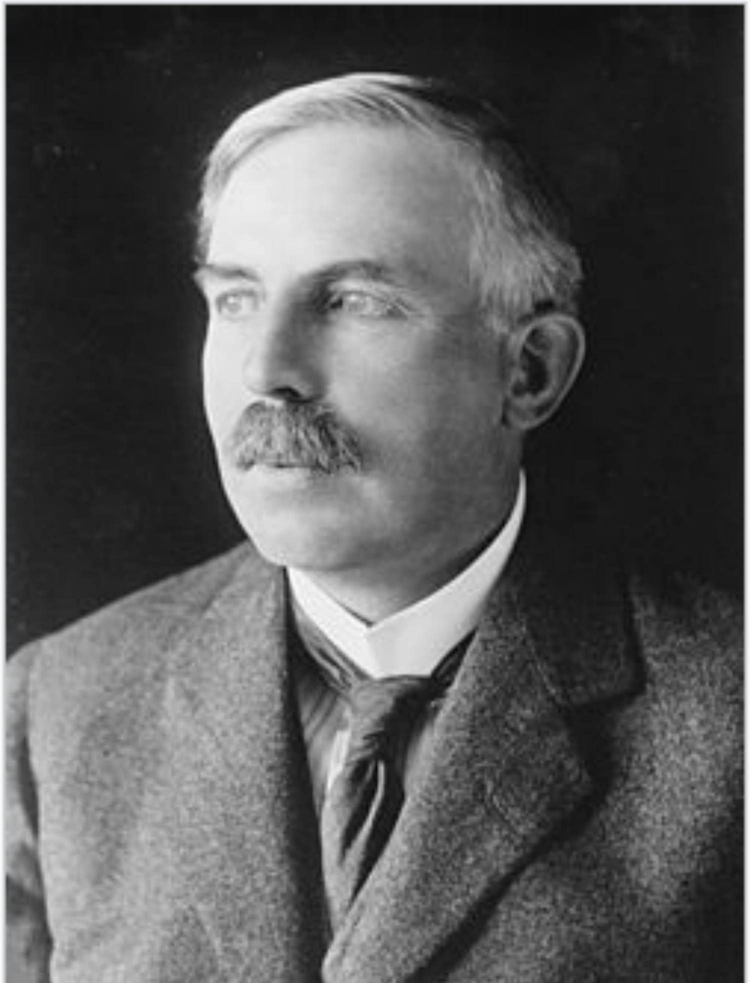
AFIT - 11 R&D Divisions;

Airworthiness Division Responsbile for supporting of the Armed Forces within ASIP programme, Service Life Extensions Programmes and Legacy activities within existed framework.

Agenda:

- Diagnostics;
- Introduction to Legal Framework;
- NDI/SHM;
- Use Cases Desription;
- Question (discussion if any :)).

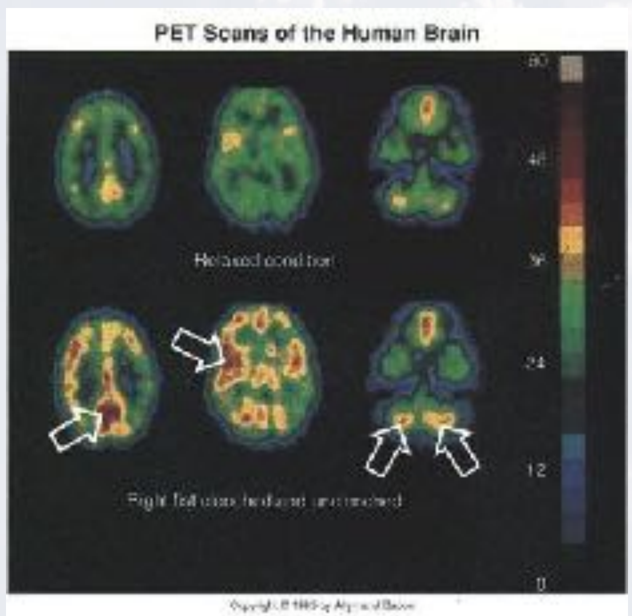
Tribute to Physics :


Ernest Rutherford (1871-1937)

All **science** is either **PHYSICS** or **stamp collecting**.

DIAGNOSTICS:

- **Urine Test;**
- **Blood Test;**
- **X-RAY, CT, PET;**
- **MRI;**
- **OTHERS…**



HIDDEN ENEMY…

To Aircraft

- Aging:
  - Fatigue (cycles);
  - Corrosion (SCC, pitting, exfoliation);
  - Atmospheric conditions (UV, temp. gradients, moisture, salinity);
  - Impacts/strokes (thermal, mechanical)
- Human Factor;
  - New Materials;
  - Maintenance Mistakes;
  - Other…
- Murphy’s Law ☺️

Direct A/C Flight Loads Monitoring - OLM Programs

PZL-130 „Orlik” TC-I (2000 yr)
PZL-130 „Orlik” TC-II (2010 yr)

Mi-14PS (2002 yr)

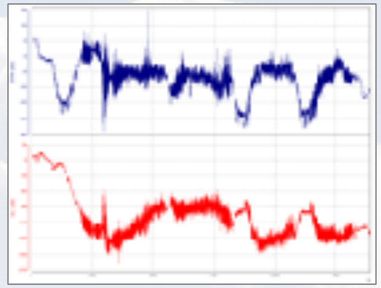
Su-22M4 (2004 yr)

MiG-29 (2006 yr)

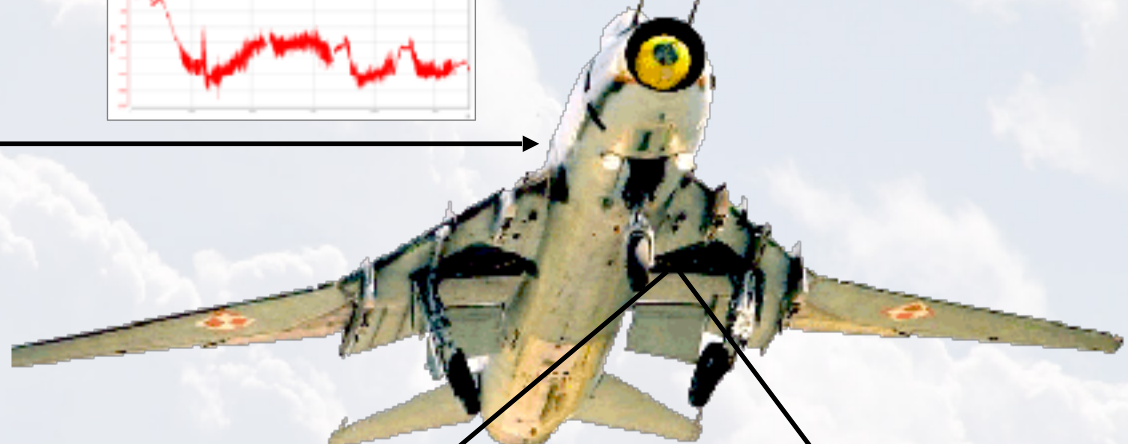
MiG-29UB (2007 yr)

Mi-24 (2009 yr)

Operational Loads Monitoring

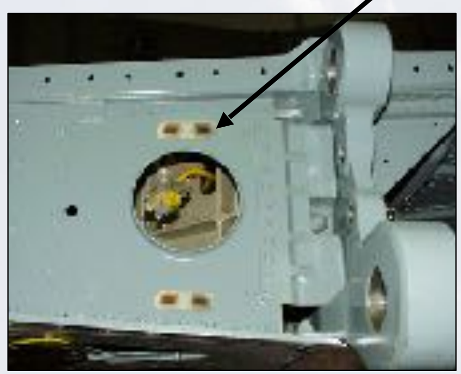


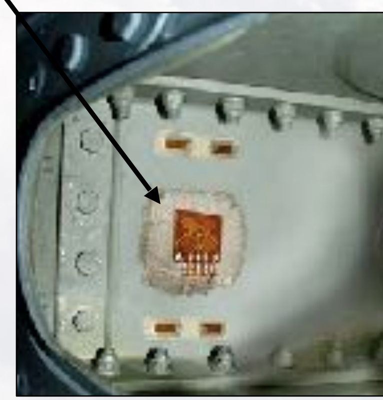
Strain collected



FDR

KAM-500 (Su-22)





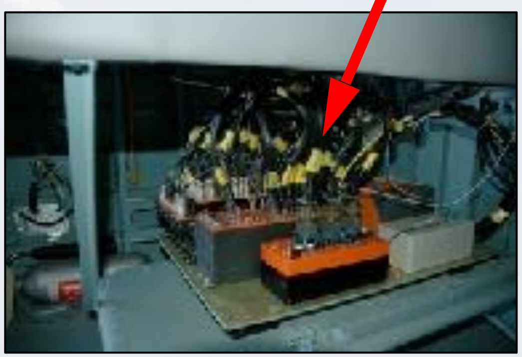
Strain Gauges on the wing

LMS - DATA RECORDER LOCATION

Mi-24 Hind Helicopter OLM Program

Testing equipment consisted of:

- ➢ Multichannel Data Acqusition System;
- ➢ 72 strain gauges;
- ➢ sensor to measure shock absorber stroke;
- ➢ Nz sensors.



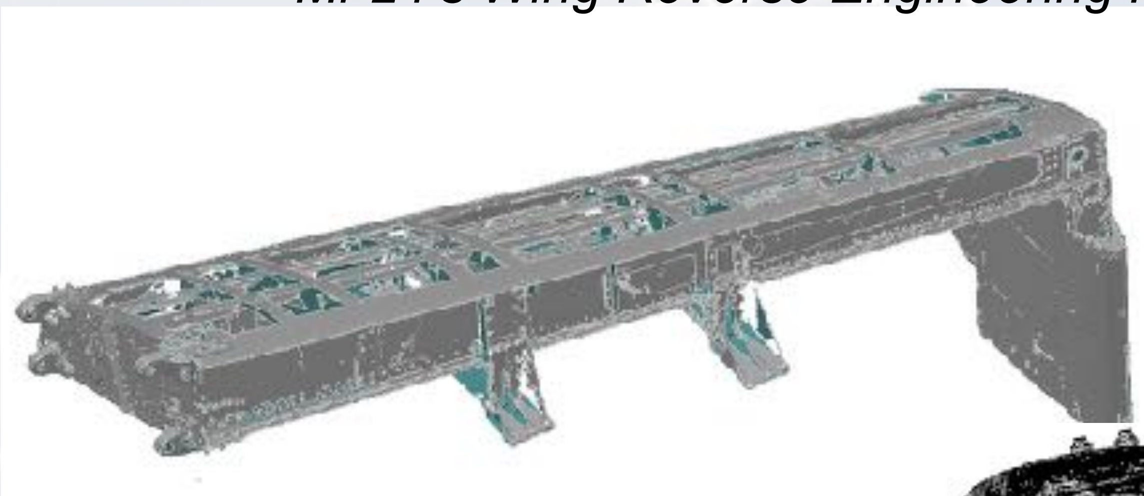
Multichannel Data Acqusition System

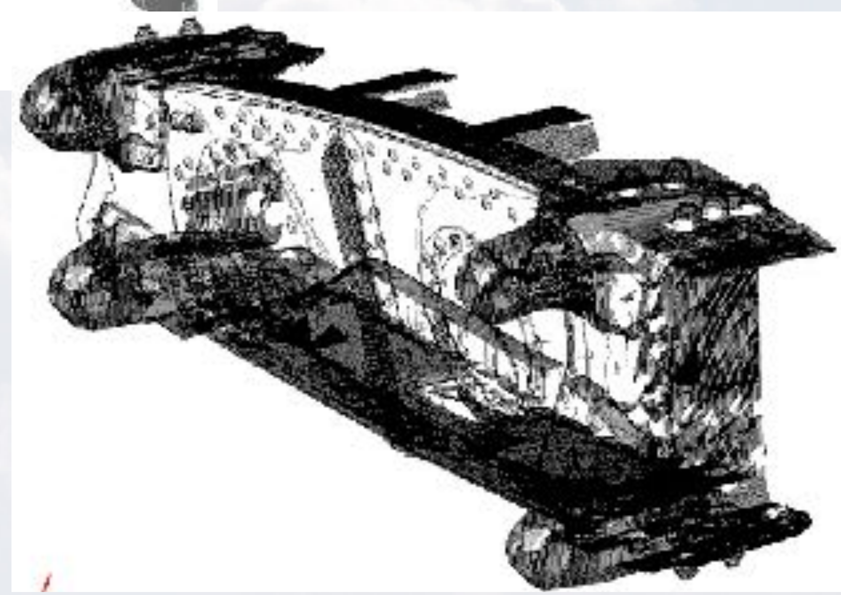
Shock absorber stroke sensor

Strain gauge

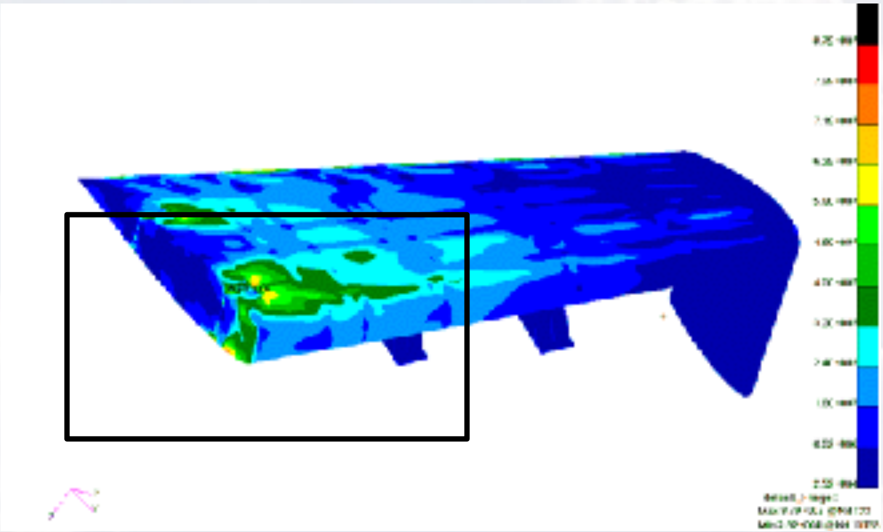
Mi-24's FEM Model Development

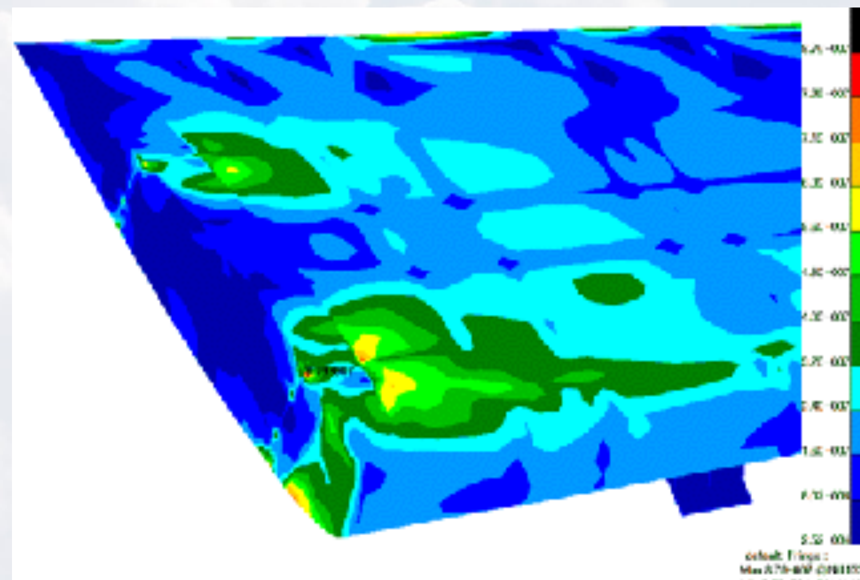
Mi-24's Wing Reverse Engineering Measurements Results





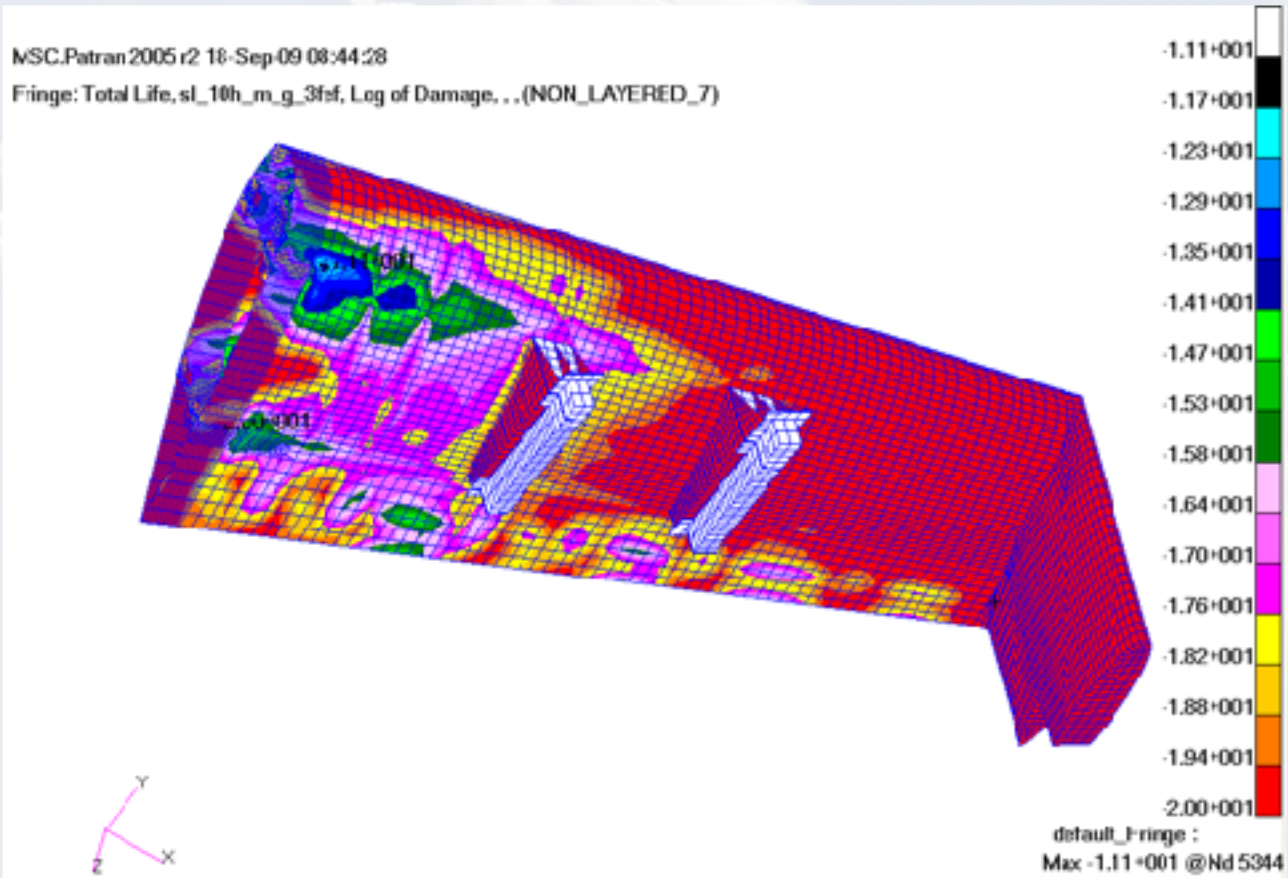
Mi-24's Wing FEM Stress Analysis Results



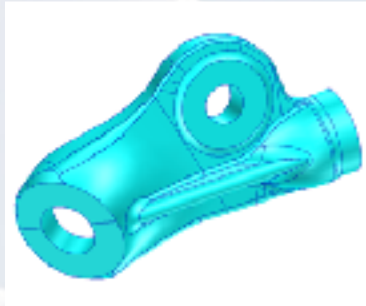
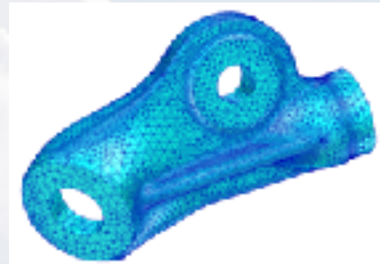
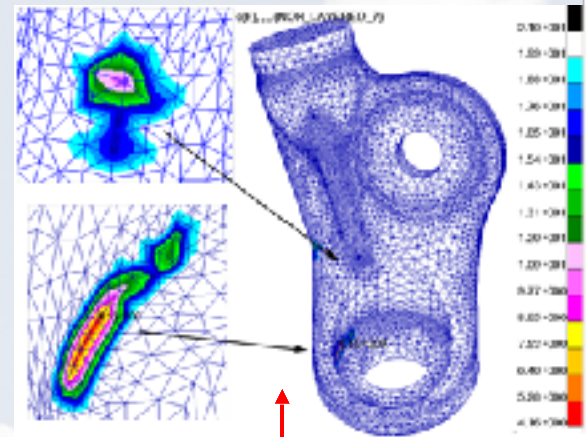


Mi-24 Wing Fatigue Life Calculations

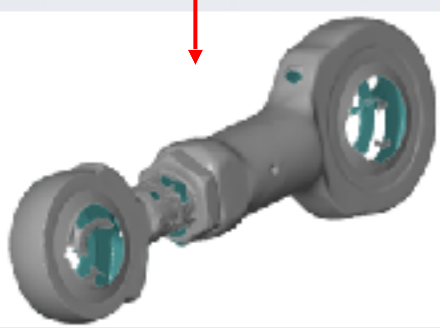
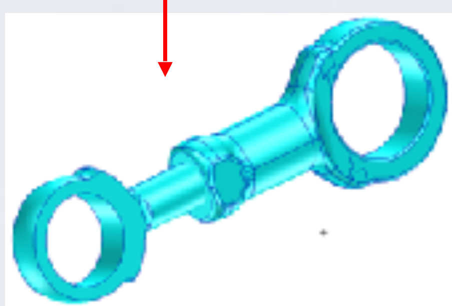
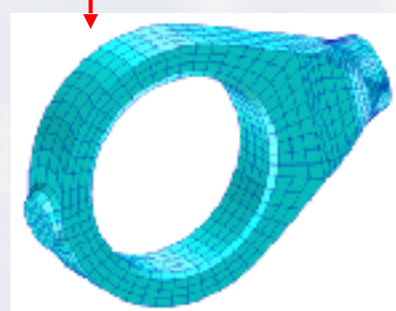
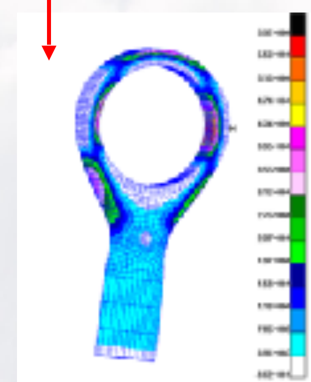
Case #, Goodman mean stress correction, k_t=3



Fatigue life estimation

3D Image → **Computer Model** → **FE Model** → **Calculation results**

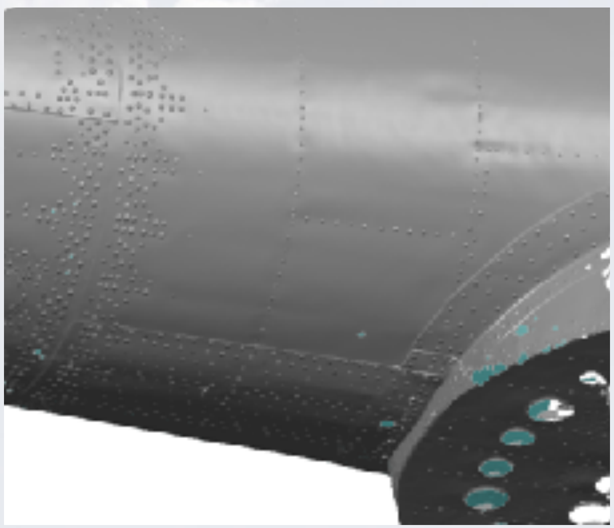





Reference markers

ATOS III measurement process

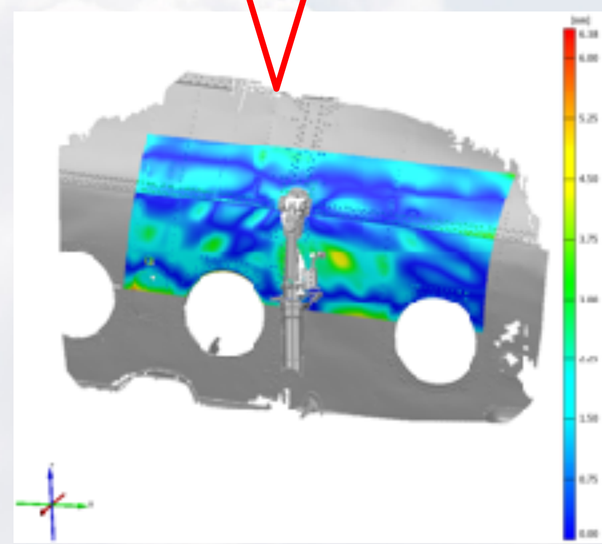
ATOS III sensor unit

Controlled area – shock's absorber joint



Measurement's result

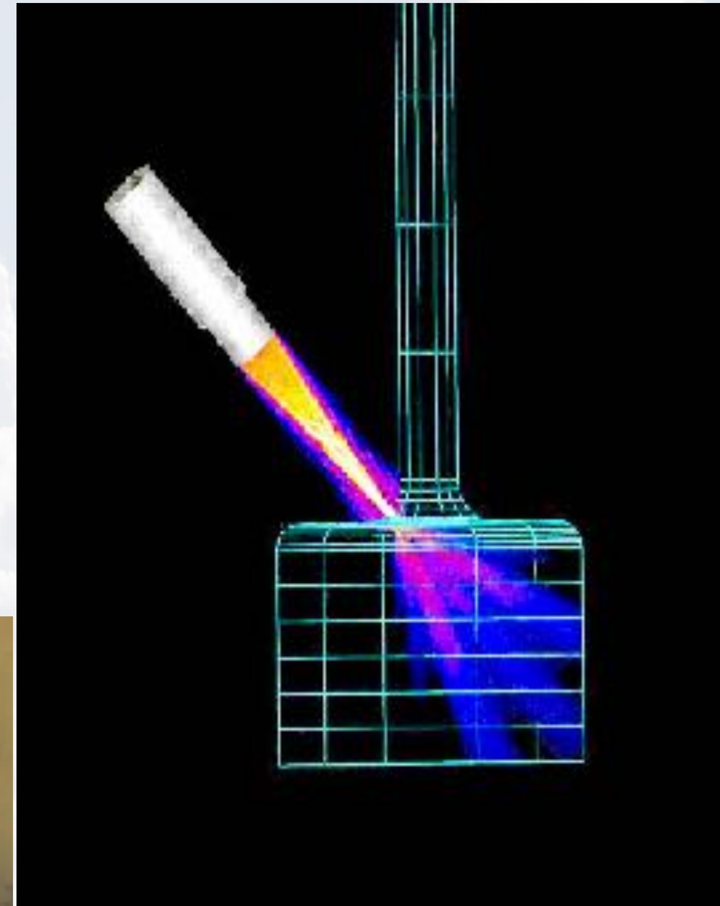
- Reverse Engineering
- Quality Control
- Rapid Prototyping
- Rapid Milling
- Digital Mock-Up



Skin waviness around shock's absorber joint

NDT/E/I

The use of noninvasive (1)
Techniques *Testing*/Evaluation/*Inspection*)
NDT to determine
the structural integrity of a material,
component or structure
or quantitatively measure
some characteristic of
(*)



„...reach where the eye does not goes back to..”

A. Mickiewicz (1798 - 1855)

(*) www.ndt-ed.org

Automated Inspections

- Methods of inspection:

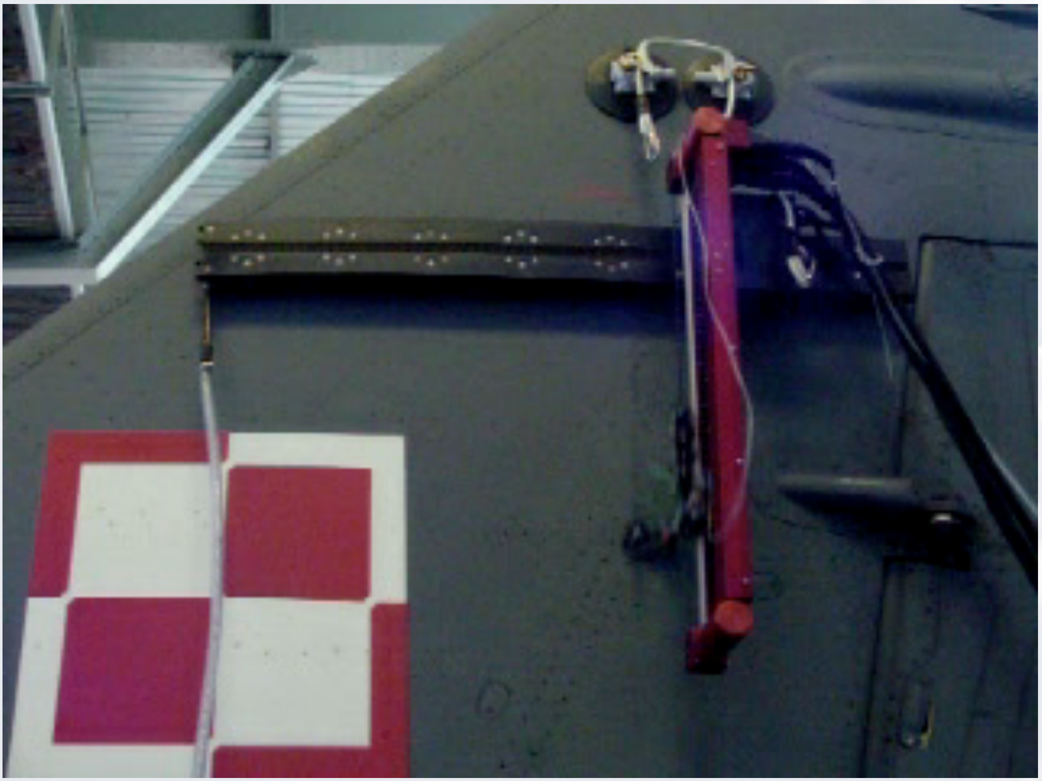
➢ Ultrasound (longitudinal & shear wave, P-E, T-T)
➢ Ultrasound Phased Array,
➢ Eddy Current (single & dual frequency)
➢ Resonance (H-F, Pitch – Catch, MIA)
➢ Multiple methods inspection in single scan

- Results presentation:

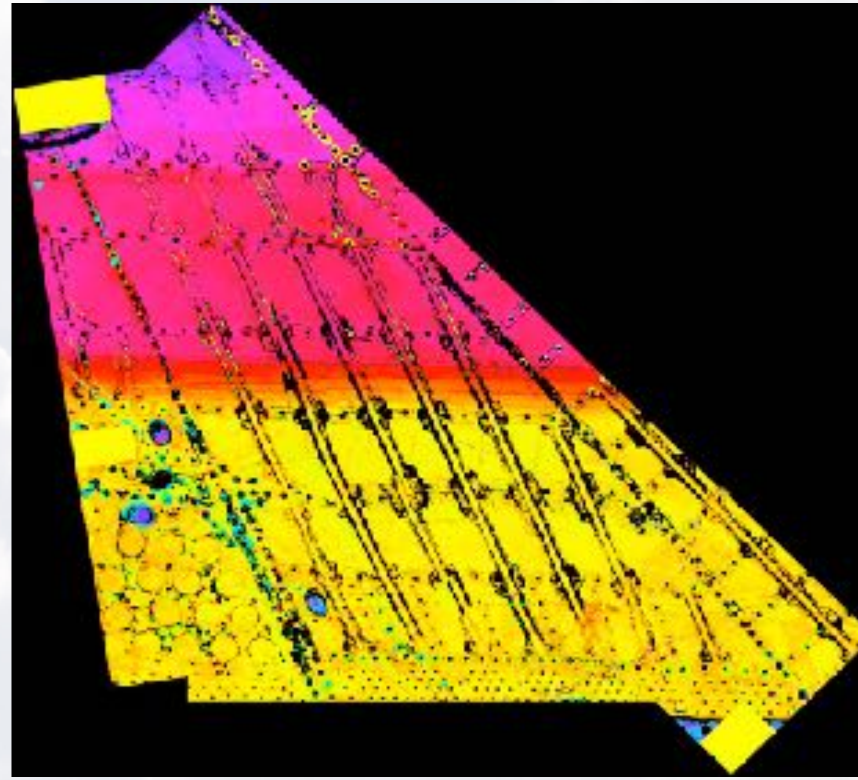
➢ A-scan, B-scan & C-scan
➢ Dynamic B-scan Phased Array

- Flexible tracks system
- High speed inspection of large areas
- Vacuum pump system enables vertical and bottom wing skin inspection

MiG – 29 vertical stabilizer inspection



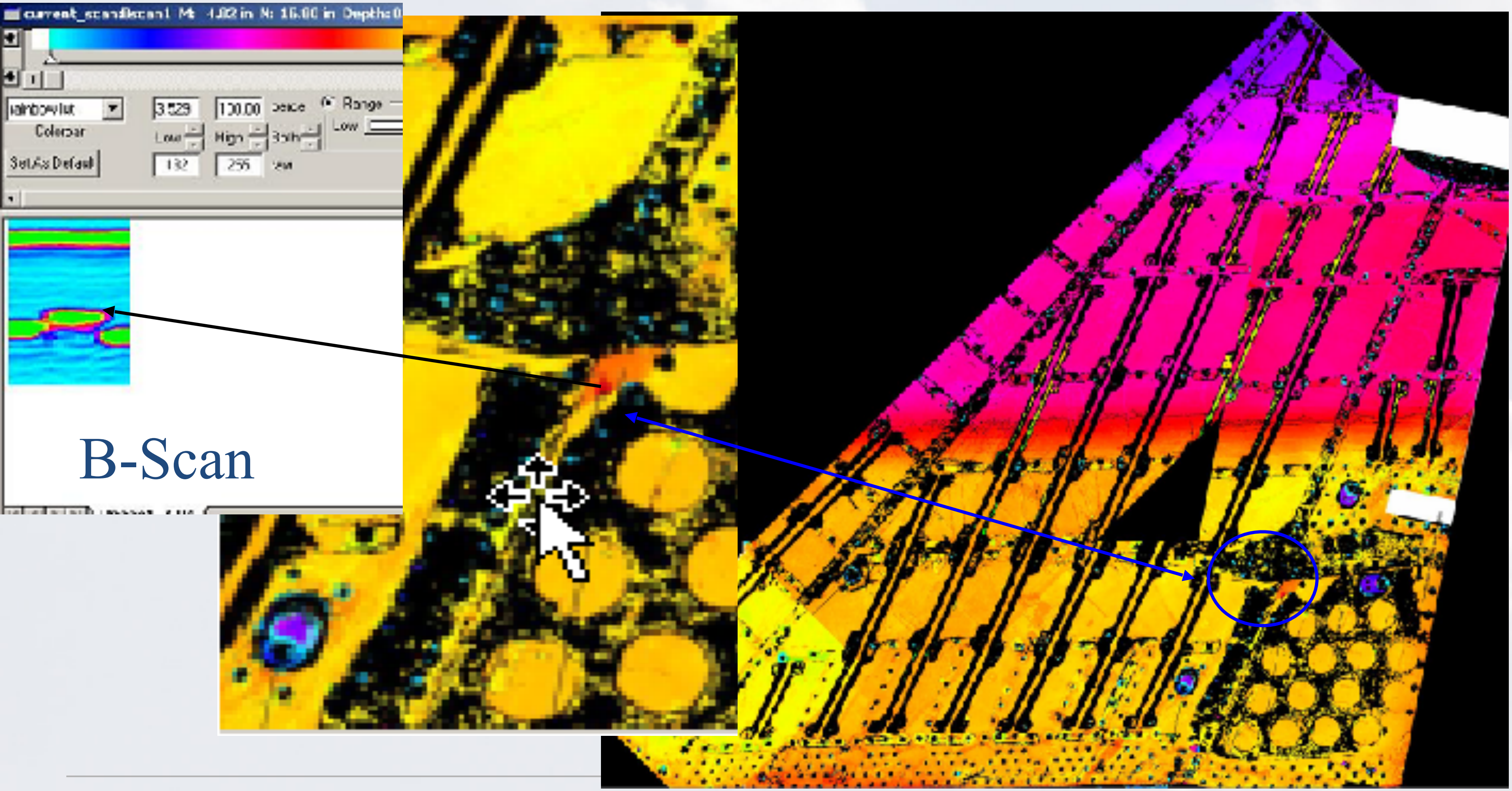
Composite skin inspection of MiG-29 vertical stabilizer



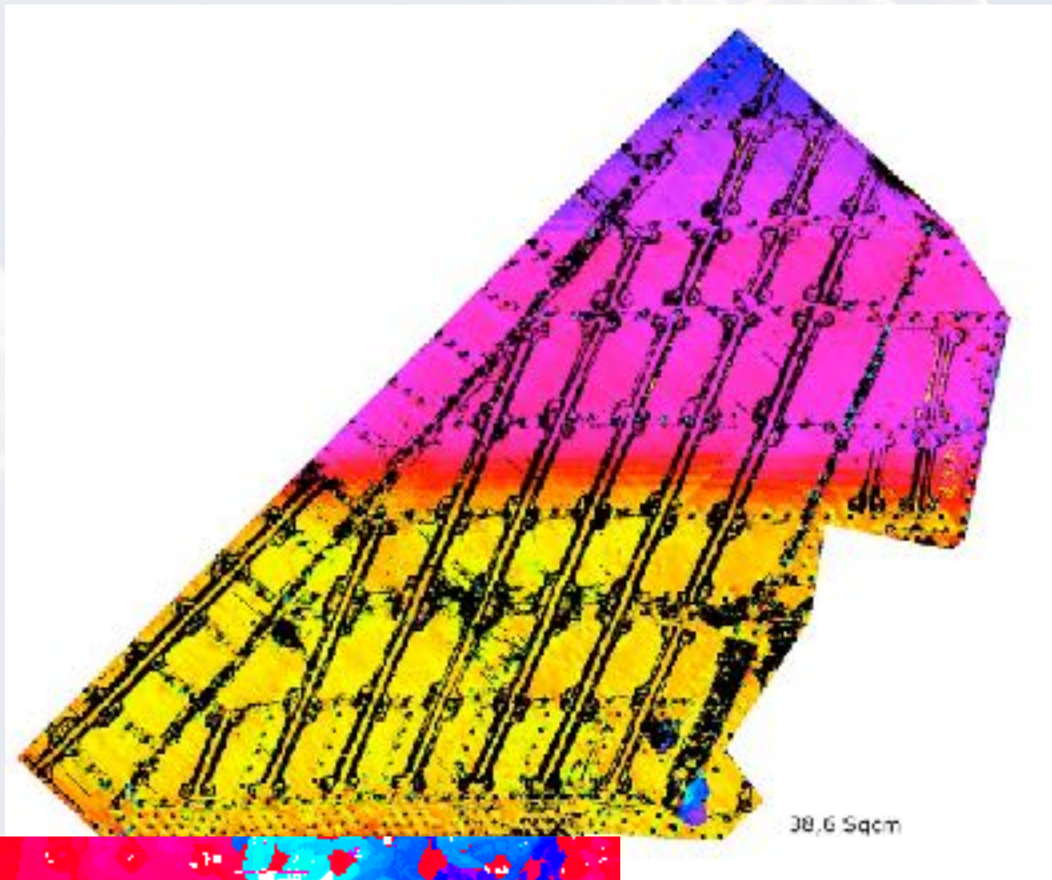
UT C-scan result data P-E ToF

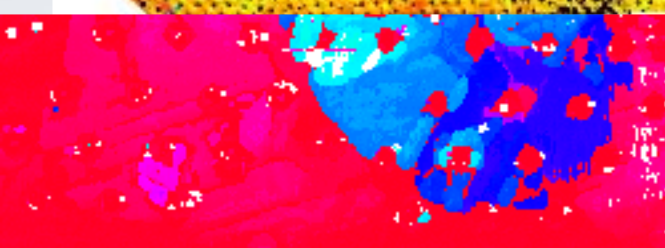
Foreign object inclusion

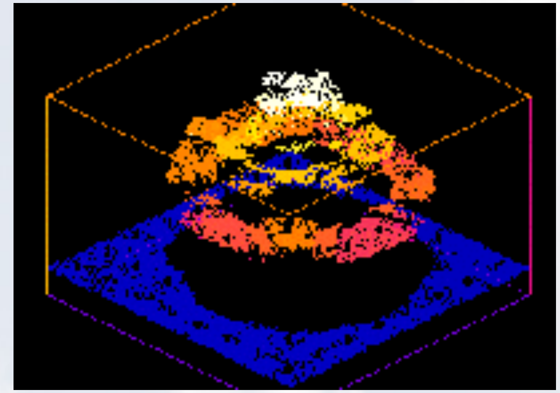
Ultrasonic Results



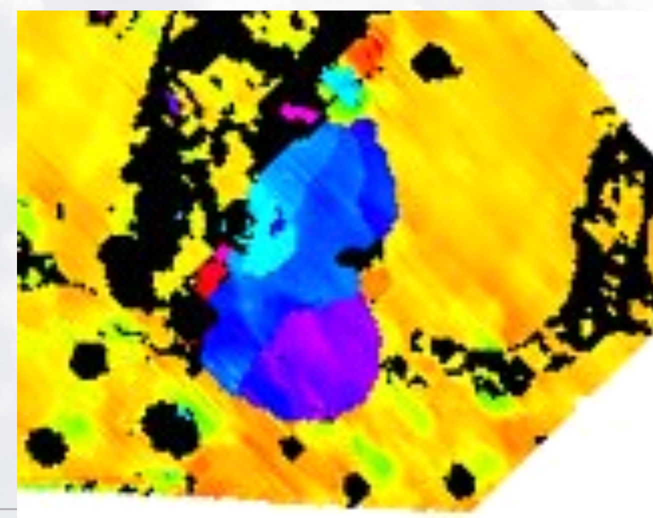
Impact Damage





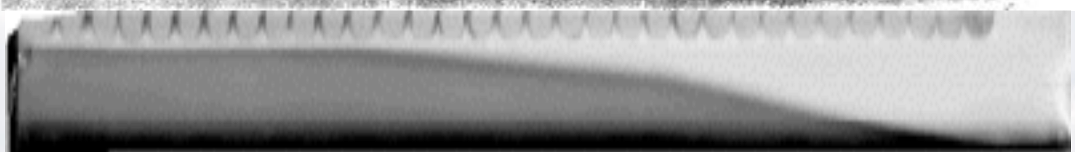


www.andscan.com

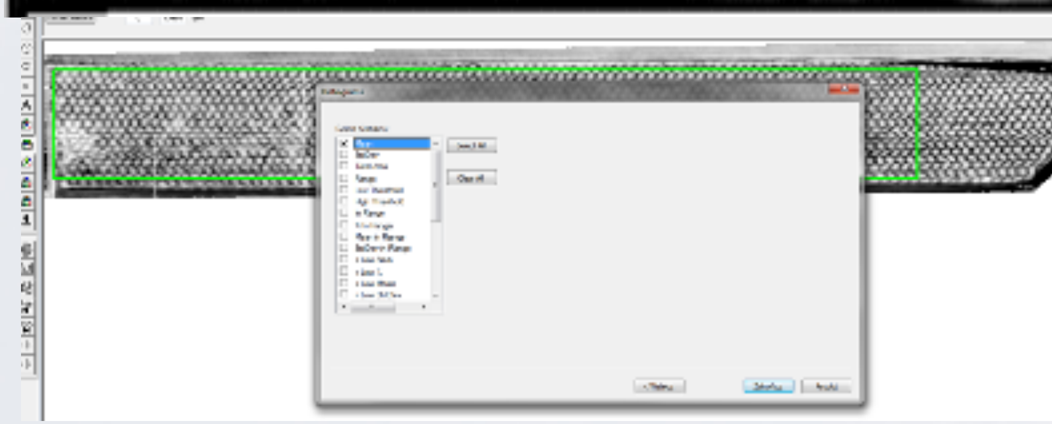


SERVICE LIFE EXTENSION PROGRAM & SERVICE BULLETINS

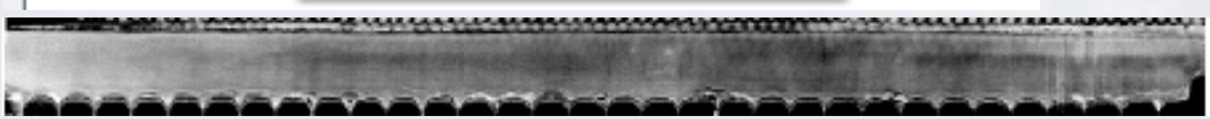
ET- skin



ET- spar



MIA- skin to honeycomb disbonds



MIA- spar to leading-edge abrasion strips

STRUCTURAL HEALTH MONITORING

Condition Based Maintenance

Relies on:

- profound knowledge of material properties, e.g. its fatigue strength
- preassumed load spectrum (and its monitoring)

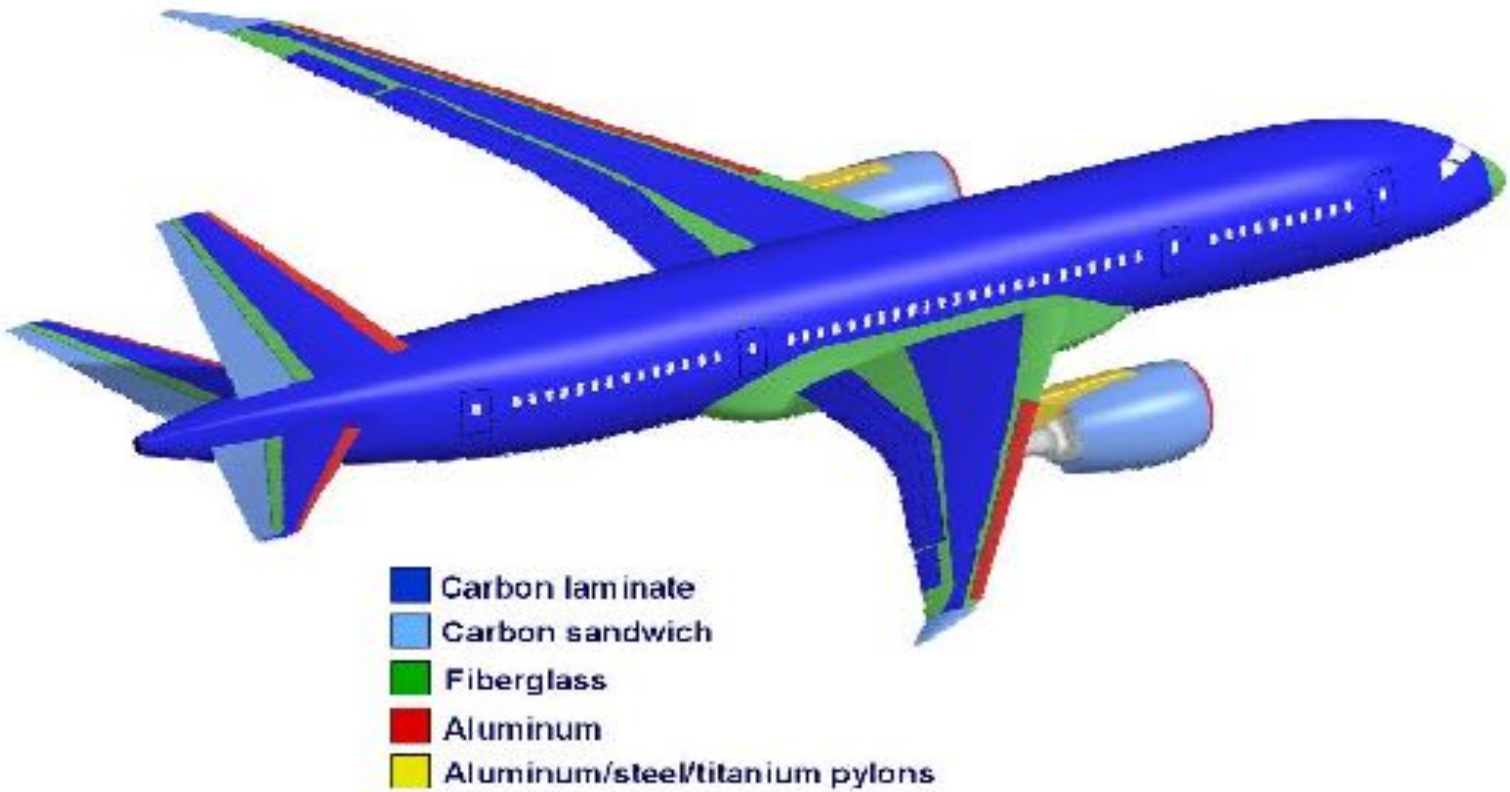
↓

Detailed NDI programme needs to be provided for each aircraft type:

↓

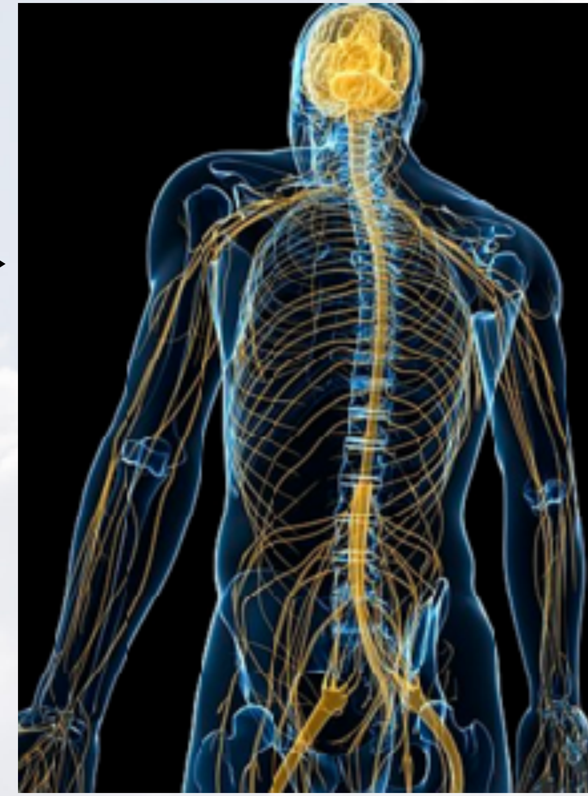
- increased maintenance cost
- safety issues (especially for composite structures)

Composites in new design



SHM - IN SITU NDI

?



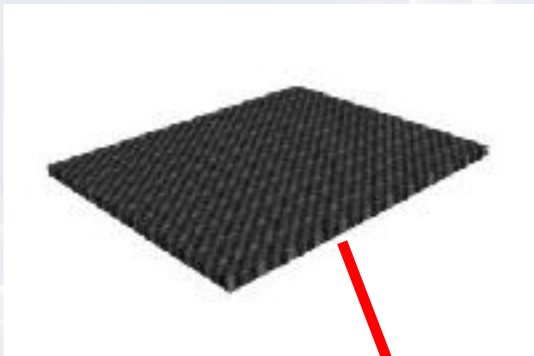
SHM – Structural Health Monitoring

Application of NDT techniques for signals acquisition by network of sensors embedded in a monitored structures. Structure condition is assessed based on characteristic signals parameters.

SHM. Level 1: damage detection;
SHM. Level 2: damage identification;
SHM. Level 3: damage assessment;
SHM. Level 4: health and usage forecast;

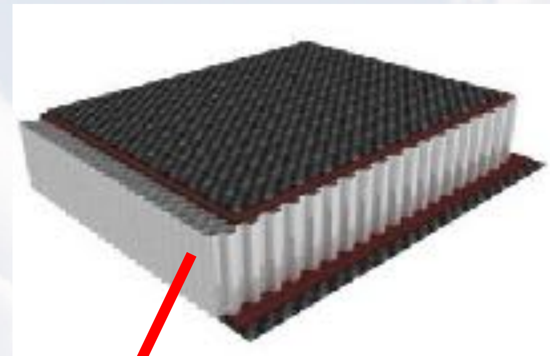
Types of monitored structures:

Laminate composite

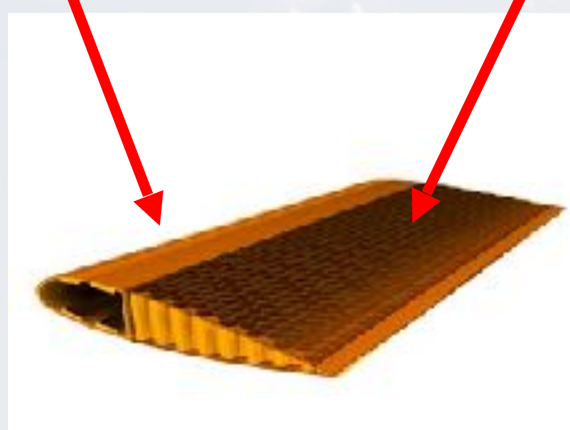


Composed of matrix and fibers

Sandwich



Composed of composite laminates enclosing a foam or honeycomb structure as a core



SHM systems

Structural Health Monitoring Systems

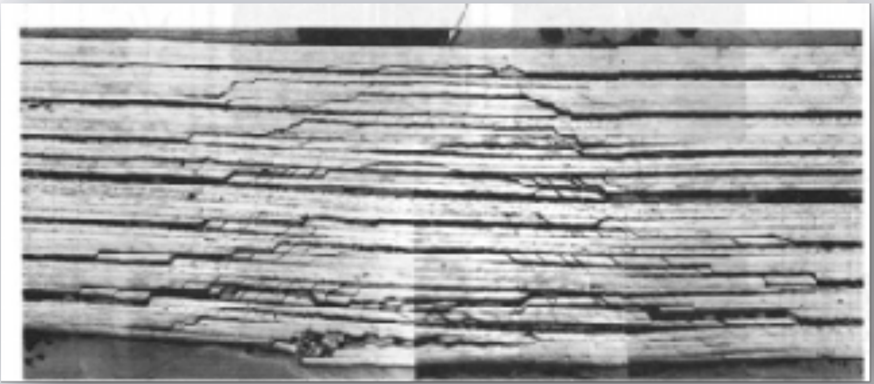
(local):

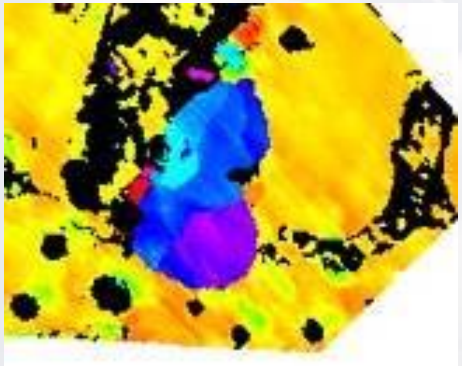
Local methods:

- strain gauges, resistive ladders, eddy current sensors, CVM, FBG

Global methods:

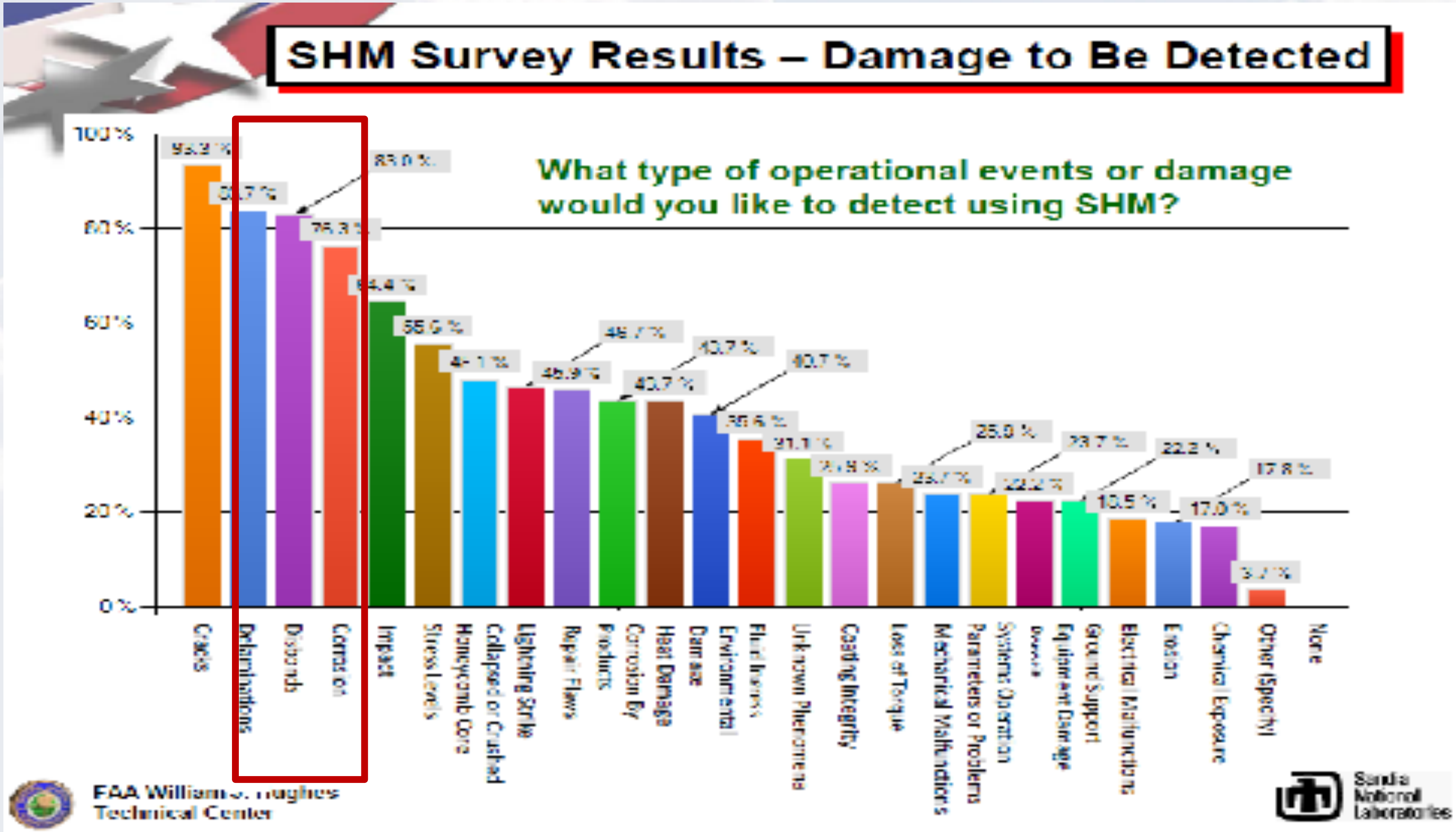
- PZT transducers



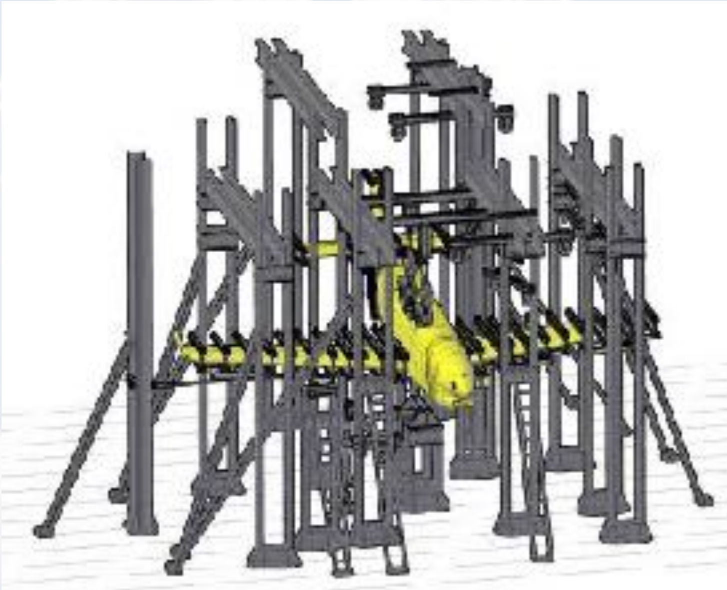


Results of UT inspection - MiG-29 stabilizer impact

SHM necessity



Industry Survey of Structural Health Monitoring Technology and Usage -
Dennis Roach FAA Airworthiness Assurance Center Sandia National Laboratories



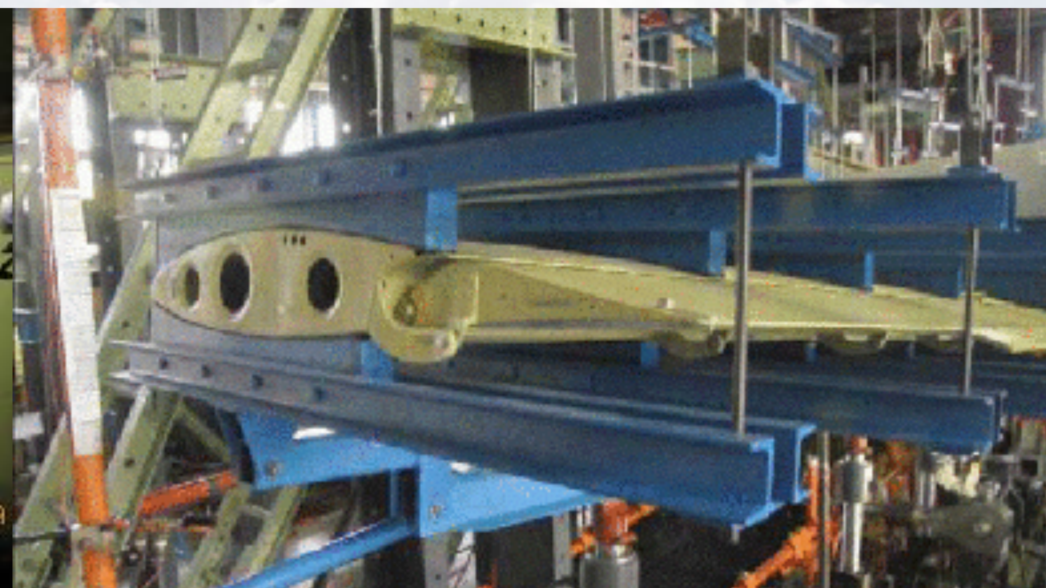
PZL 130 TC II „Orlik”

Full Scale Fatigue Test:

2011 – 2014.

Different approaches to crack detection:

PZT sensors, resistive ladders, CVM™



Elastic waves motion in solid media

Wave propagation modes in infinite linear isotropic continuum:

$$\nabla^2\Phi = \frac{1}{c_1^2}\Phi_{,tt} \qquad c_1 = \left(\frac{\lambda + 2\mu}{\rho}\right)^{\frac{1}{2}}$$

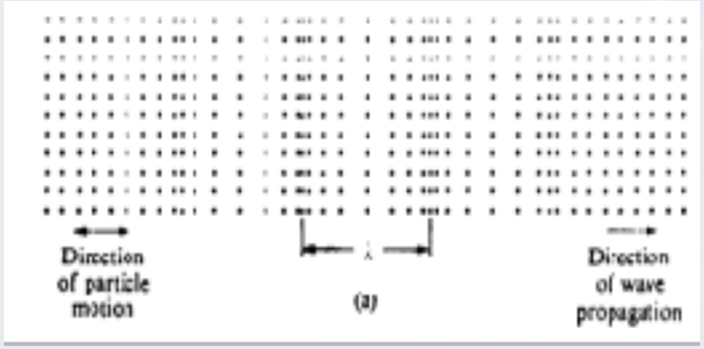
longitudinal P-wave

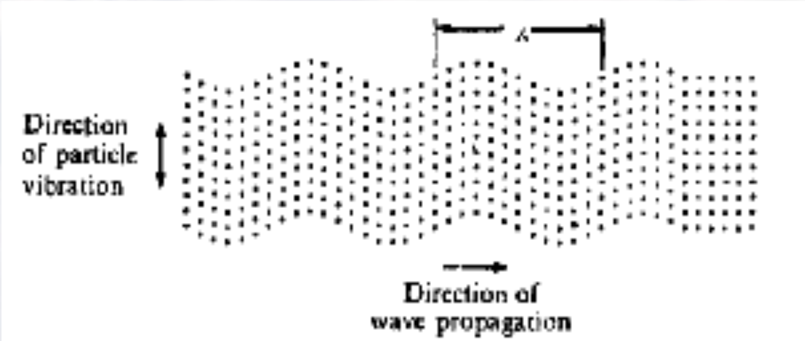
$$\nabla^2\mathbf{H} = \frac{1}{c_2^2}\mathbf{H}_{,tt} \qquad c_2 = \left(\frac{\mu}{\rho}\right)^{\frac{1}{2}}$$

transverse S-wave

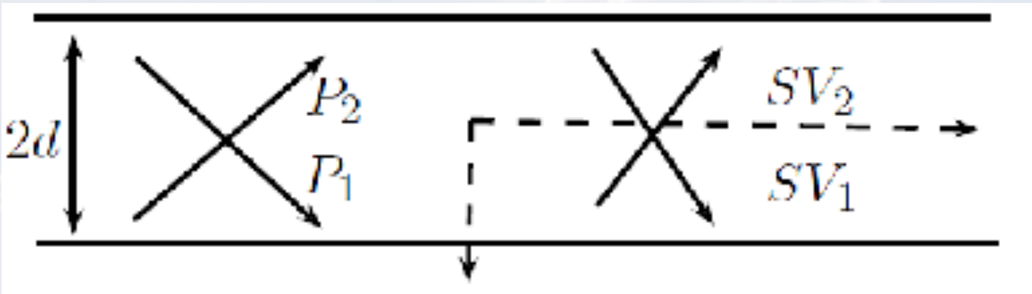
where $\Phi, \mathbf{H}$ are Helmholtz potentials determining the displacement

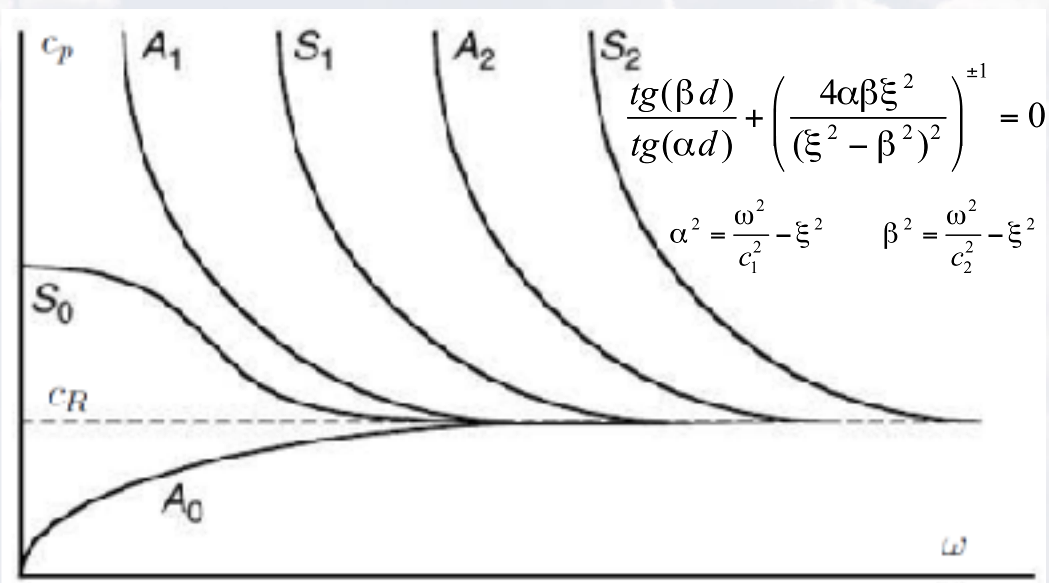
$$\mathbf{u} = \nabla\Phi + \nabla\times\mathbf{H}, \qquad \nabla\cdot\mathbf{H} = 0$$





Lamba Waves





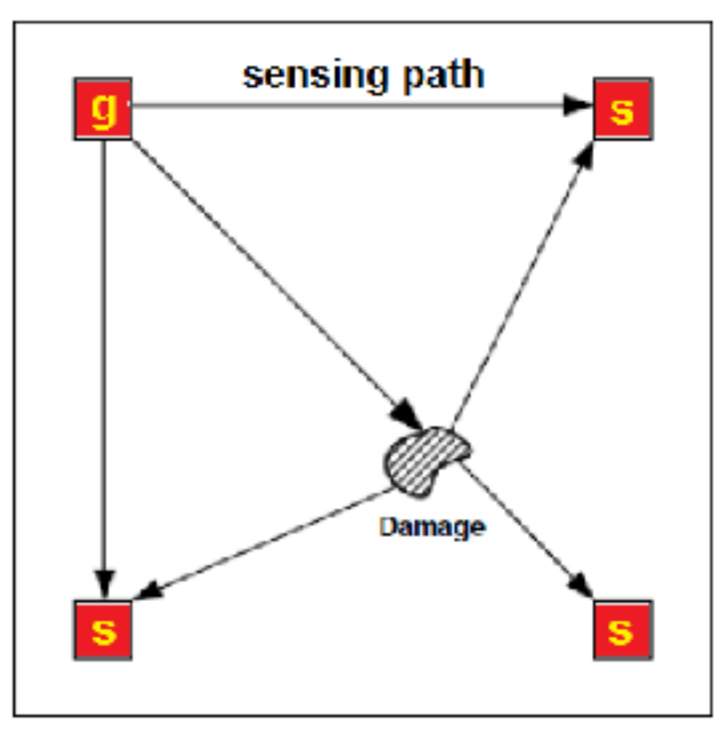
$$\frac{tg(\beta d)}{tg(\alpha d)} + \left(\frac{4\alpha\beta\xi^2}{(\xi^2-\beta^2)^2}\right)^{\pm 1} = 0$$

$$\alpha^2 = \frac{\omega^2}{c_1^2} - \xi^2 \qquad \beta^2 = \frac{\omega^2}{c_2^2} - \xi^2$$

In plates many propagation modes with different propagation velocities can occur at a given excitation frequency due to multiple reflections from plate boundaries.

At least two modes exist at a given frequency, corresponding to the flexural and extensional classical plate theory propagation modes in the low frequency limit.

Overview of the approach:



The system presented works in the so called pitch – catch mode.

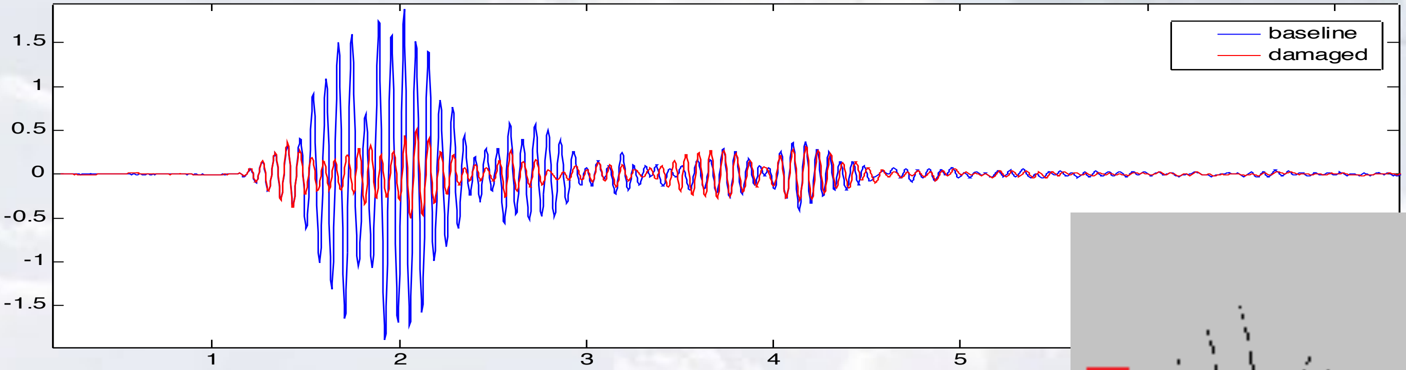
Elastic wave propagating in the monitored structure can be distorted by a damage resulting in measurable effects.

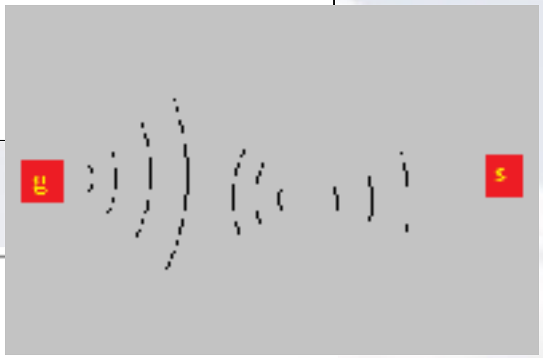
The inference about the state of the structure is done based on signal transformations, called the Damage Indices - *DI(g,s)*.

$$\text{sensing path} \rightarrow \text{signal} \rightarrow DI(g,s) \rightarrow \text{structure health assessment}$$

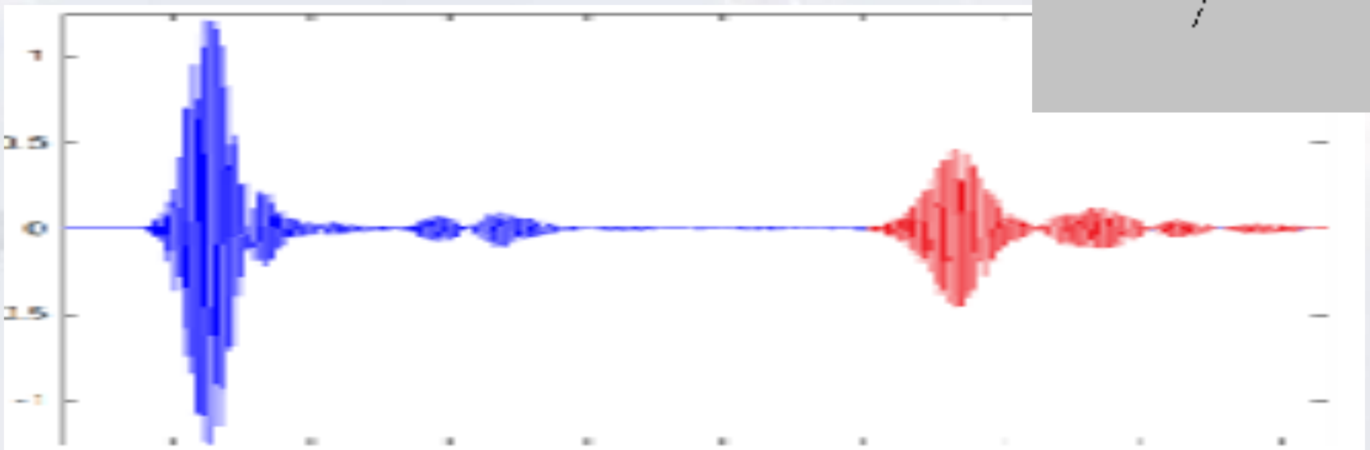
Modes of operation

- wave transmission





- wave reflection



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Overview of the approach

Damage Indices issues:

- ✓ the damage type
- ✓ the complexity of signal and the fine tuning problem
- ✓ the balance between sensitivity and specificity

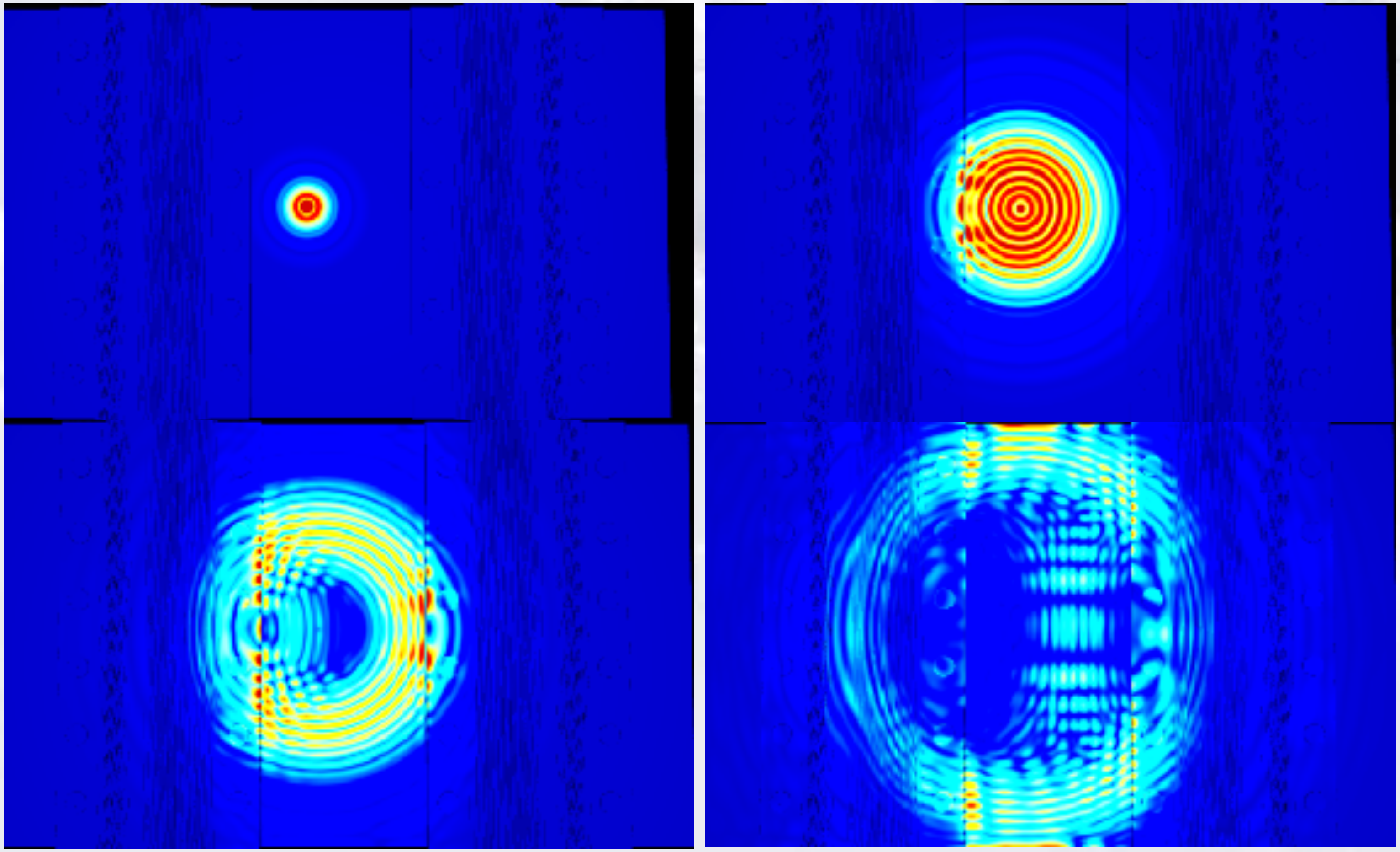
$$DI_1(g,s) = 1 - r_{f_{gs}^{env} f_{gs,b}^{env}} \quad ; \quad DI_2(g,s) = \left| \frac{\int (f_{gs}^{env} - f_{gs,b}^{env})^2 dt}{\int (f_{gs,b}^{env})^2 dt} \right|, \quad \ldots \quad \text{and more}$$

$f_{gs}^{env}, f_{gs,b}^{env}$ - envelopes of the signal and the baseline on a sensing path;

r_{xy} - the sample correlation of x and y

Wave propagation – LISA/SIM model

Local Interaction Simulation Approach / Sharp Interface Model



Averaged Damage Indices:

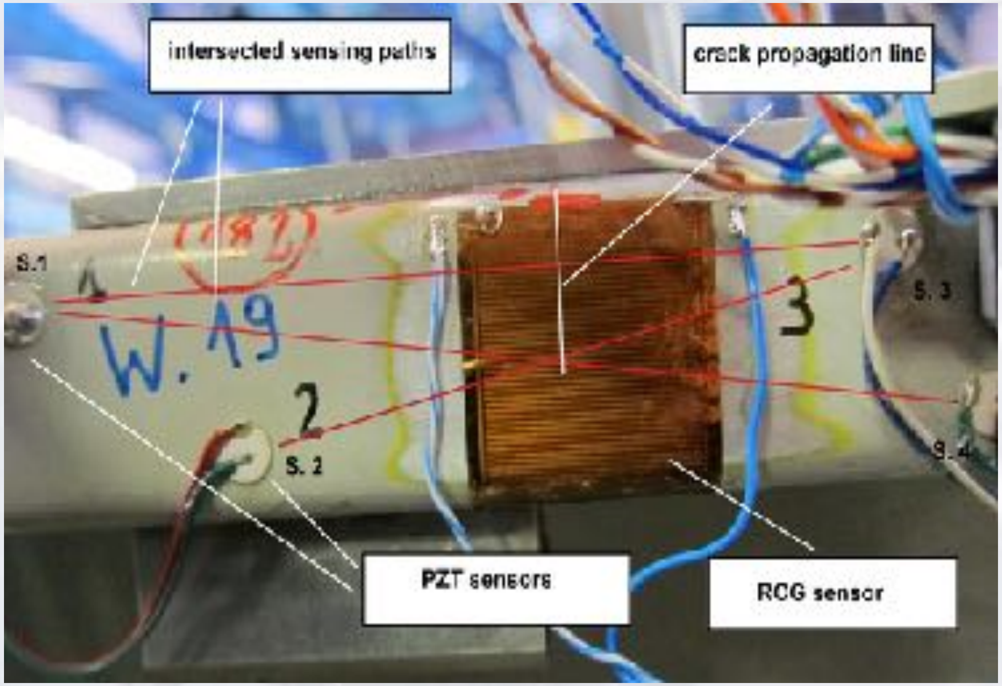
Information merging via DI’s averaging (after DI’s compensation):

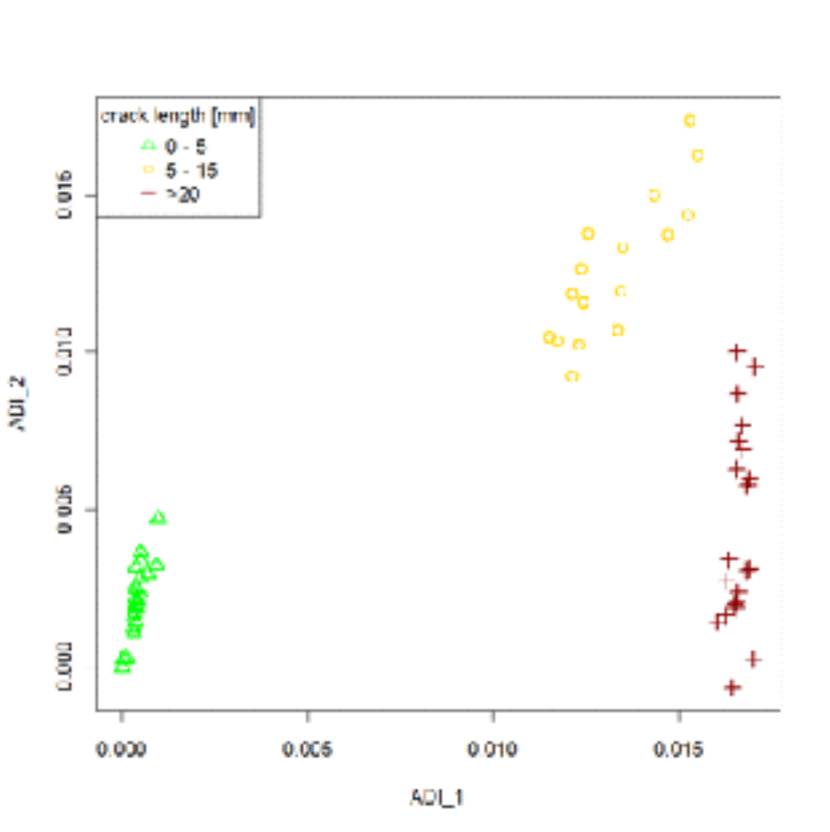
$$ADI = \frac{1}{G(S-1)} \sum_{s,g:s\neq g} DI(g,s).$$

Properties:

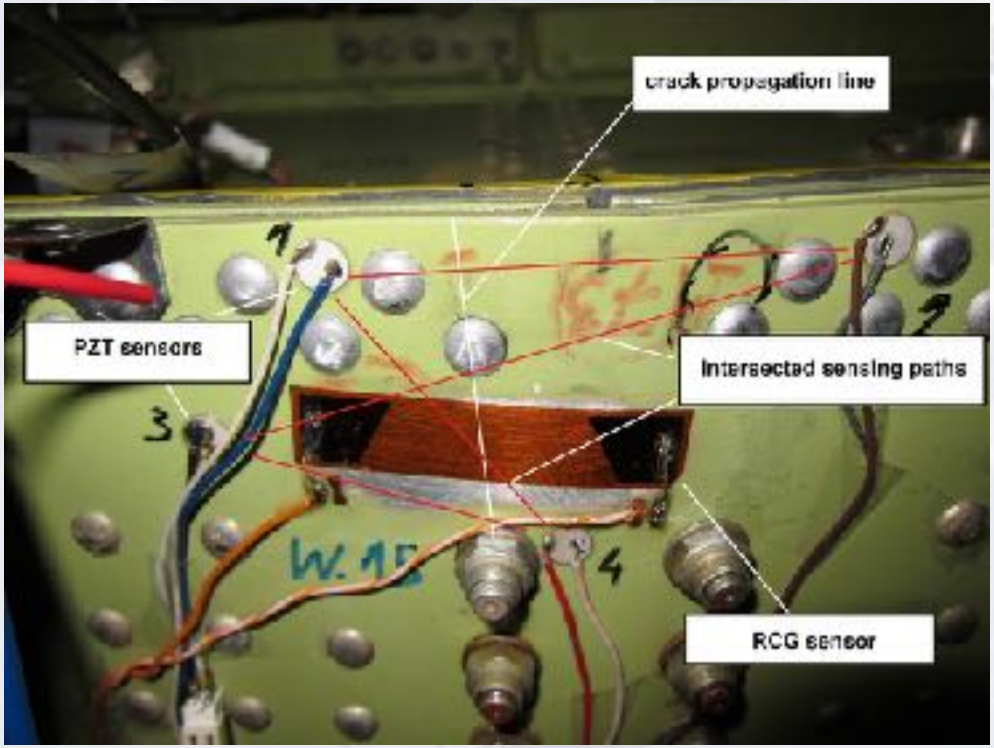
- the least dependent linear combination of DI’s on the geometry of a problem(invariant with respect to permutations of sensors) – used in many models of data classification or regression
- easier statistical inference due to linearity (confidence bounds, statistics distribution)

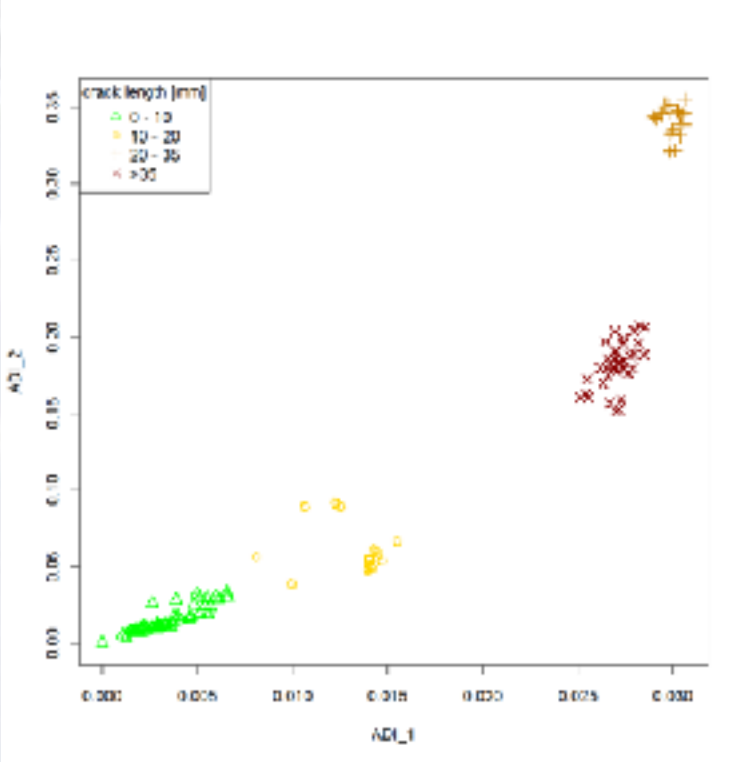
Monitoring system based on PZT network: selected results





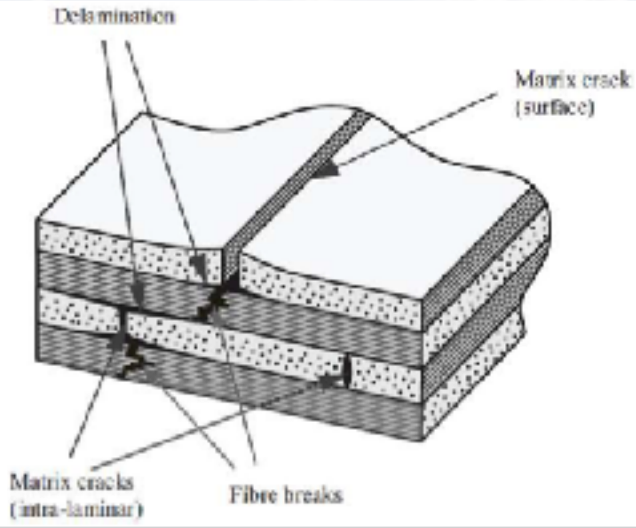
Monitoring system based on PZT network: selected results





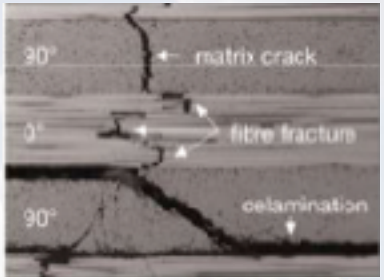
Composite material damages

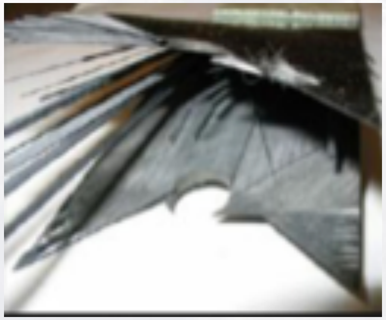
Composite materials are rather complicated to model due to **inhomogeneity** and **anisotropy** behaviour, reason for the experimental tests to be carried out. Due to their characteristics, composite material may be subject to different types of damage:

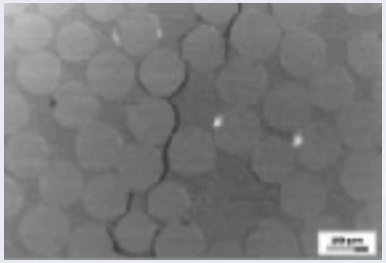


Intra-laminar damage:
- Matrix cracking
- Fibre breakage
- Fibre-matrix debonding

Inter-laminar damage:
- Delamination







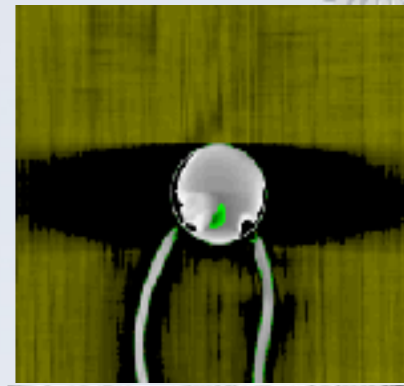
Examples of multi-mode damage (top image), delamination (up), matrix cracking (left)

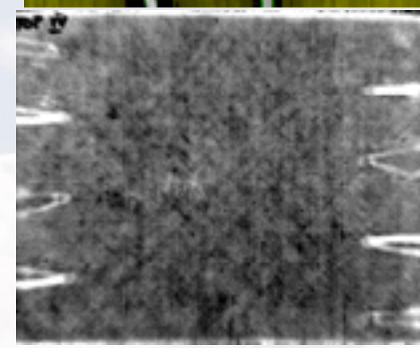
Composites - research programme

The structures:
- CFRP, GFRP composite structures
- Fibre Metal Laminates (Al-G,Al-C)

The transducers integration:
- surface bonding and **embedding**

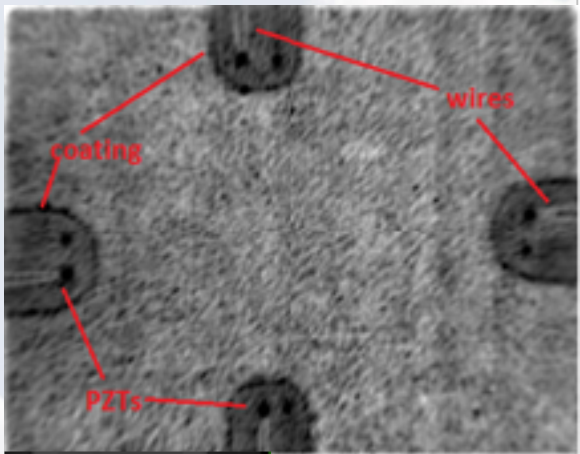
Impact tests:
- NDI of delaminations (UT, IR)
- signal analysis for structure monitoring (**PZT**)





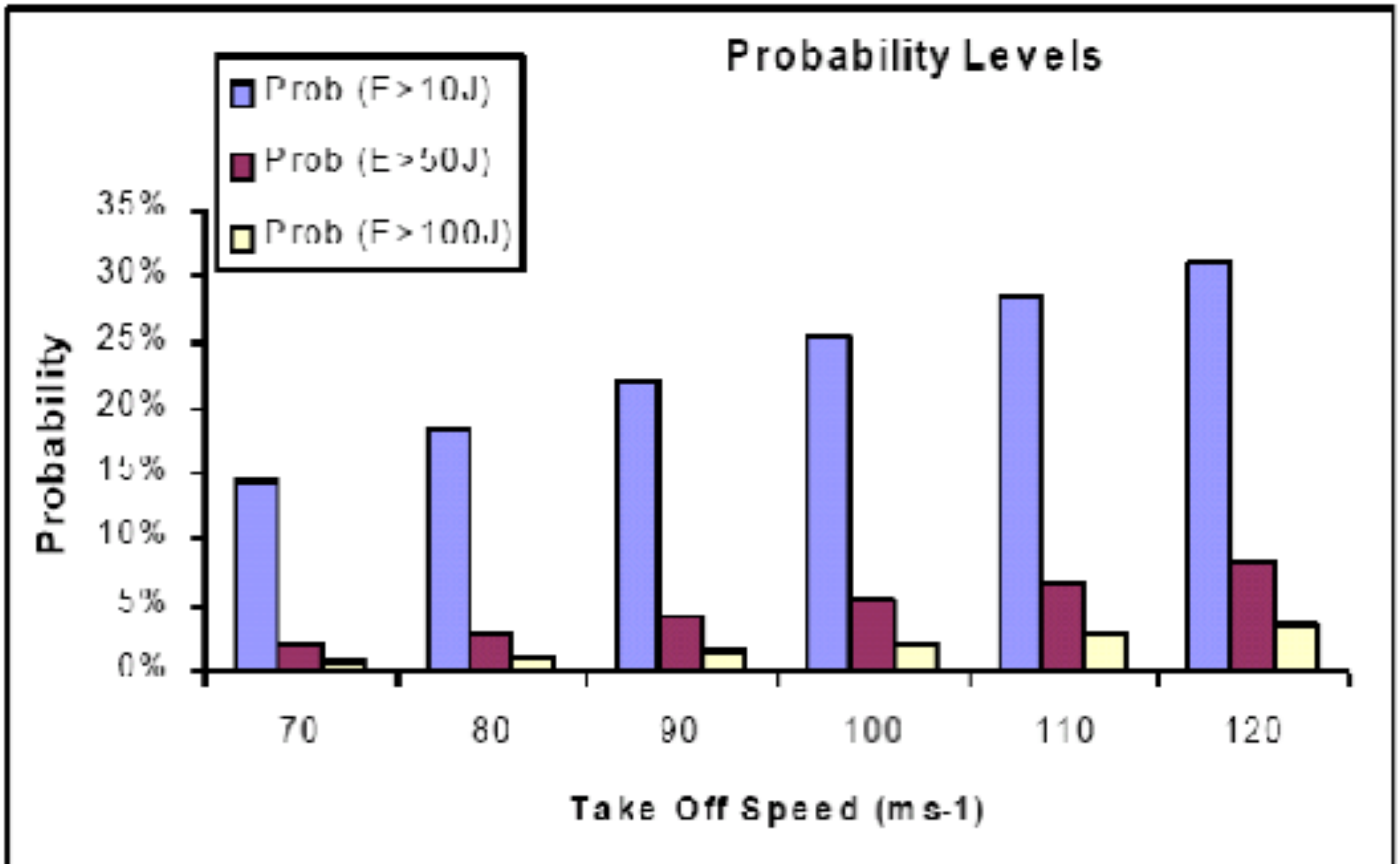
The transducers integration

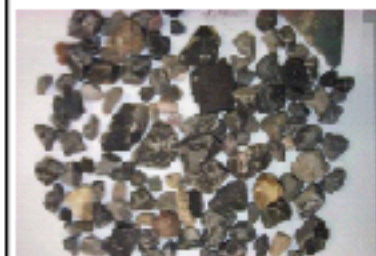
- testing different kind of transducers (size, piezoelectric properties) and wires
- testing nonconductive coatings in the case of CFRP (resin, GFRP)
- transducer properties change after embedding (capacity, frequency response, SNR)
- embedding verification (CT, UT, IR)



BVID possible occurence

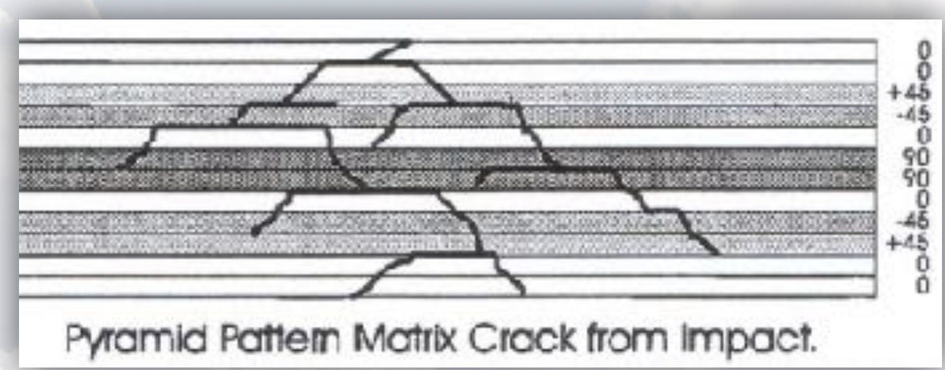
(based on runway debris collected from 4 UK military air bases)

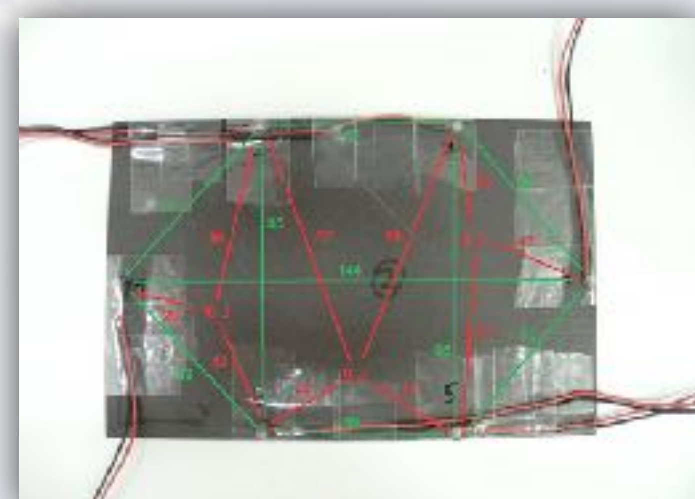




Typical Runway Debris

PZT – signal analysis





Possible effects of BVID:
• modes conversion at cracked layers and wave reflection
• local propagation speed changes due to local stiffness (and thickness) changes

Clock-like sensor network structure to capture different cross sections of a damage as well as intrinsic anisotropies of the composite.

UAV NEWS

NASA Researchers Evaluate Sensor Technology

by Staff Writers
Edwards AFB CA (AFNS) Jul 17, 2008

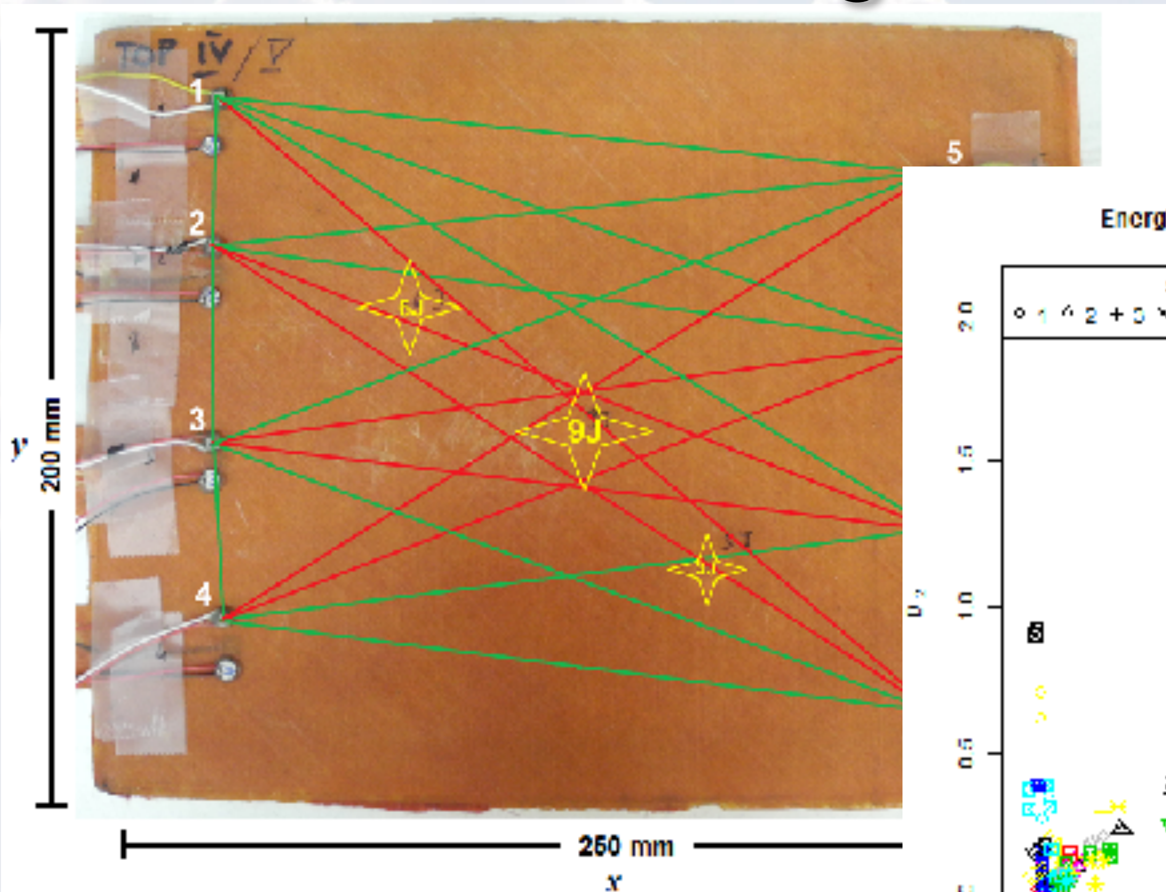
NASA researchers are evaluating an advanced, fiber optic-based sensing technology that could aid development of active control of wing shape. Controlling a wing's shape in flight would allow it to take advantage of aerodynamics and improve overall aircraft efficiency.

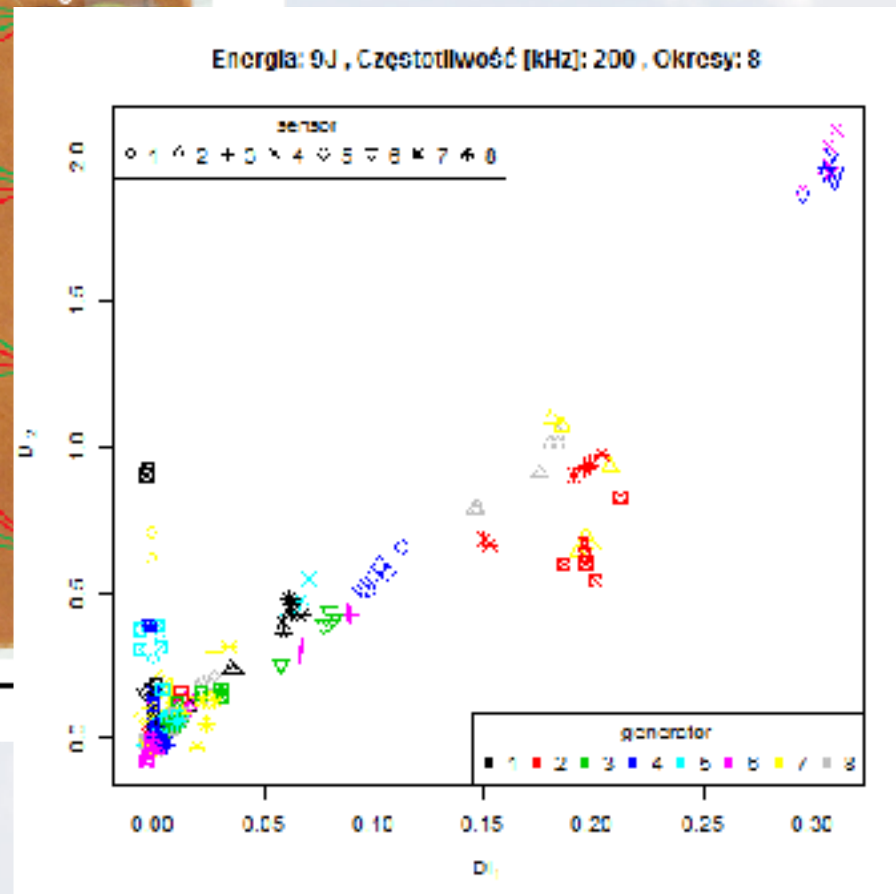
The Fiber Optic Wing Shape Sensor system measures and displays the shape of the aircraft's wings in flight. The system also has potential for improving aircraft safety when the technology is used to monitor the aircraft structure.

NASA's Ikhana, a modified Predator B unmanned aircraft adapted for civilian research, is being used to test advanced, fiber optic-based sensing technology that could aid development of active control of wing shape. (NASA photo/Jim Ross)

http://www.spacewar.com/reports/NASA_Researchers_Evaluate_Sensor_Technology_999.html

BVID damage localization



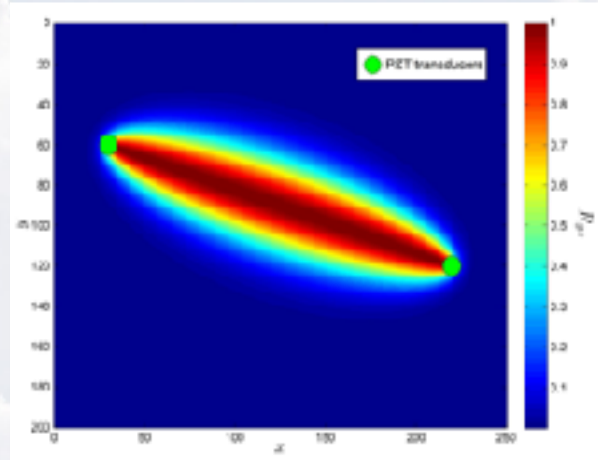


RAPID algorithm (Zhou et al. 2007):

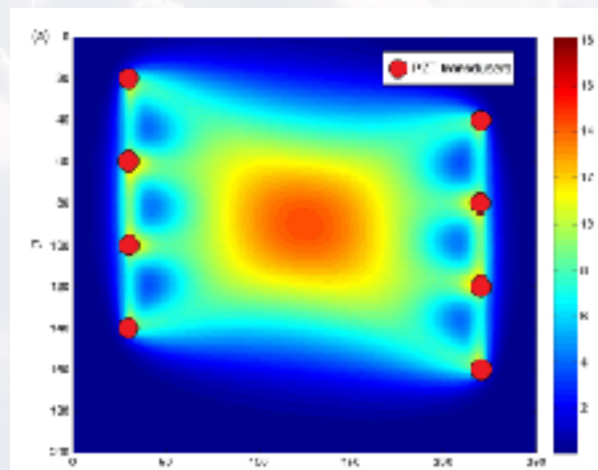
$$I(p) = \frac{1}{N(p)} \sum_{g \neq s} I_{gs}(p),$$

$$I_{gs}(p) = DI(g, s) R_{gs}(p),$$

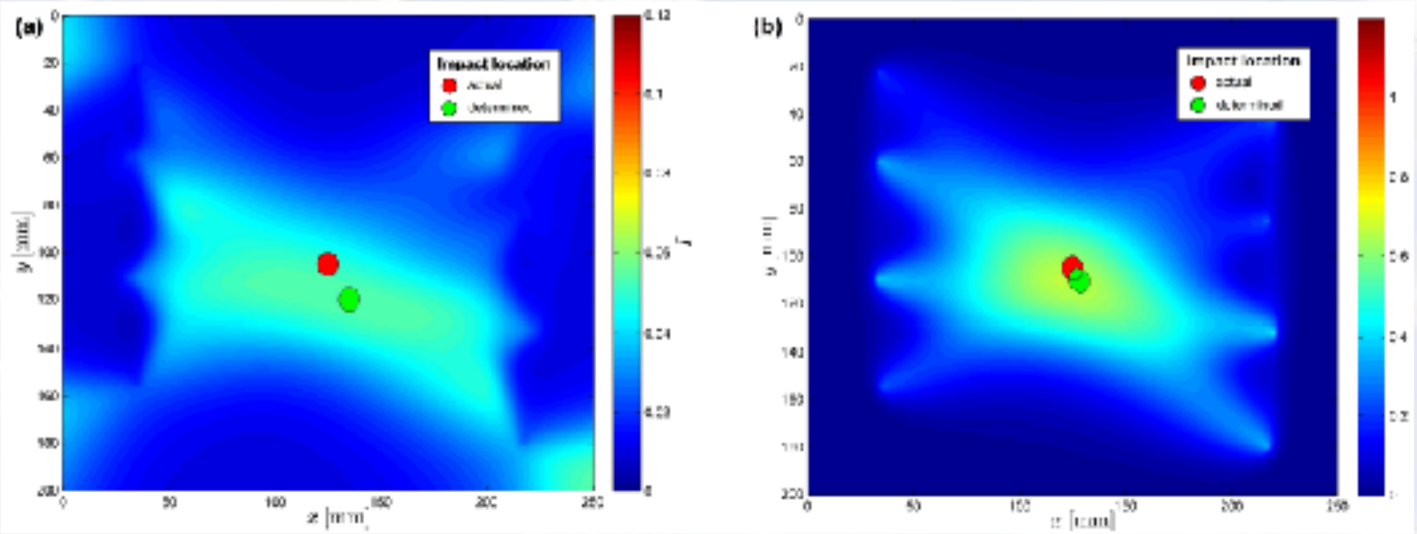
$$R_{gs}(p) = \left(\frac{l_{gs}}{l_{gp} + l_{sp}} \right)^{\alpha}$$



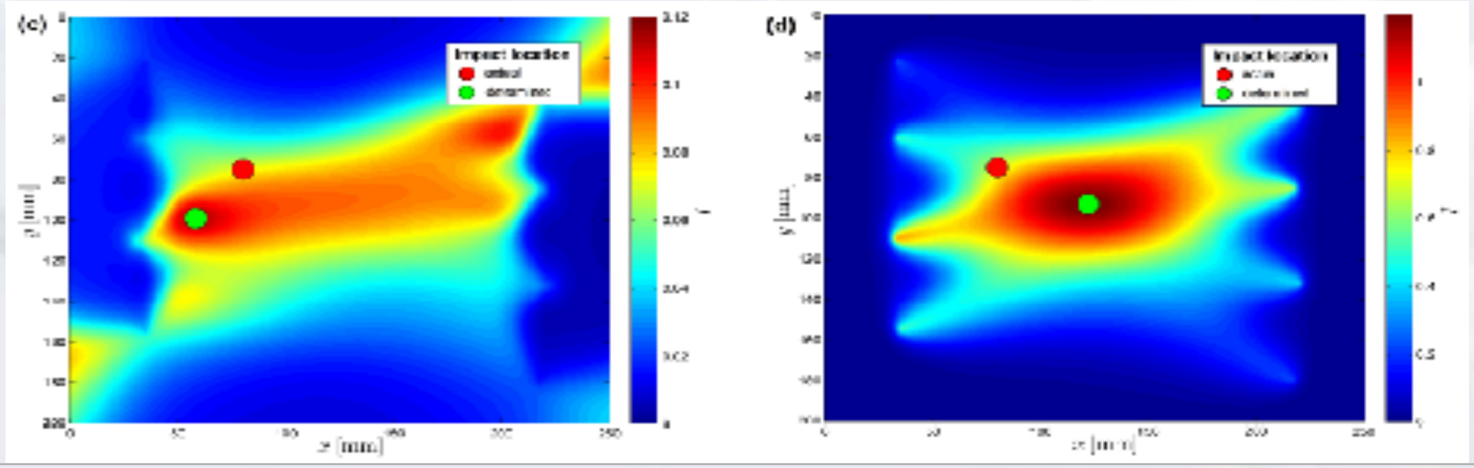
$$N(p) = \sum_{g \neq s} R_{gs}(p)$$



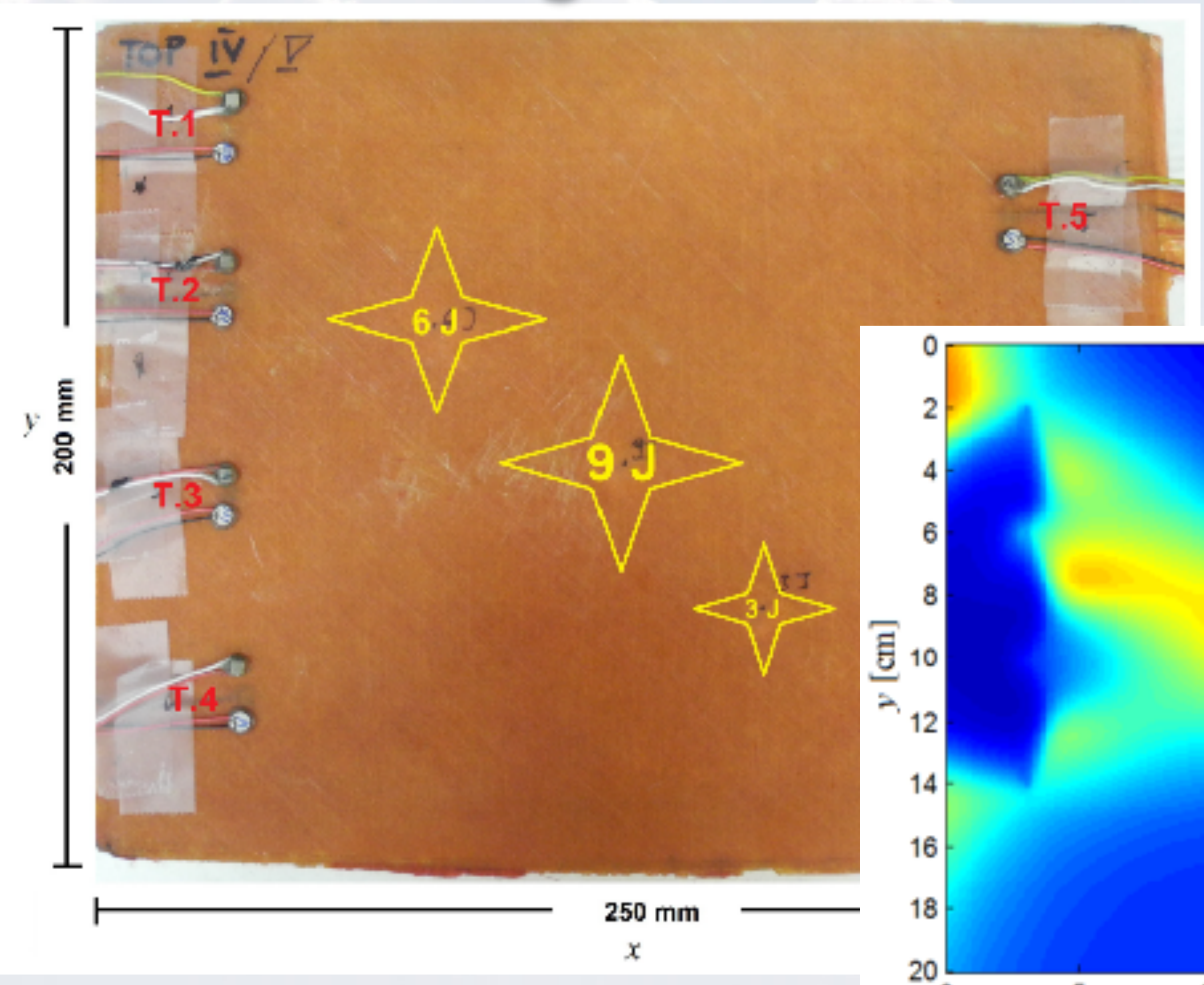
BVID localization:

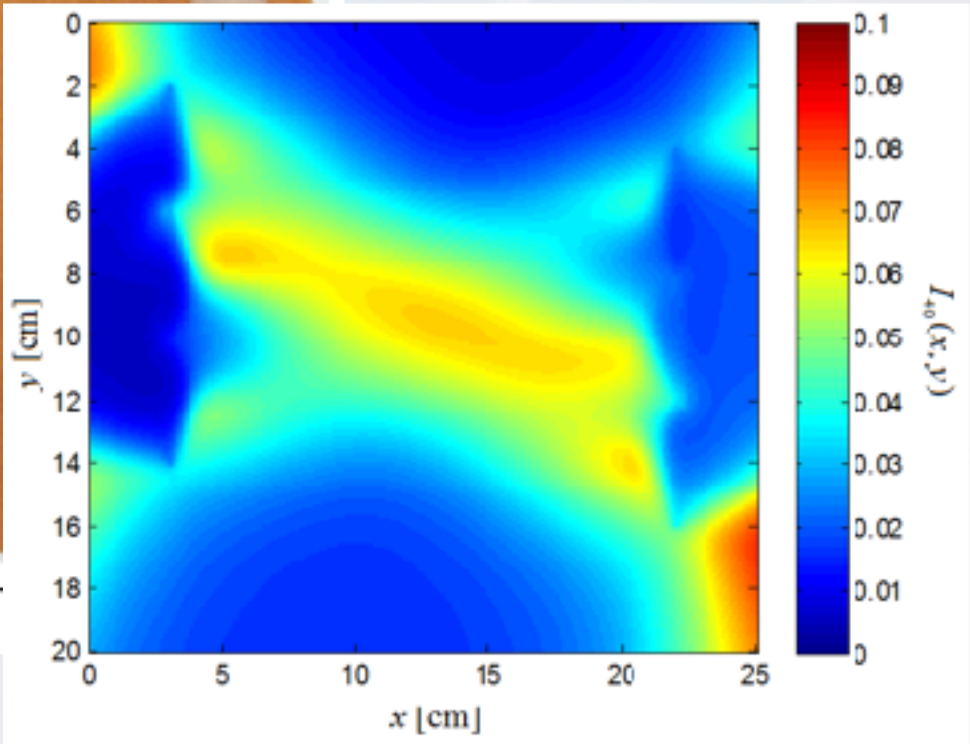


RAPID modified RAPID

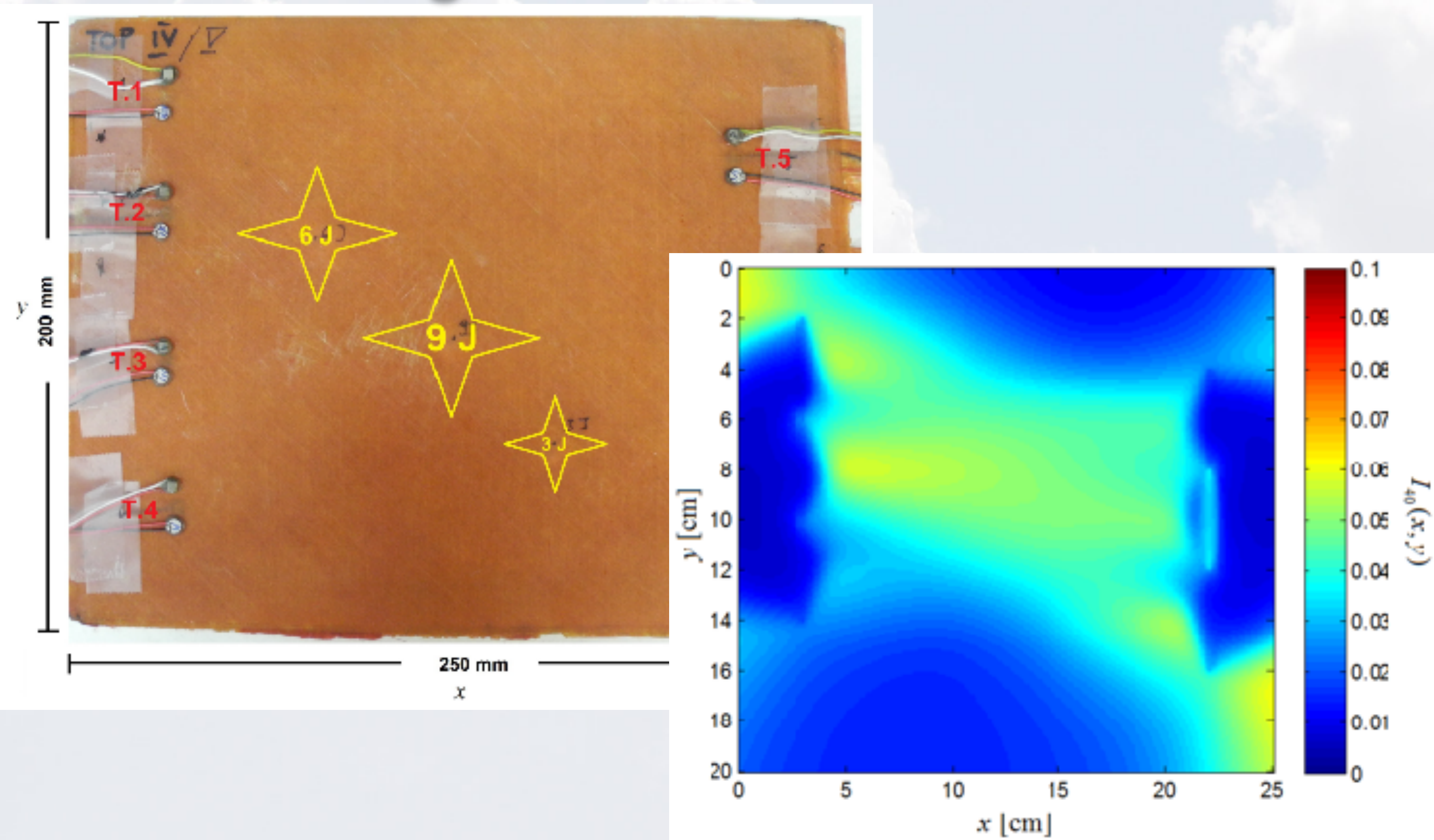


Damage localization BVID – 9 J

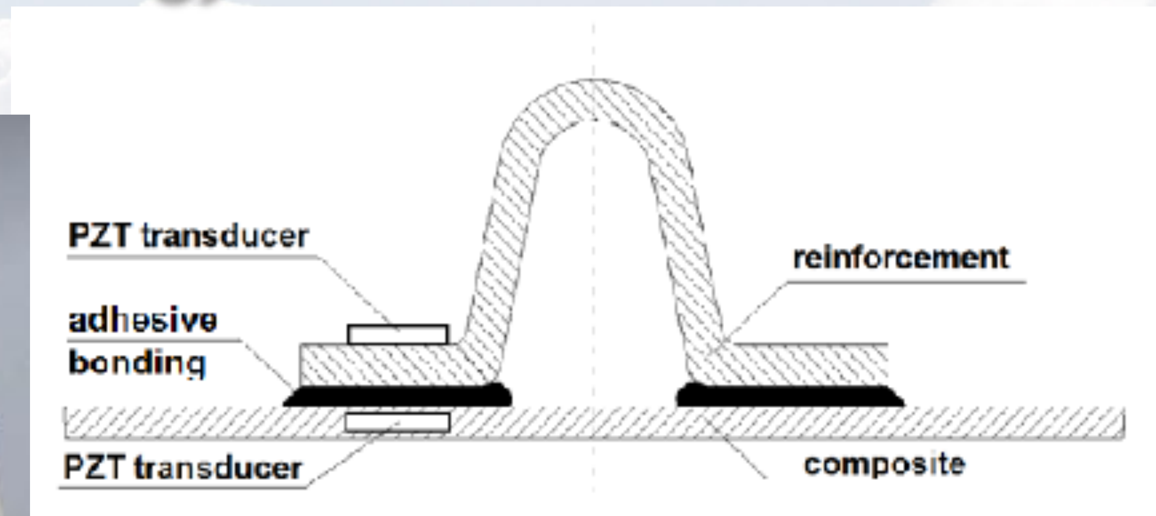




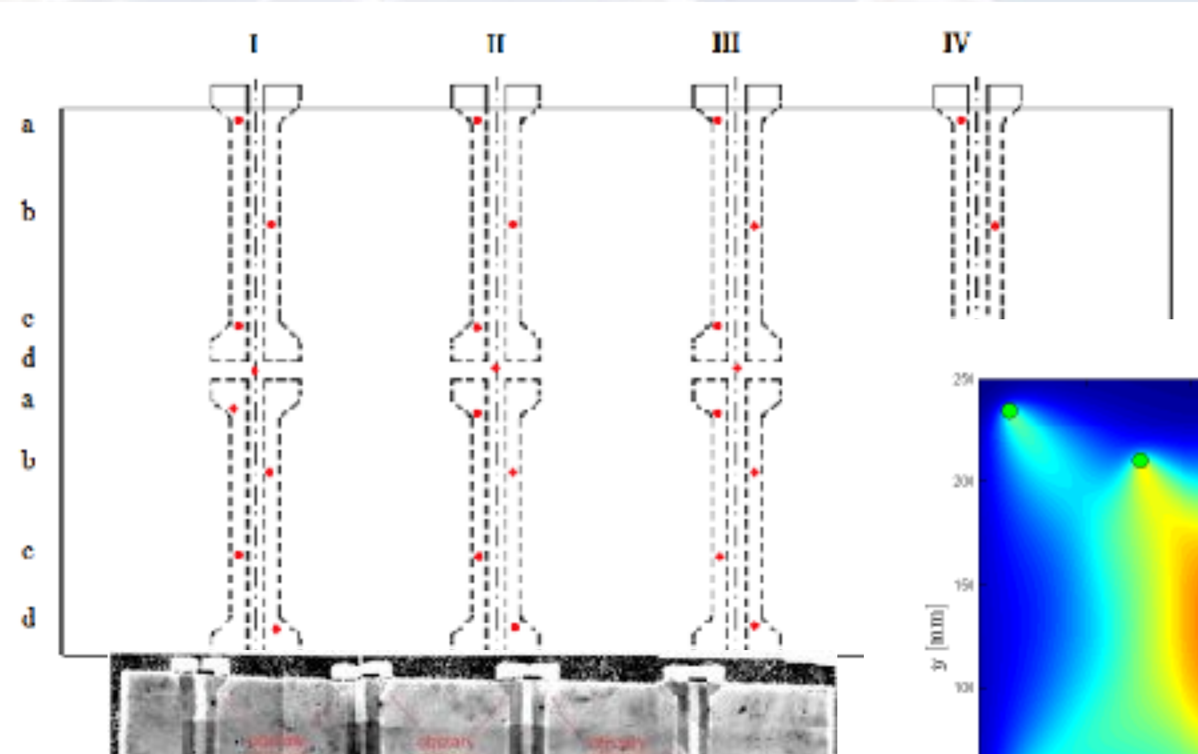
Damage localization BVID – 6 J

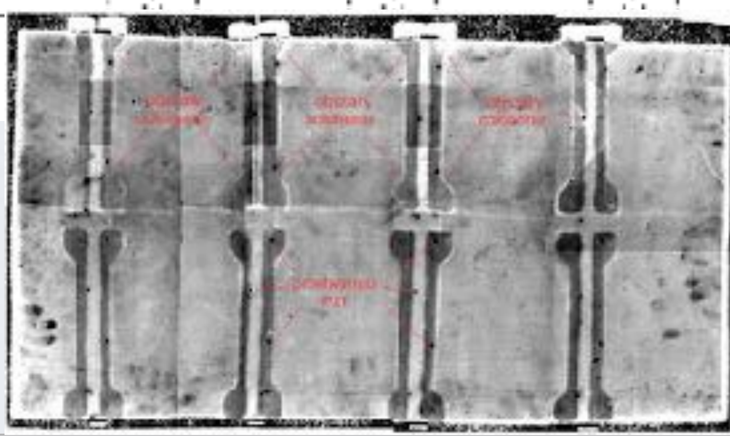


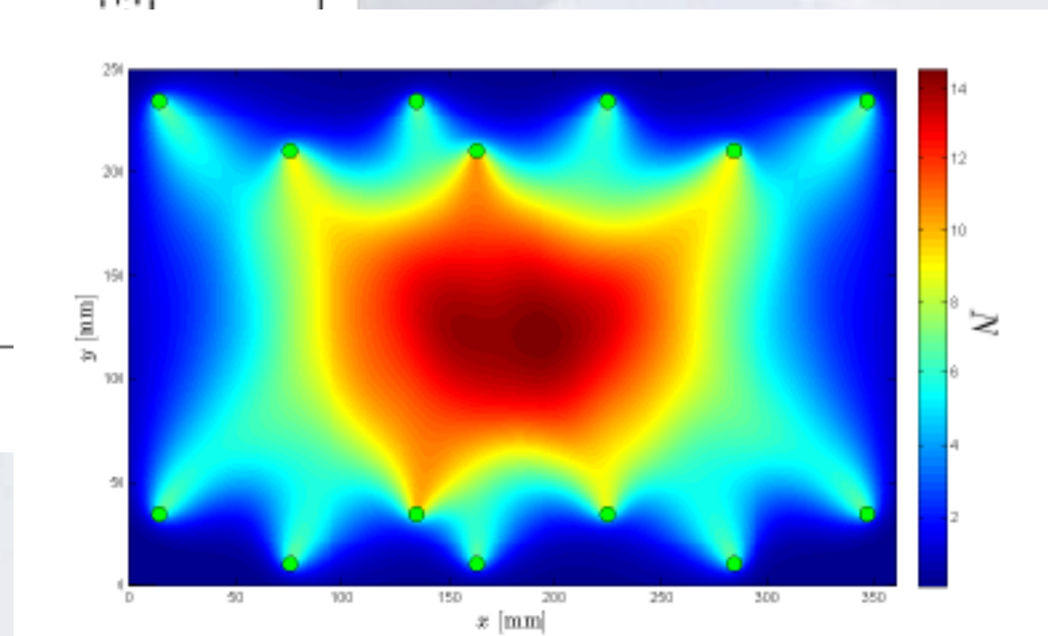
POC - technology verification



Smart structure example

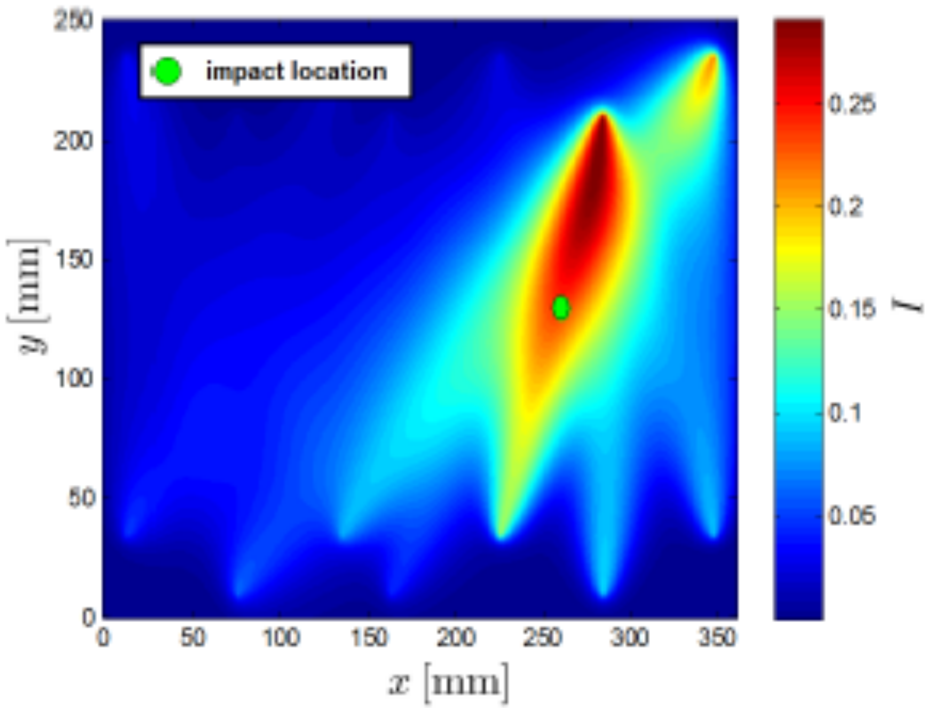




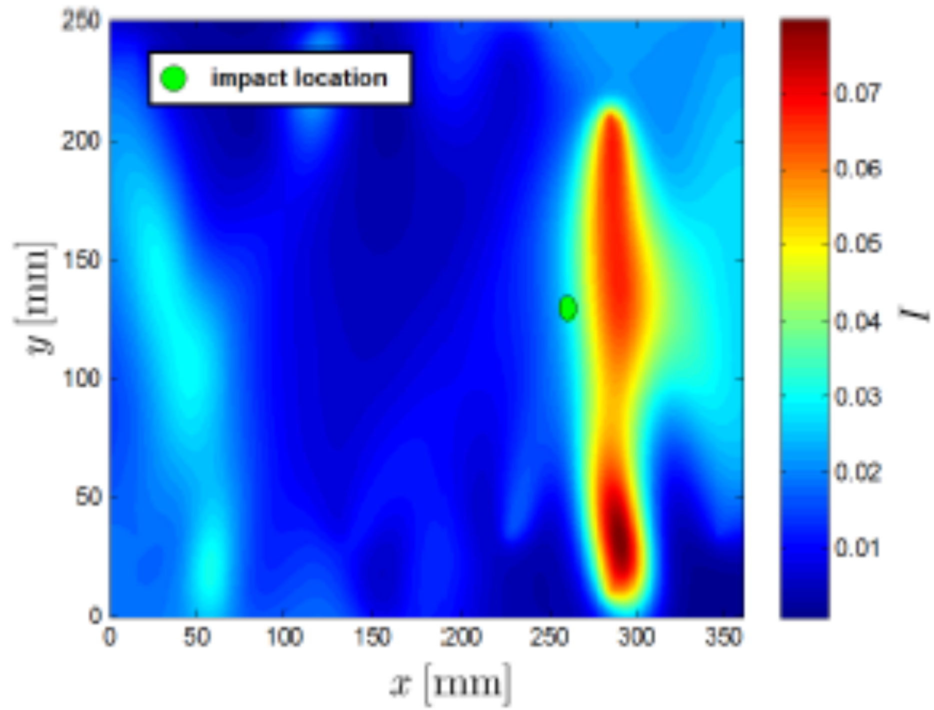


IRT - NDT

Smart structure – BVID localization

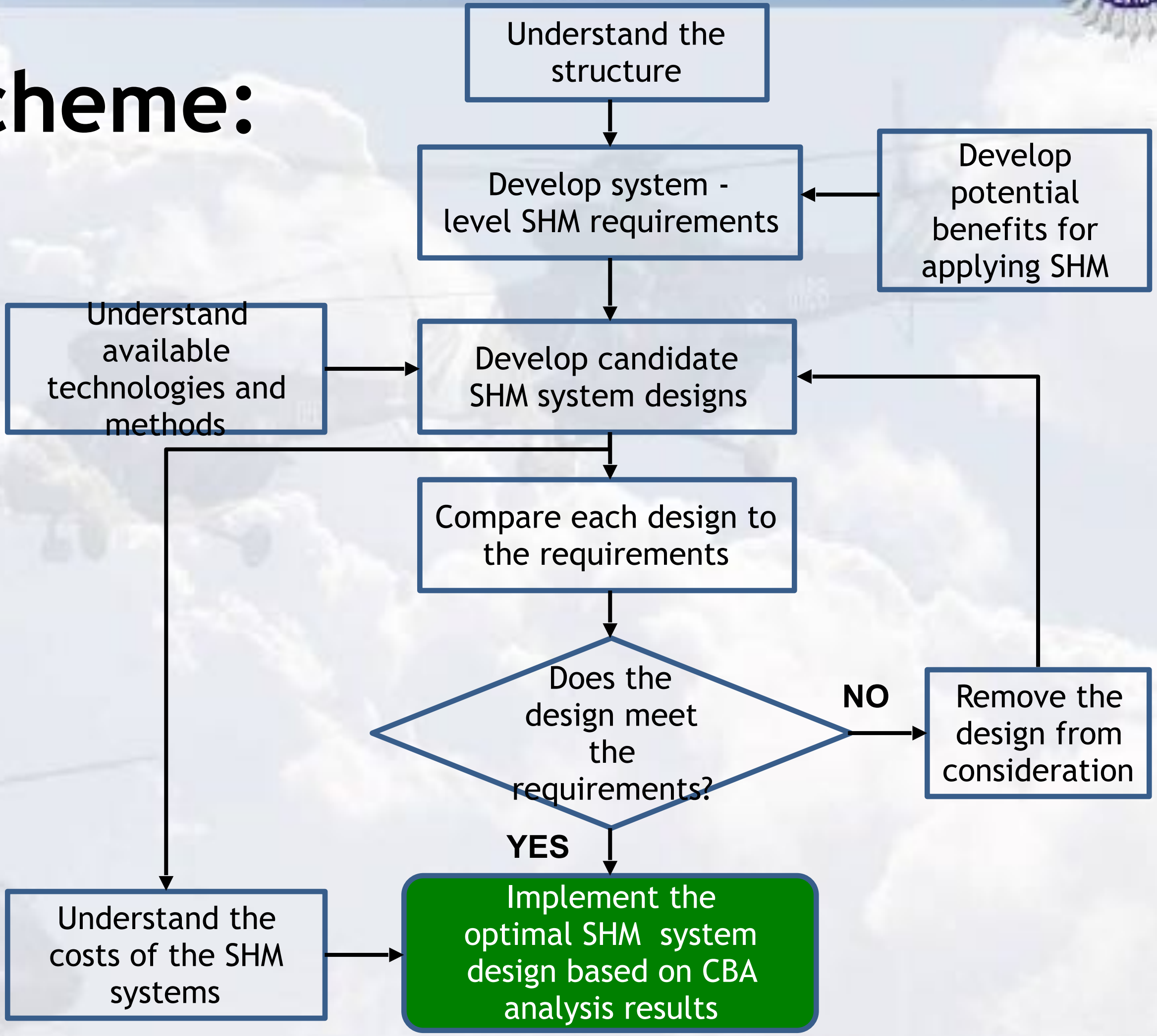


RAPID



RAPID modified

SHM design scheme:



[1] M.Malkin et all, *Hot Spot Monitoring: Development of a Framework for SHM System Design,* Proceedings of the 6th International Workshop on Structural Health Monitoring: Quantification, Validation and Implementation, Stanford University, 11-13 Sept 2007 volume 1,786–792. Lancaster, PA: DEStech Publications Inc, 2007

Further perspectives

- System improvement:
  - technology of transducers integration;
  - optimizing modified RAPID method (different network topologies);
  - sensor self – diagnostics;
- System validation – reliability, PoD studies;
- Optimization - models needs to be designed;
- System (or its selected components) tests to be used on-board.

SAMAS project

In progress, there are negotiation of joint ITA – PL
project under EDA programme.

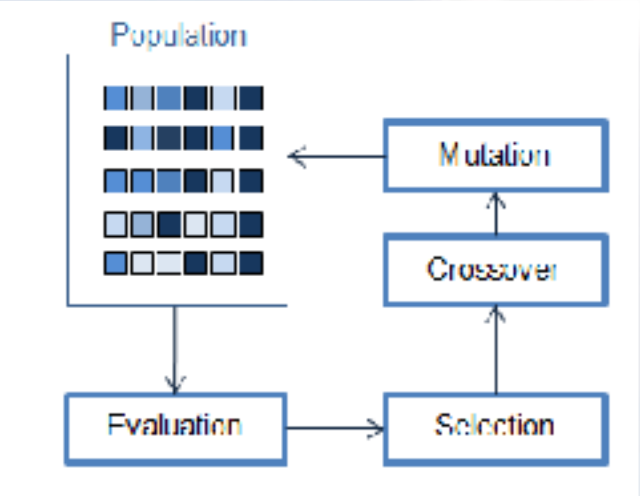
The main project deliverables is to provide composite UAV with OLM and SHM systems.

The main goals which are going to be achieved are:

- development of operational loads monitoring system based on embedded FBG sensors,
- development of impact detection system (and their evaluation in terms of energy, location etc.);
- development of numerical model for BVID prediction based on parameters of impact;
- development of SHM system of BVID detection and evaluation.

Optimization of sensor positions

In order to obtain the best results with a low number of sensors, their positions need to be carefully designed



Try all the available positions within the structure and choose the best configuration is NOT feasible due to the number of possible combination

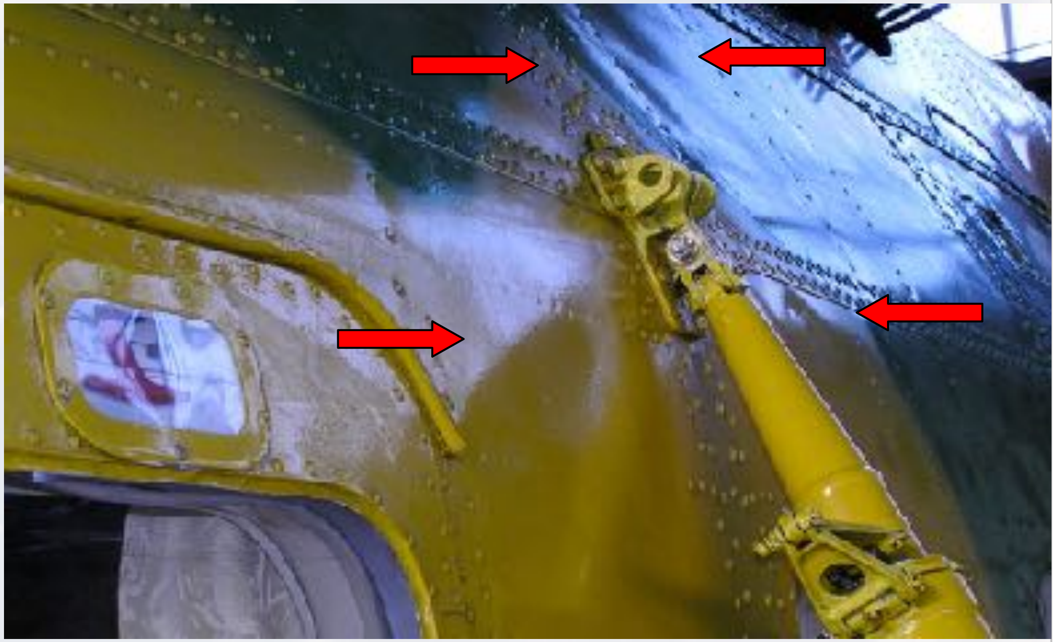
Evolutionary algorithms ?

LAST BUT NOT LEAST

HARSH LANDING

Hard landings effects to helicopter's structure

Typical wrinkling in the tailboom region



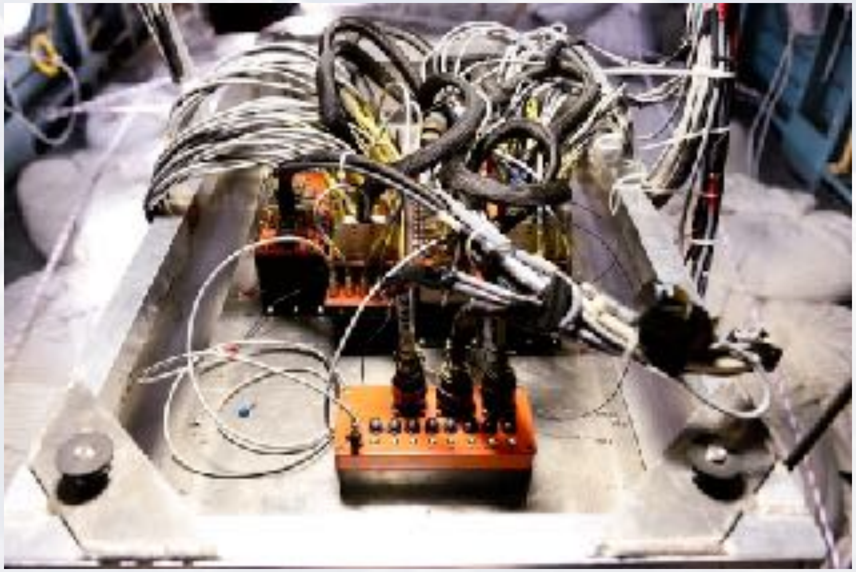
Fuselage skin deformation around landing gear shock-absorber attachments

The ASTYANAX project

Hard landing test

- Hard landing tests of Mi-8 helicopter were performed within the project;
- For the tests: strain gauges, MEMS accelerometers, FBG sensors were used, e.g. for detection of structure deformation;

Main & tail rotor blades equivalent masses



The heart of SHM system

HEALTH MONITORING IS NEED :

- provide safety;
- increase reliability;
- cost driven (time);
- collect historical data;
- others ?

HEALTH MONITORING BECOME NECESSITY:

- new materials;
- far more extensive usage (RPAS, UAV..);
- legal aspects - e.g. OLM

Thank you !

