POLITECNICO
MILANO 1863

DIPARTIMENTO DI MECCANICA
Department of Mechanical Engineering

SIGMALab
Thesis presentation
2022

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mecc

DIPARTIMENTO DI ECCELLENZA
MIUR 2018-2022

SIGMA Lab

Politecnico di Milano ...since 1863...

12 departments – more than 1430 Researchers/Professors – almost 50.000 students

Department of Mechanical Engineering

http://www.mecc.polimi.it/

More than 120 people as permanent staff – more than 190 PhD students – approximately 12-14 M€ of annual funding (Mainly from EU and Industry)

Research lines

Dynamics and Vibration, ***Machine and vehicle Design,*** Manufacturing and Production Systems, Materials, Measurements, Methods and Tools for Product Design

Structural Integrity of Mechanical Components and Systems – SI

SIGMA Lab research group

SIGMALab

Competences

Structure Impact proGnosis Monitoring MAterial LABoratory

SIGMALab: Outlook of the research team

Our mission:

Main aim of the research team is an advanced engineering approach for the **assessment, new design and optimization of mechanical and aerospace components**. Research activities and topics concern with several aspects related to:

- **assessment and optimization** of components under spectrum loads and extreme loads (ballistic damage, etc.);
- **monitoring, diagnosis and prognosis** of critical structures, under fatigue loads and impact loads;
- **application of novel approaches in structural integrity design** (flaw tolerant approach, vulnerability, A.I. etc.).

Experimental investigations and **modelling approaches** are synergically exploited in order to find "**state of the art** " **solutions tailored** to challenging requirements.

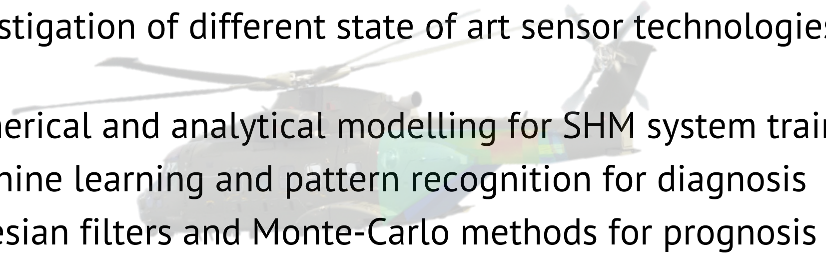
Our vision:

A reference team for tailored assessment of critical components under extreme conditions.
More that 15 years of challenging research activities with academic and industrial partners and customers (included security and defence).

SIGMALab: Outlook of the research team

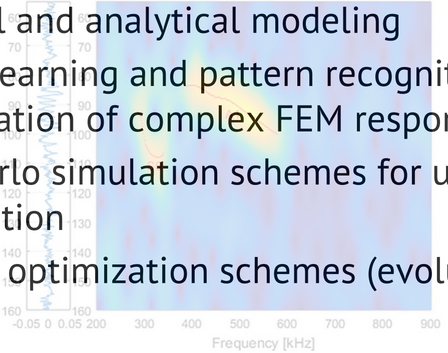
Research Areas:

Model-based Health and Usage Monitoring and prognosis



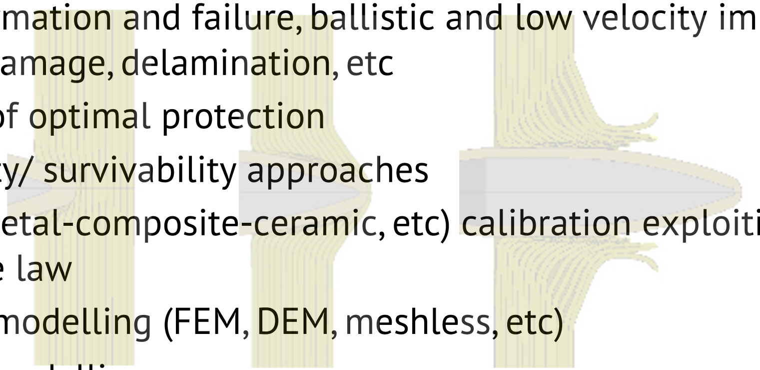
- Investigation of different state of art sensor technologies for SHM
- Numerical and analytical modelling for SHM system training
- Machine learning and pattern recognition for diagnosis
- Bayesian filters and Monte-Carlo methods for prognosis
- Experimental SHM verification and performance qualification

Reliability and statistical approaches for structural integrity



- Numerical and analytical modeling
- Machine learning and pattern recognition for cheap approximation of complex FEM responses
- Monte-Carlo simulation schemes for uncertainty effects quantification
- Advanced optimization schemes (evolutionary algorithms, etc.)

Structural integrity under extreme loads



Large deformation and failure, ballistic and low velocity impact, explosion, crack and damage, delamination, etc

Definition of optimal protection

Vulnerability/ survivability approaches

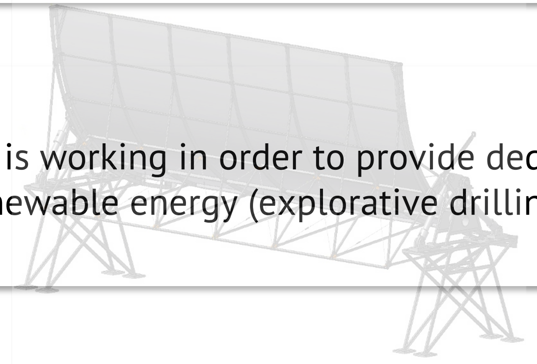
Material (metal-composite-ceramic, etc) calibration exploiting innovative constitutive law

Numerical modelling (FEM, DEM, meshless, etc)

Analytical modelling

Experimental testing (from micro to full scale)

Energy



- SIGMALab team is working in order to provide dedicated solutions both for O&G and renewable energy (explorative drilling and innovative solar troughs).

SIGMALab: People




Team Leader

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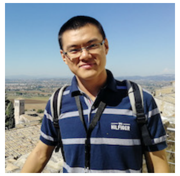




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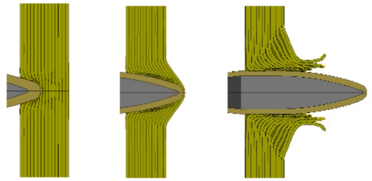
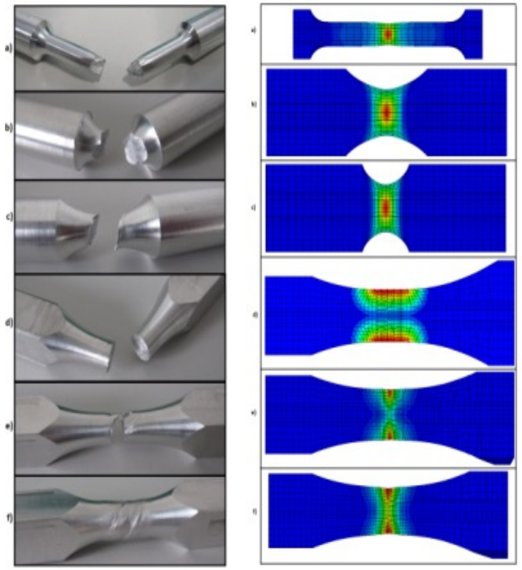
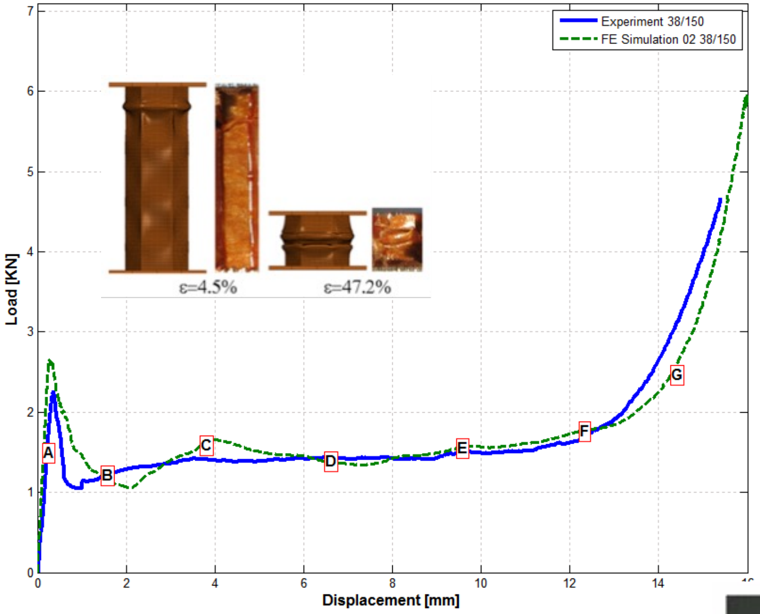
Ph.D. graduate student

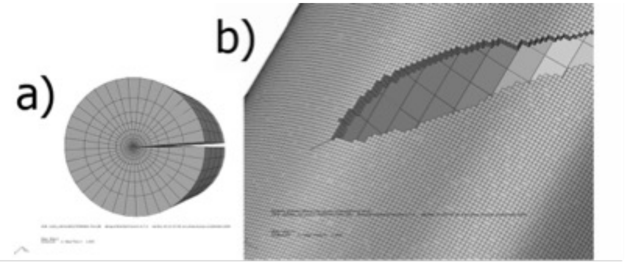
Structural integrity under extreme loads



Large plasticity, strain rate, damage, temperature, low triaxility, high pressure, crack propagation, delamination, impact, explosion, etc.…

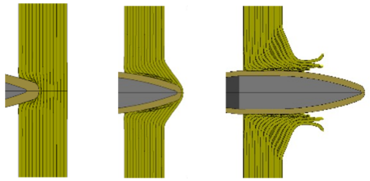




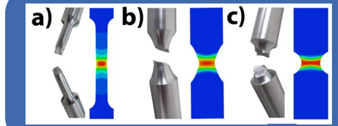


SIGMA Lab

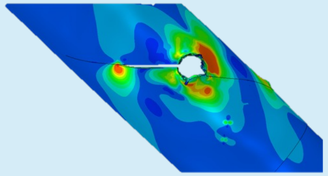
Structural integrity under extreme loads



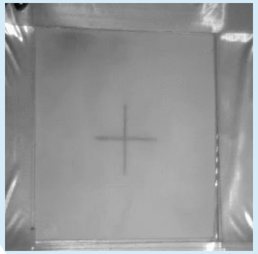
A deep investigation both in practical aspects and state of the art



Material calibration



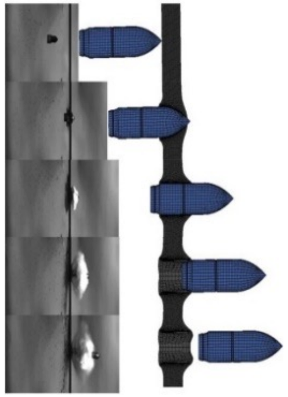
Numerical and analytical modelling - algorithm

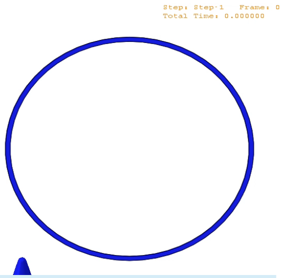


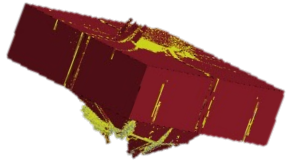
Experimental tests

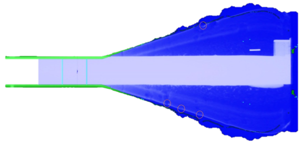
Validation of the modelling - algorithm approaches

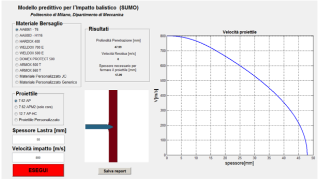
Definition of predictive models/methods – virtual test
Design optimisation
Structural Health Monitoring
Fitness for purpose

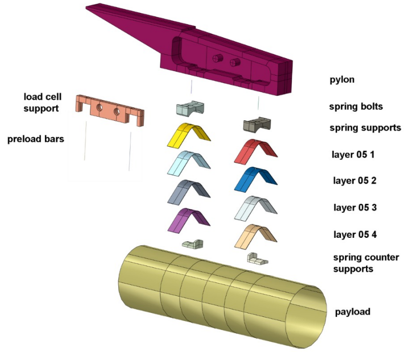


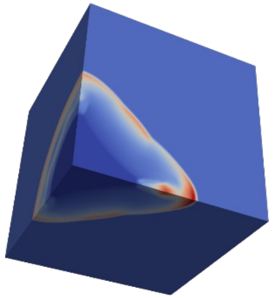




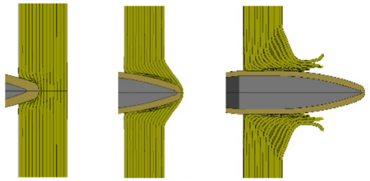








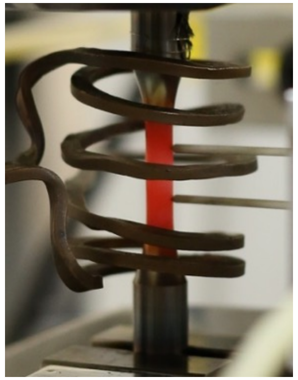
Structural integrity under extreme loads

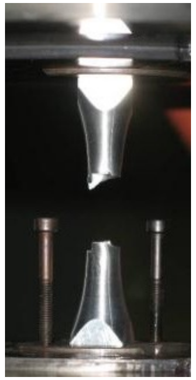


Experimental Tests

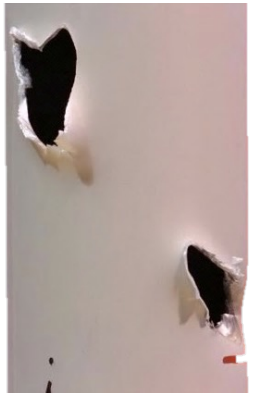
Test on coupon and small specimens to determine mechanical behavior

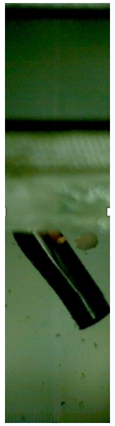
Metal, Composite and Ceramic: plasticity, damage - Access to fully equipped materials lab including quasi-static tension, compression and torsion testing at different temperatures, hardness measurements, fatigue testing, optical microscopy, scanning electron microscopes with coupled EDS and EBSD probes, X-ray diffractometer, CT scan, HIP - test under quality system

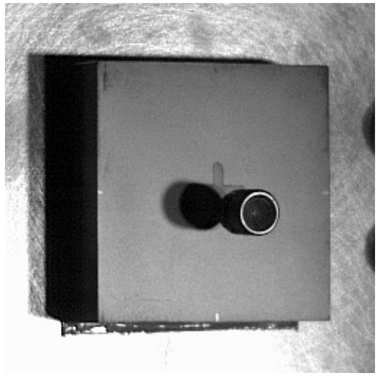


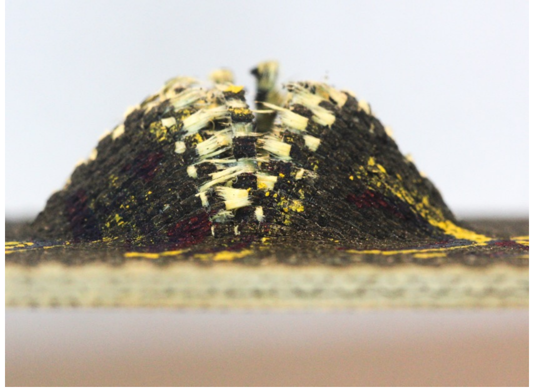


Test on subsystem also in presence of extreme loading condition including drop tower



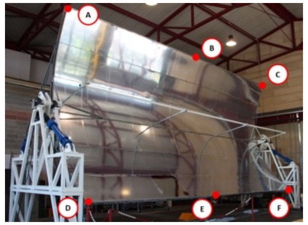




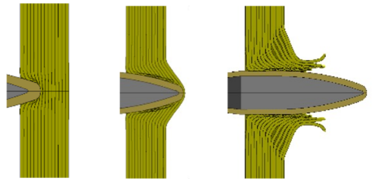


Test on full-scale components also for FAA certification

Federal Aviation Administration

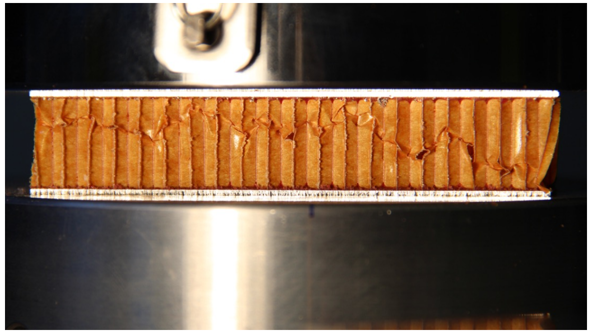


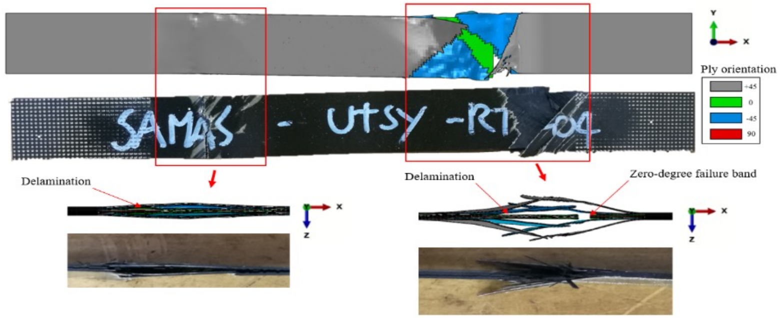
Structural integrity under extreme loads

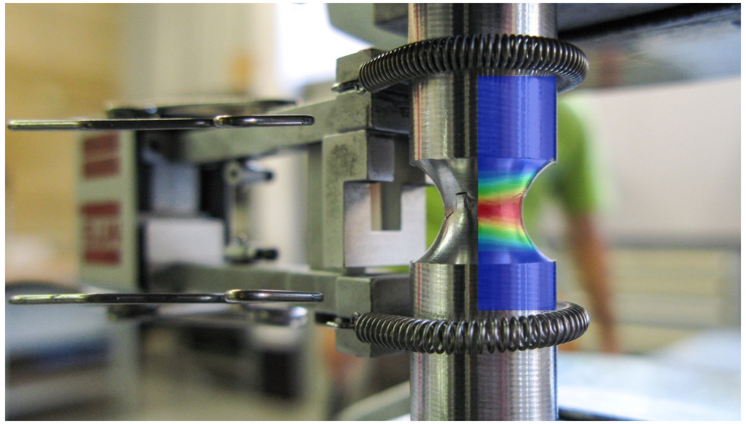


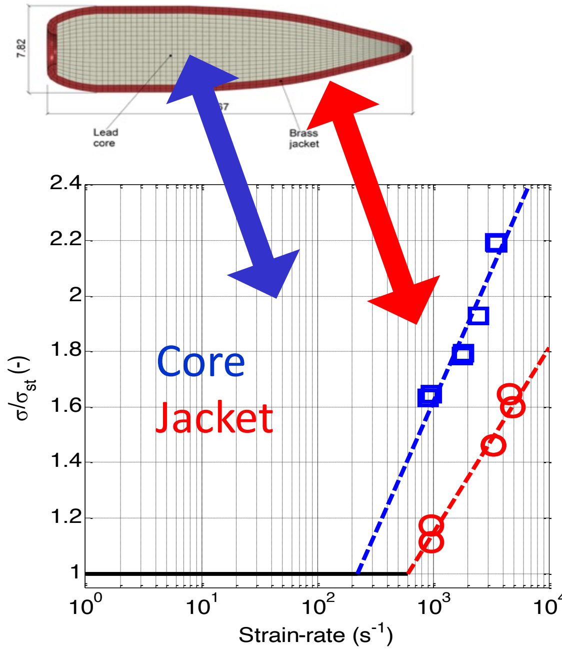
Material calibration

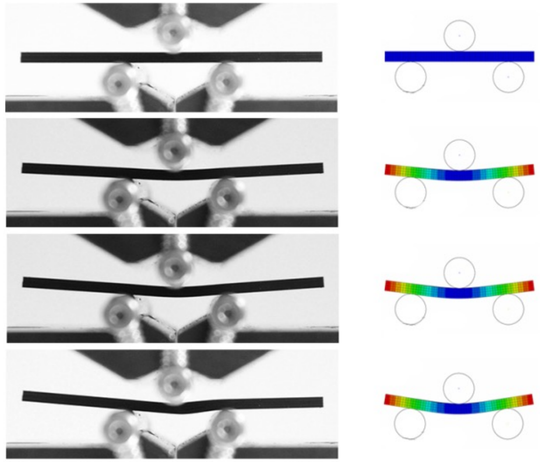
- Material behaviour: focus on metal - ceramic – composite – nano-composite
- Inverse methods for calibration of mechanical properties
- Nano, micro and Macro approaches
- Definition of constitutive models able to describe high plasticity, ductile/brittle failure, strain rate, delamination, etc.
- Creation of ad-hoc routine

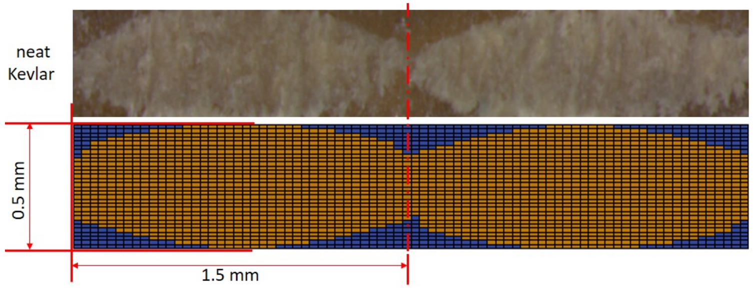


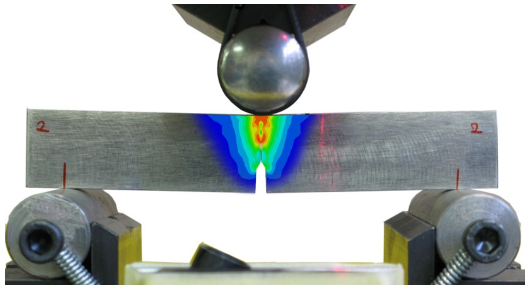












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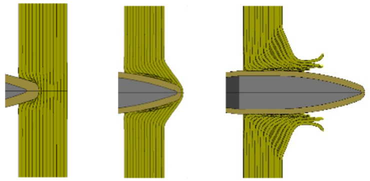
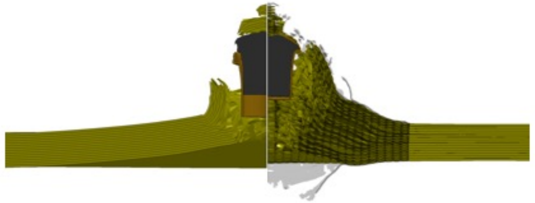
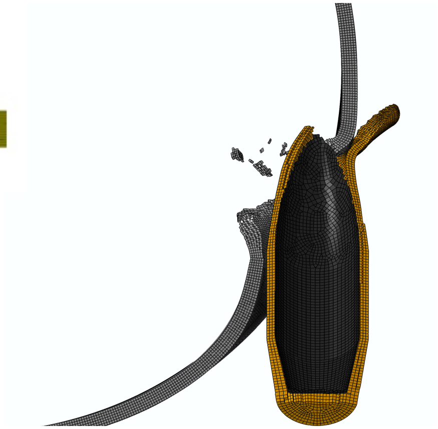
Structural integrity under extreme loads

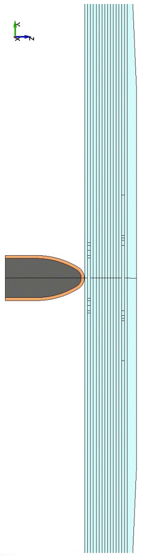


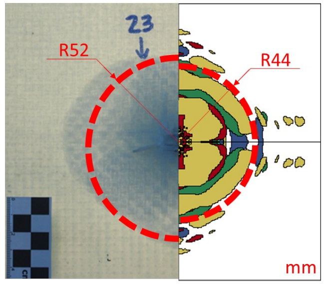
Modelling

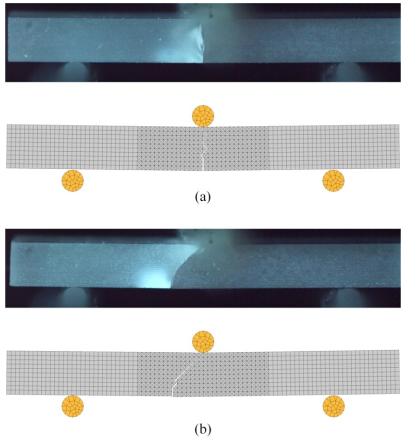


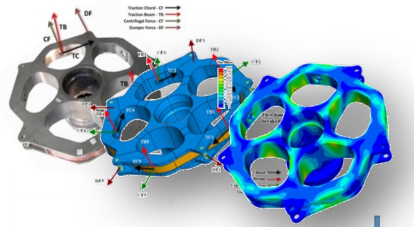
- Creation of analytical models for simulation of ballistic impact against Metal (cavity expansion) – Composites (energy balance and wave theory) – Ceramic (modified Bernoulli equation)
- Creation of numerical models (ABAQUS – Ls-Dyna)
  - ✓ large plasticity, high strain rate, high temperature and pressure, fracture and damage criteria, large fragmentation, delamination, blast loading, FSI.
  - ✓ Lagrangian, ALE, SPH, perydinamics and in general expertise in mesh-free methods and coupling with Lagrangian elements.

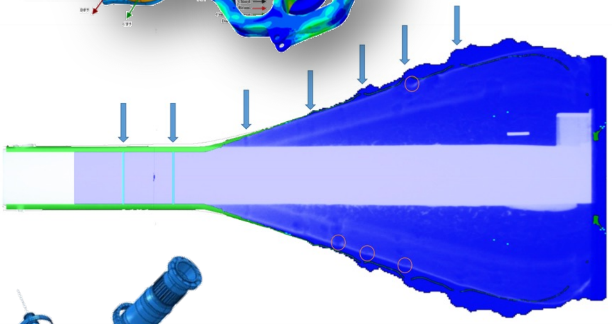


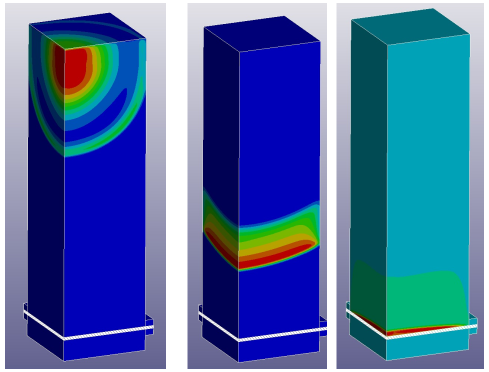


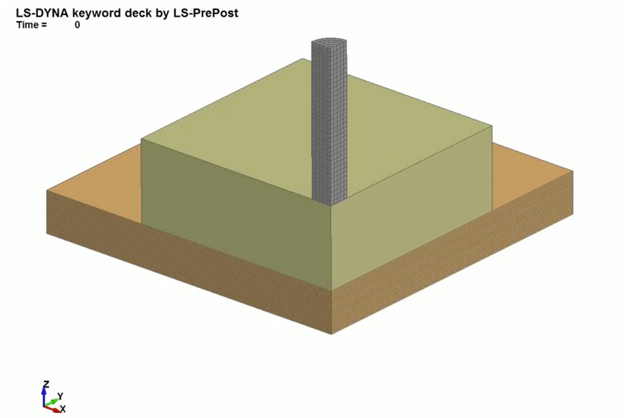


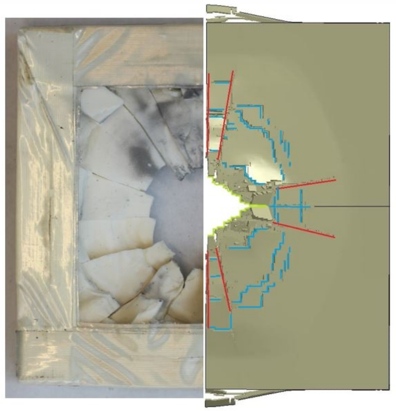




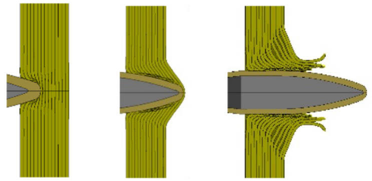




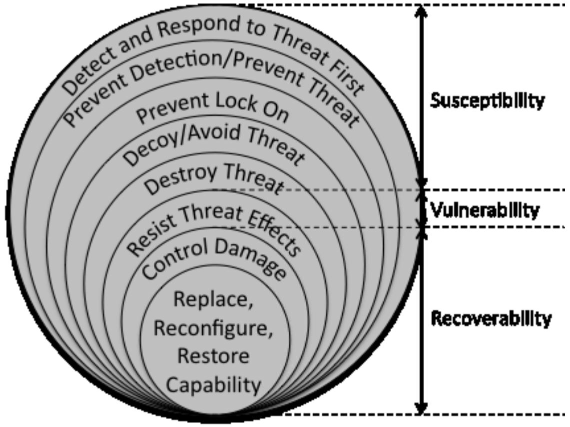


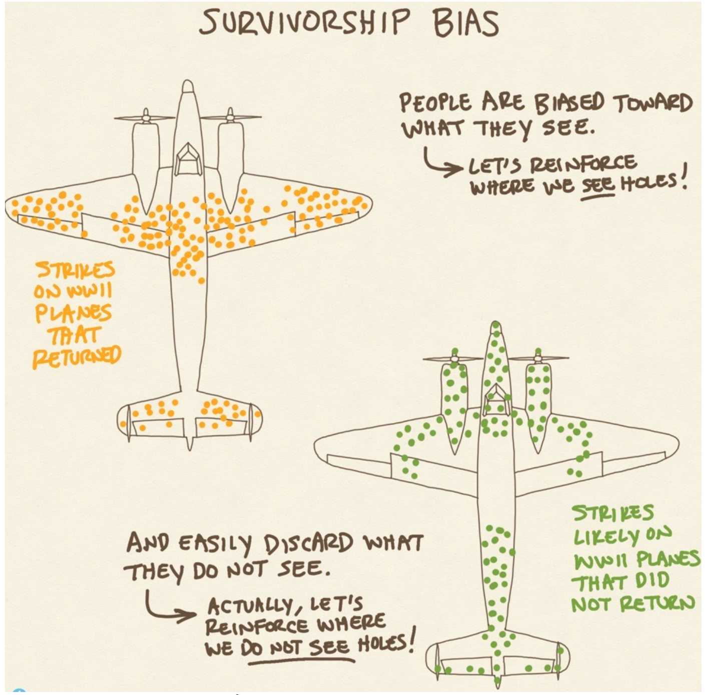


Structural integrity under extreme loads

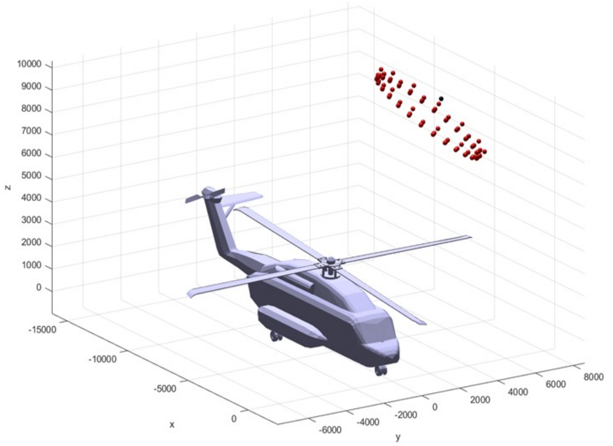


A method to estimate the vulnerability of complex systems



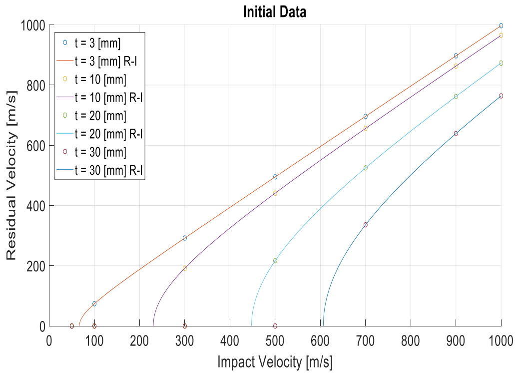


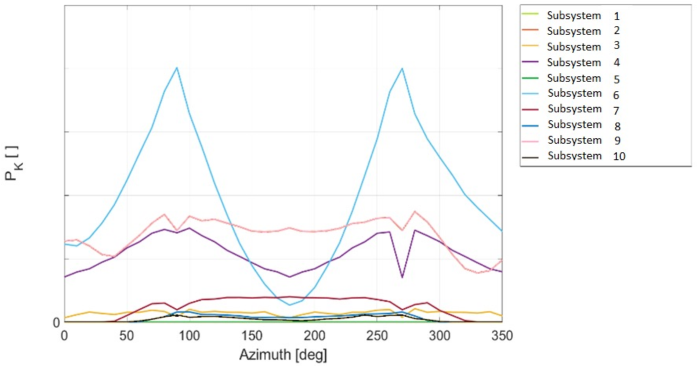
Vulnerability analysis may consider several types of threats (including multi-hit):



- The system is analysed under all possible attack directions with different threats (In-house software developed by POLIMI).
- Through specific penetration models (In-house software developed by POLIMI) the damage capability of different threats are assessed.

- The analysis allows to create a comparative environment between different systems and identify possible critical subsystems





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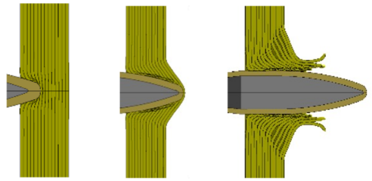
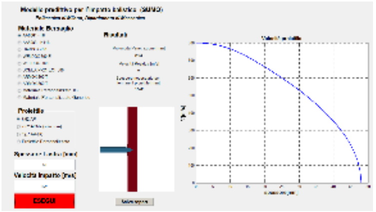
Structural integrity under extreme loads

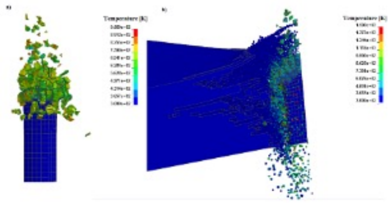


Definition of predictive methods

Numerical and analytical modelling

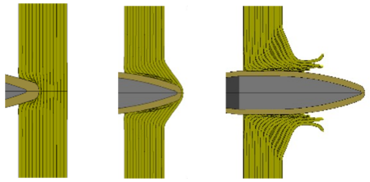


Why are so important



- Better understanding of the physical phenomena involved
- Better understanding of effects of several parameters (in highly non-linear environment)
- Possibility to perform "virtual test" when experimental approach is unsafe and/or unfeasible
- Reduction of the number of the experimental tests (time and costs reduction) and better design of testing activities
- Possibility to perform optimization process and fitness for purpose approach

Structural integrity under extreme load



Topic: In-depth investigations on composite materials

•TITLE: Investigation into the uncertainty effect for composite materials

•RESEARCH BACKGROUND:

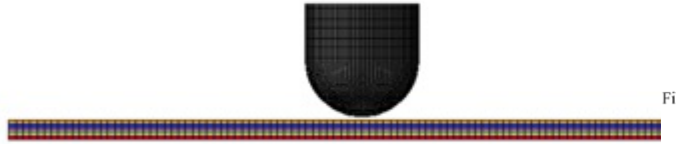
•The complex geometrical characteristic of unidirectional composites leads to a large number of uncertainty sources in turn leading to variability in the mechanical and thermal properties, which has been noticed in both material and structural levels. Thus, uncovering the uncertain issues for composites can be helpful for their development and applications.

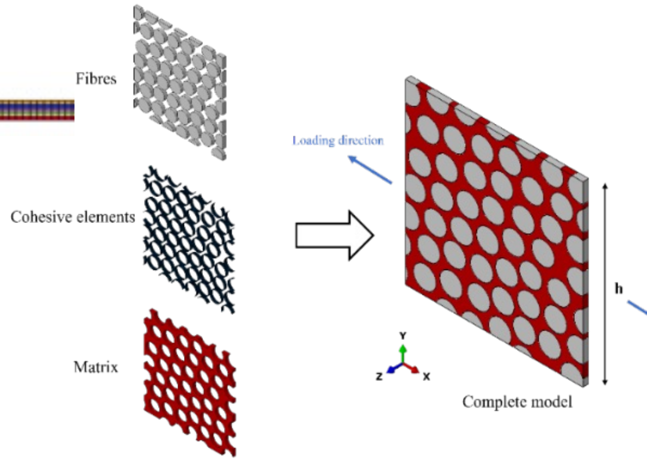
•RESEARCH ACTIVITIES:

1. Study different sources of material uncertainty in micro and macro scale
2. Develop models in micro/macro scale capable of considering the material uncertainty
3. Build numerical model to replicate the mechanical behaviours of composites under simple and impact loading conditions
4. Establish the relationship between uncertainty and related properties in different scales (optional)

•METHODOLOGY: Numerical – Programming – Experimental

•DURATION: 7-9 months





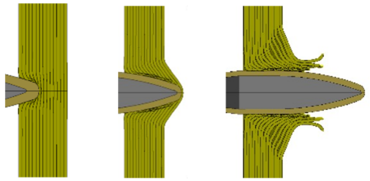
•CONTACTS:

•andrea.manes@polimi.it
•dayou.ma@polimi.it
•marco.giglio@polimi.it

•POSSIBLE COLLABORATIONS:

•Federal University of Rio Grande do Sul (Brazil)

Structural integrity under extreme load



Topic: In-depth investigations on composite materials

•TITLE: Investigation on the interface of composite materials (with and without nanofillers)

•RESEARCH BACKGROUND:

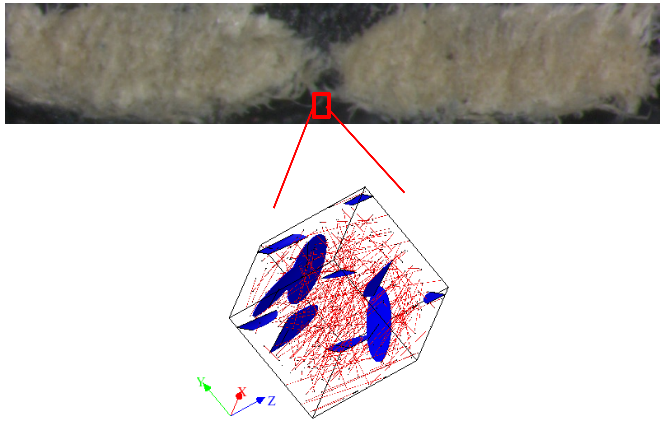
•Interface of composite materials is generally believed as the weak point of the whole structures, which is between layers and fibre/matrix. However, adding nanofillers may provide a good solution for it. The work is planned to investigate this issue.

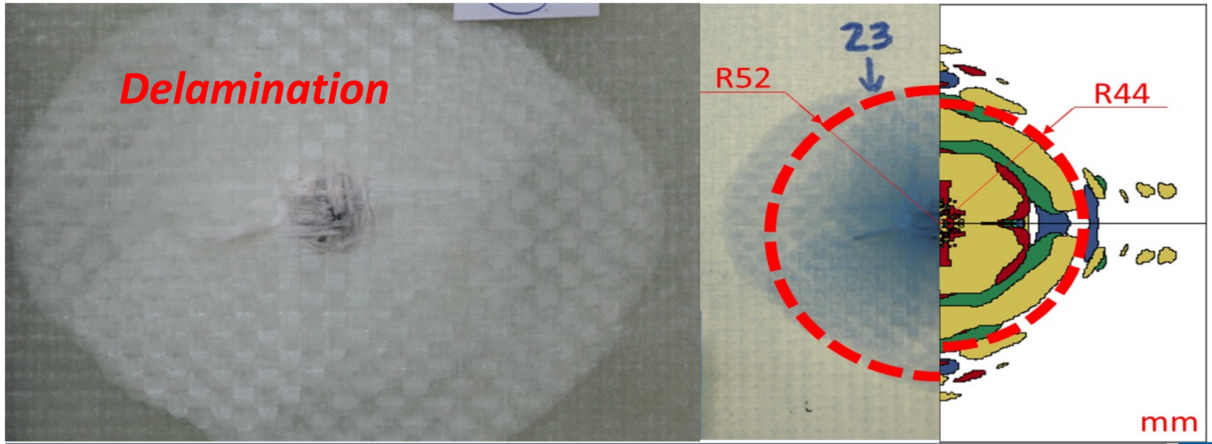
•RESEARCH ACTIVITIES:

1. Study capability of different modelling strategies on interface replication
2. Consider the effect of nanofillers on the interface of fibre-reinforced composites
3. Develop a reliable modelling methods on interface of composites (optional)
4. Carry out experiments on interface of composites for further understanding its behaviours (optional)

•METHODOLOGY: Numerical – Programming – Experimental

•DURATION: 9 months





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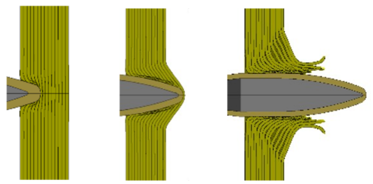
Structural integrity under extreme load



Topic: In-depth investigations on composite materials

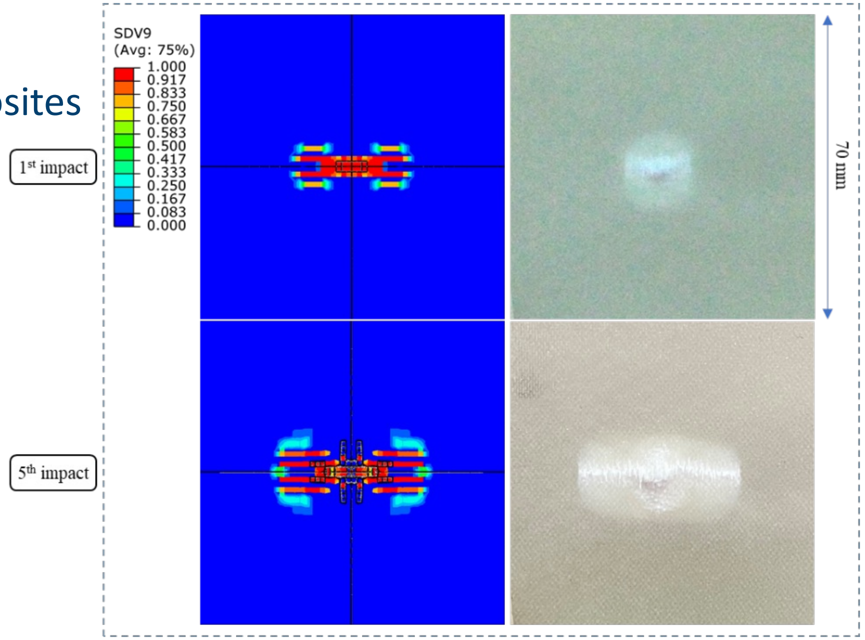
•**TITLE: Long term durability of woven fabric composites subjected to impact loads**

•**RESEARCH BACKGROUND:**

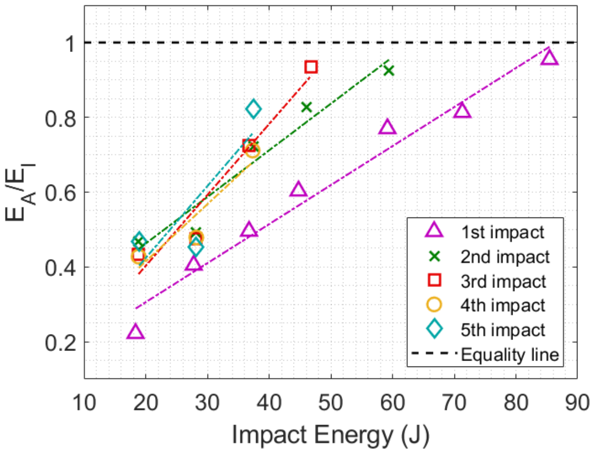
• The durability of composites subjected to repeated impacts has been an ongoing issue that can affect the service life and limit their usage in many engineering applications. This adds to the complex material behaviour and different failure modes expected during the repeated low-velocity impact which necessitate more in-depth experimental and numerical studies.

•**RESEARCH ACTIVITIES:**

1. Doing experimental impact tests on different composite laminates
2. In-dept analyses of experimental data to characterize the long term durability of composites
3. Developing models to better understand the physics with a focus on failure models



•**METHODOLOGY:** Experimental-Numerical



•**DURATION:** 6 months

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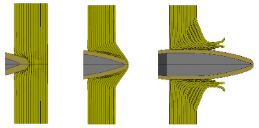
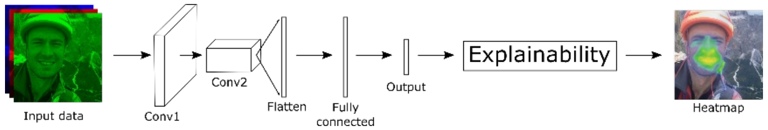
Structural integrity under extreme load





Topic: In-depth investigations on composite materials

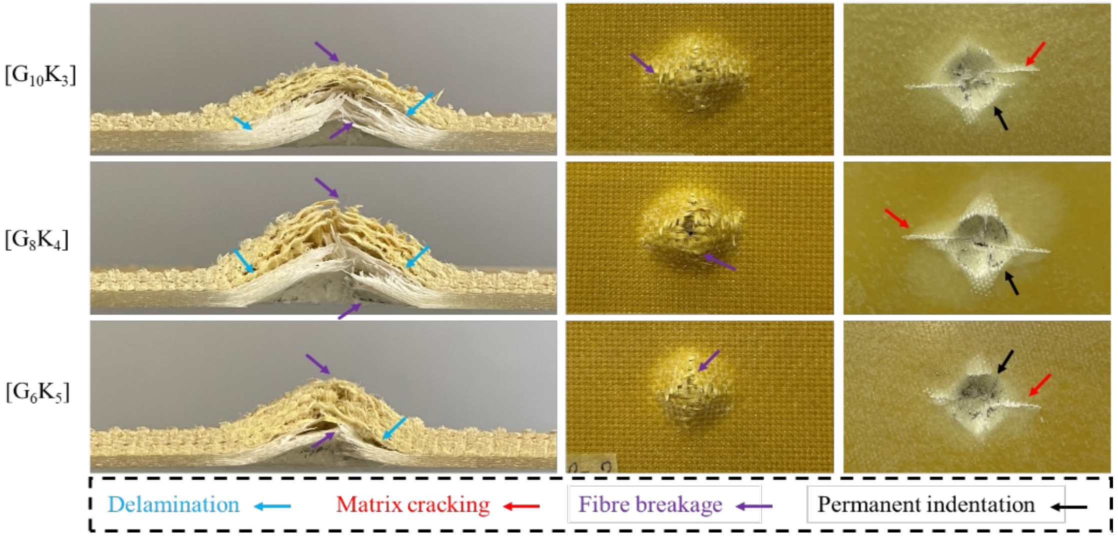
•**TITLE: Application of machine learning in prediction of low-velocity impact response of hybrid composites**

•**RESEARCH BACKGROUND:**

• The combined use of two or more reinforcing fibres in a single matrix, i.e., hybridization, has been considered a practical way of improving composite performance. Is there a method to predict the impact response of the hybrid composites using AI?

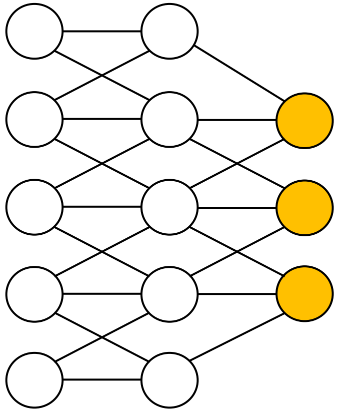
•**RESEARCH ACTIVITIES:**

1. Understanding the machine learning approaches and their application in prediction of mechanical response of structures.
2. Working on the training data for the model using the experimental and numerical methods.
1. Verification and validation of the new model.



•**METHODOLOGY:** Experimental-Programming-Numerical

•**DURATION:** 9 months



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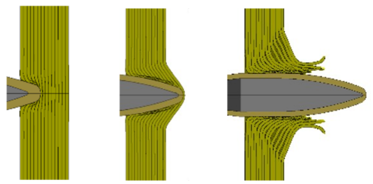
Structural integrity under extreme load



Topic: In-depth investigations on composite materials

•**TITLE: Performance evaluation of thermoplastic and thermoset woven fabric composites under impact loadings**

•**RESEARCH BACKGROUND:**

• Low-velocity impacts introduce internal damage in several forms such as delamination, matrix cracking, and fibre failure while leaving a small or no indentation on the surface. What is the role of resin type in initiation and propagation of these failure modes?

•**RESEARCH ACTIVITIES:**

1. Working on the experimental data from low-velocity impact tests of different composite materials.
1. Microscopic characterization of different failure modes.
2. Developing models sensitive to resin type (optional).

•**METHODOLOGY:** Experimental-Numerical

•**DURATION:** 6 months

•**CONTACTS:**
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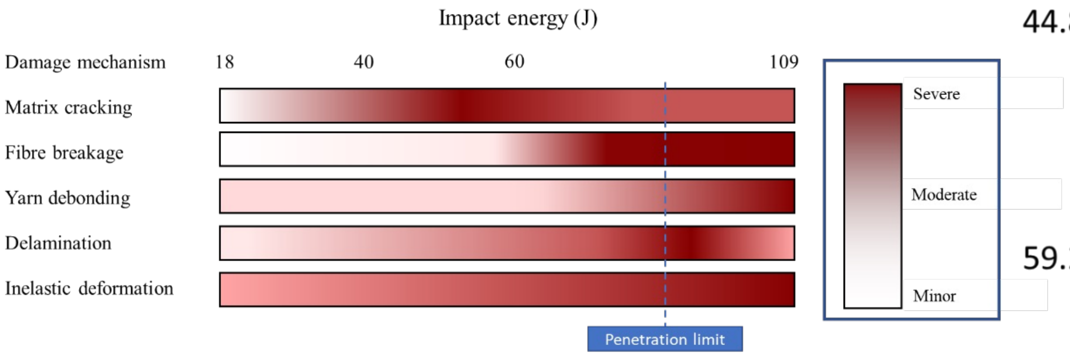

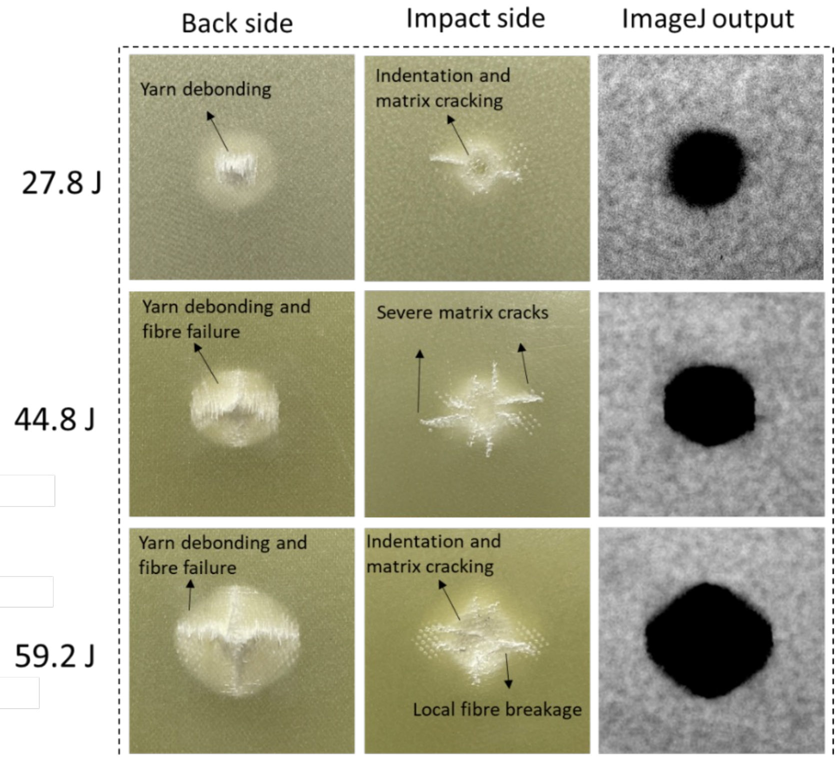

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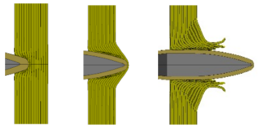
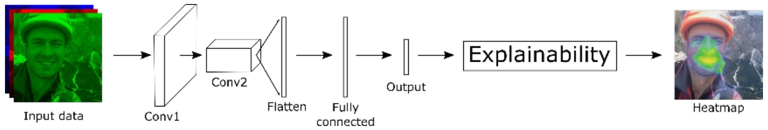




Topic: In-depth investigations on composite materials

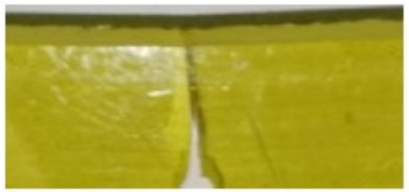
•**TITLE: Modelling of nanocomposites**

•**RESEARCH BACKGROUND:**

•Adding nanofillers inside composite materials can not only improve the mechanical properties but also introduce multifunctional applications. The modelling of nanocomposites can be helpful for their design and applications.

•**RESEARCH ACTIVITIES:**

1. Study different modelling strategies on nanocomposites (with a special focus on their fracture behaviours)
2. Modify/develop methods for the modelling of nanocomposites
3. Introduce multifunctional properties into the numerical modelling (optional)
4. Develop an algorithm with machine learning method for nanocomposites (optional)



•**METHODOLOGY:** Numerical – Programming – Experimental

•**DURATION:** 9 months

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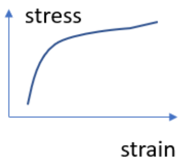
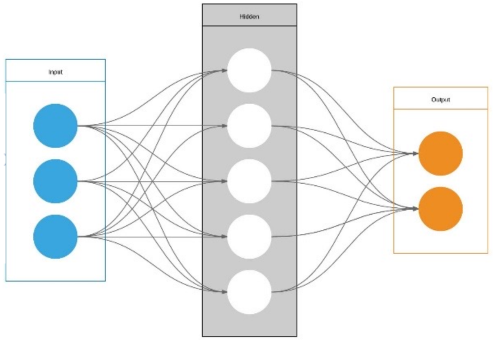
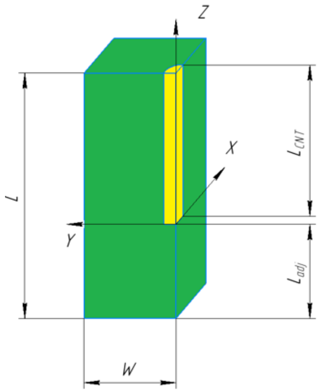
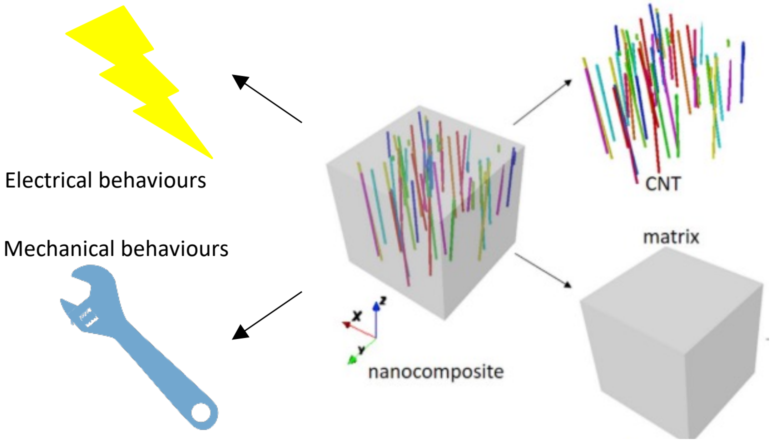


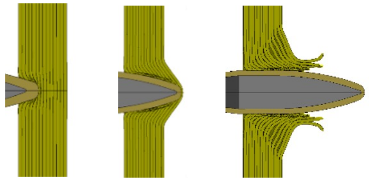






•**POSSIBLE COLLABORATIONS:**
•Ghent University (Belguim)

Structural integrity under extreme load



Topic: In-depth investigations on composite materials

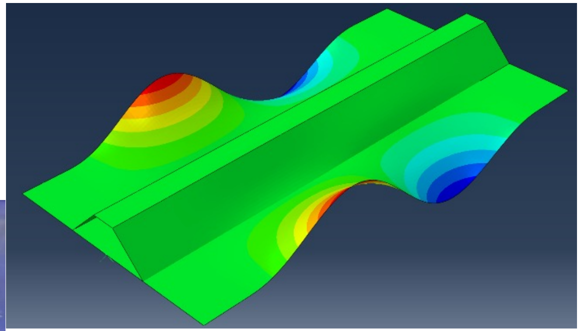
- **TITLE: Double-Double, a new family of composite laminates**

- **RESEARCH BACKGROUND:**

Recently a novel method to design UD composites has been proposed by Prof. Tsai, it is based on two pairs of angle-plies $[\pm\Phi,\pm\Psi]$ and brings several advantages over "quad" laminates $(0,\pm45,90)$, such as easier tapering and homogenisation. The research on these materials involve other universities such as TU Delft and University of Southern California. Currently the activities focus on low velocity impacts, compression after impact and buckling of stiffened panels.
A proactive student will be encouraged to investigate further the application and design of this new class of materials.

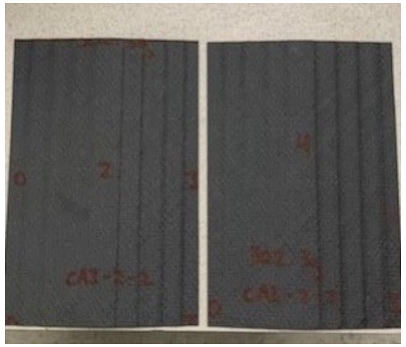
- **RESEARCH ACTIVITIES:**

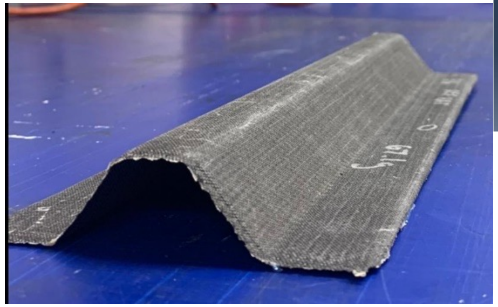
1.Experimental tests on composite laminates
2.In-depth analyses of experimental data to characterize composites behaviour, using analytical and numerical tools to enhance composite design.
3.Developing models to better understand the physics with a focus on failure models



- **METHODOLOGY:**

Experimental - Numerical - Analytical





- **DURATION:**

7-9 months

- **CONTACTS:**

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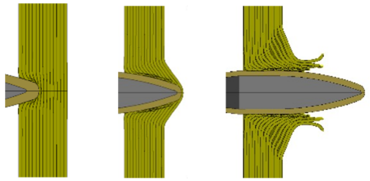
Structural integrity under extreme load

Topic: Structural batteries



•**TITLE: Design and analysis of structural batteries**

•**RESEARCH BACKGROUND:**

•Structural batteries have been attracted more attention recently due to its high efficiency and light weight, especially applied with composite structures. Thus, development of related numerical methods can be helpful for both design and applications of structure batteries.

•**RESEARCH ACTIVITIES:**

1. Development numerical models for structural batteries under simple loading conditions
2. Investigate the effect of batteries on mechanical behaviours of composite structures
3. Consider the multifunctional responses of structural batteries (optional)
4. Develop a method for description and optimization of structural batteries (optional)

•**METHODOLOGY:** Numerical – Programming

•**DURATION:** 7 – 9 months

•**CONTACTS:**

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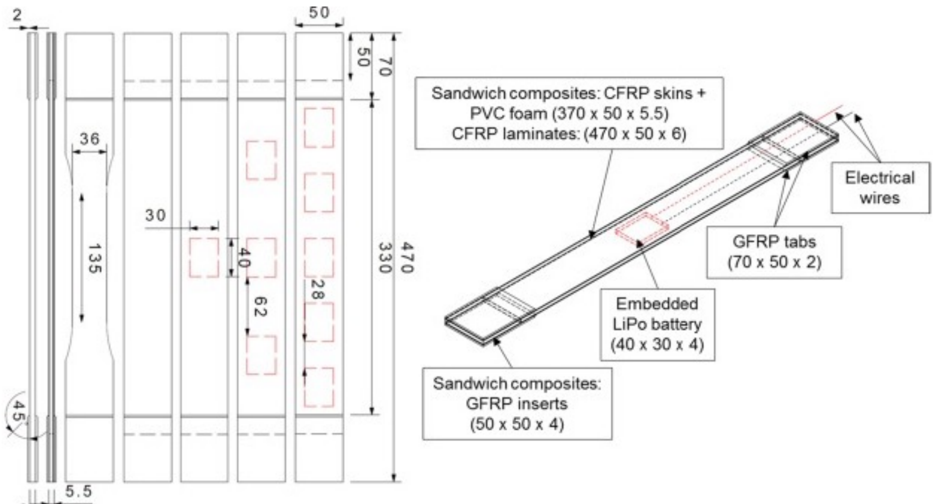
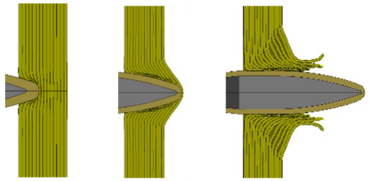


Pattarakunnan, K., et al., *Composites Part A: Applied Science and Manufacturing*. 2020

•**POSSIBLE COLLABORATIONS:**

•Nanjing University of Aeronautics and Astronautics (China)

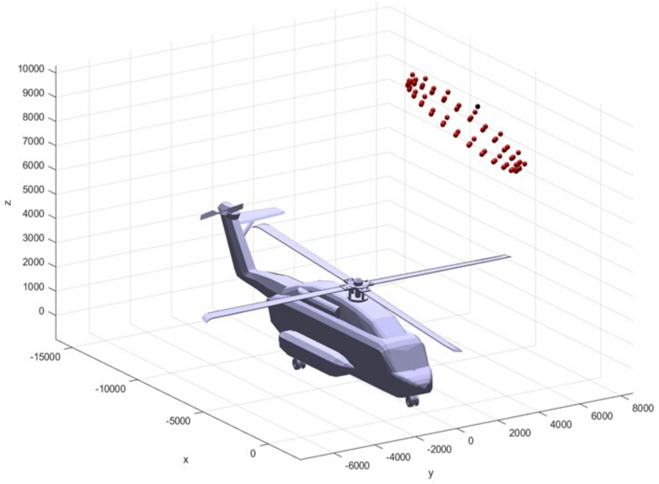
Structural integrity under extreme loads



Topic: Vulnerability

TITLE: Development of a methodological approach to describe the vulnerability of platforms subjected to complex threat mechanisms.

RESEARCH BACKGROUND:
Vulnerability assessments are paramount to evaluate the response of structures to threats. Such assessments need to be performed by means of fast running engineering tools employing statistical methods to process the results of experimental and or numerical tests.



RESEARCH ACTIVITIES:
1. Bibliographic research on state-of-the-art methods to perform vulnerability assessments.
2. Development of statistics-based analytical algorithms to model the effect of complex threat mechanisms on platforms.
3. Implementation of the developments into an in-house vulnerability software and testing on realistic case studies.

METHODOLOGY: Analytical

DURATION: 6-9 months

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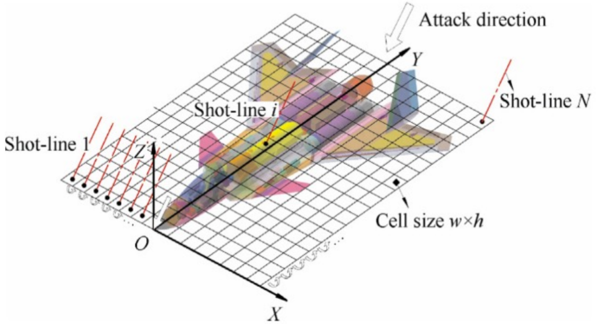
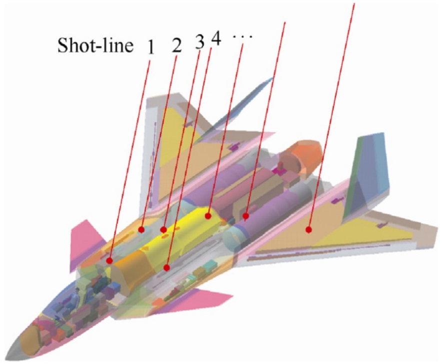
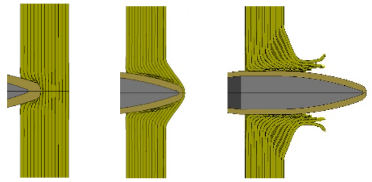
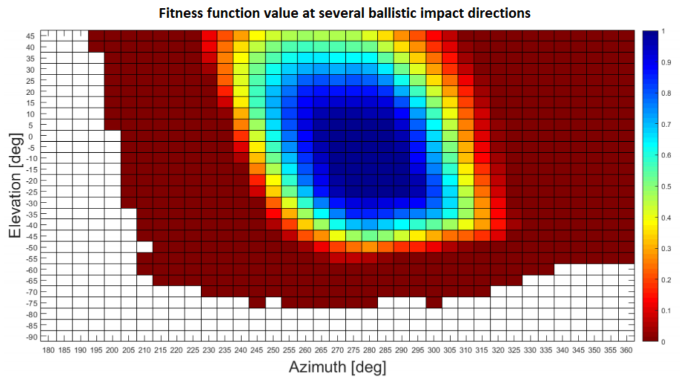




Structural integrity under extreme loads



Topic: Vulnerability

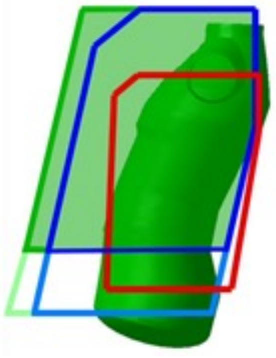


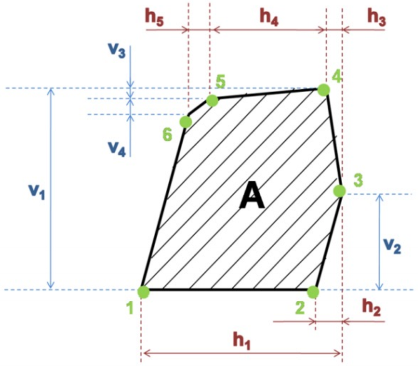
TITLE: Development of a methodological approach to the multidisciplinary topological optimisation of protections.

RESEARCH BACKGROUND:
Vulnerability assessments are paramount to evaluate the response of structures to threats. Based on the results of such assessments, protections may be designed to reduce possible weak points of platforms.

RESEARCH ACTIVITIES:
1. Bibliographic research on state-of-the-art topological optimisation techniques.
2. Development of a methodological approach to perform multidisciplinary topological optimisation including information about the platform vulnerability.
3. Testing on a realistic case study and numerical simulation of the optimised protections subjected to ballistic impact.

METHODOLOGY: Analytical - Numerical





DURATION: 6-9 months

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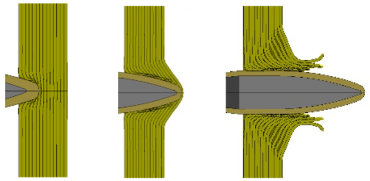
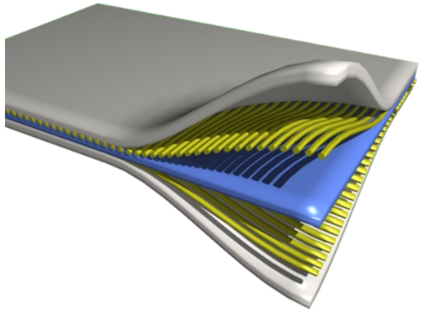
Structural integrity under extreme loads



Topic: High fidelity models of blast loaded structures

TITLE: Numerical characterisation of the behaviour of blast loaded composite structures.



RESEARCH BACKGROUND:
Blast loading represents a critical extreme loading condition for several structures. Simulating the blast response of composite plates is even more complex due to the several possible damage types intrinsically characterising composite materials.

RESEARCH ACTIVITIES:
1. Literature research on state-of-the-art techniques to simulate blast loaded structures.
2. Implementation of identified methods for free-field and confined blast scenarios.
3. Development of fast running engineering tools based on the outcomes of numerical simulations.

METHODOLOGY: Numerical - Analytical

DURATION: 6-9 months

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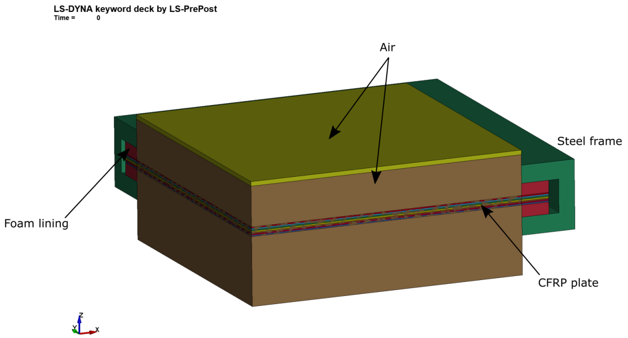
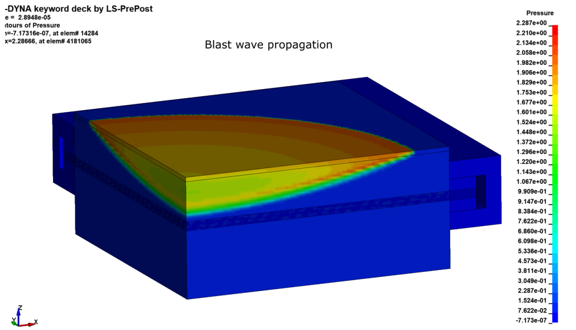
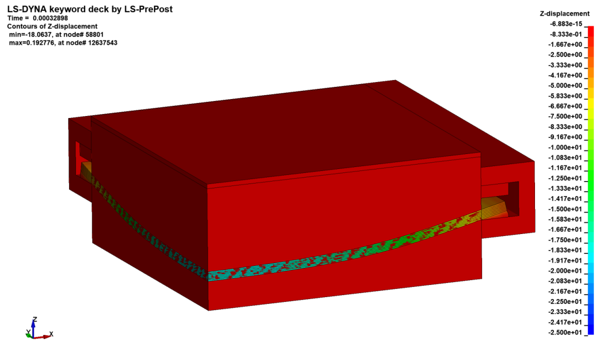
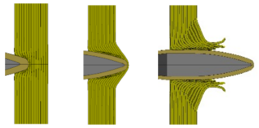
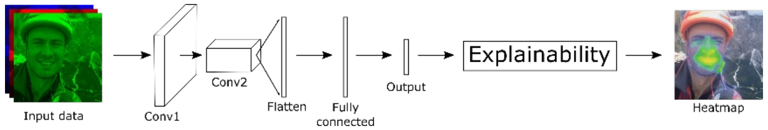






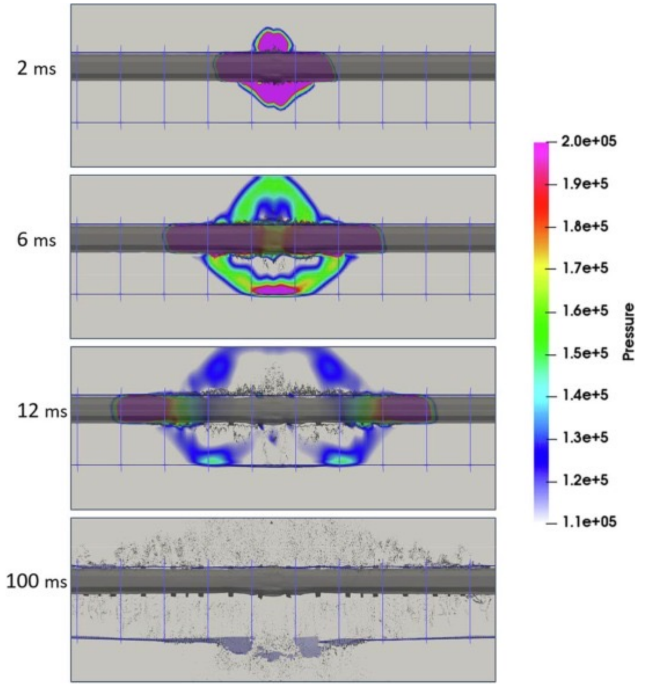
Structural integrity under extreme loads





Topic: High fidelity models and machine learning

TITLE: Numerical characterisation of blast loaded structures and development of machine learning-based surrogate models.



RESEARCH BACKGROUND:

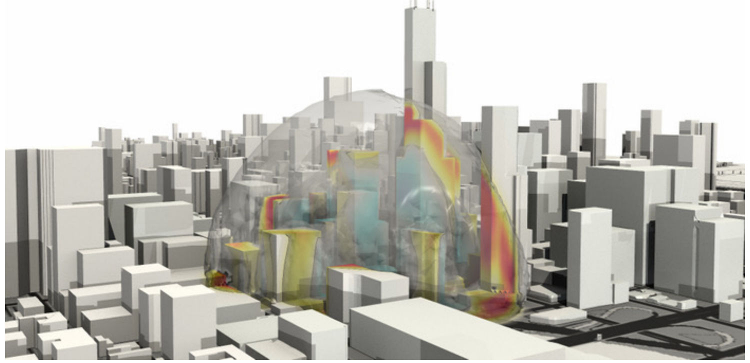
Blast loading represents a critical extreme loading condition for several structures. Numerical simulations of such scenarios may be combined with state-of-the-art machine learning methods to improve computational efficiency and accuracy.

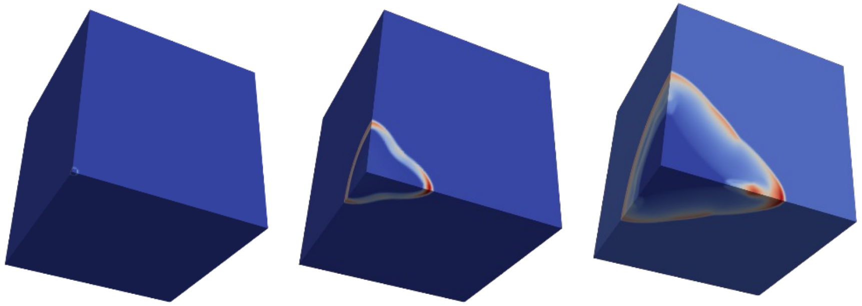
RESEARCH ACTIVITIES:

1. Numerical characterisation of blast loaded structures. Numerical simulations can consist in the finite element method and computational fluid dynamics (prior knowledge of CFD basics is not required).
2. Development of machine learning methods to replace computationally expensive numerical simulations.
3. Testing of the methodology on experimental and numerical data.

METHODOLOGY: Numerical

DURATION: 6-9 months





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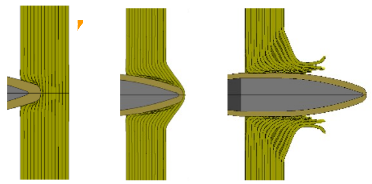
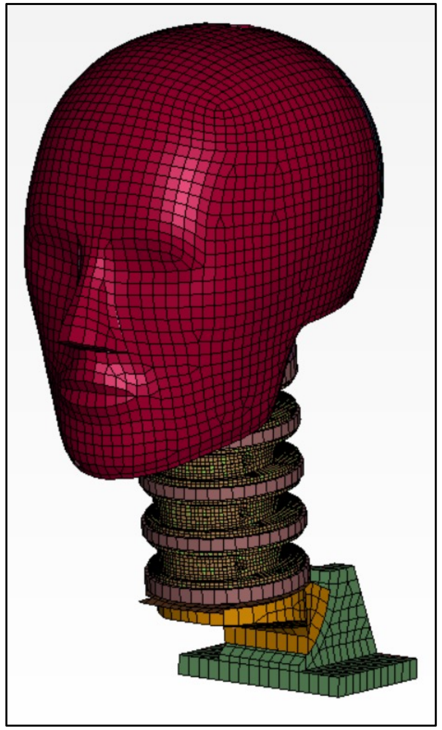
Structural integrity under extreme loads



Topic: High fidelity models

•**TITLE: Numerical modelling of helmet under high velocity and blunt impacts**

•**RESEARCH ACTIVITIES:**
1.Investigation on possible Traumatic Injury of the Skull and Brain
2.Investigation into innovative structures able to protect the head under high velocity impacts fitted for exploitation in the design of helmet
3.Focus in reducing Behind Helmet Blunt Trauma (BHBT)



•**METHODOLOGY:** numerical – experimental (TBV)

•**DURATION:** 7-9 months

•**CONTACTS:**
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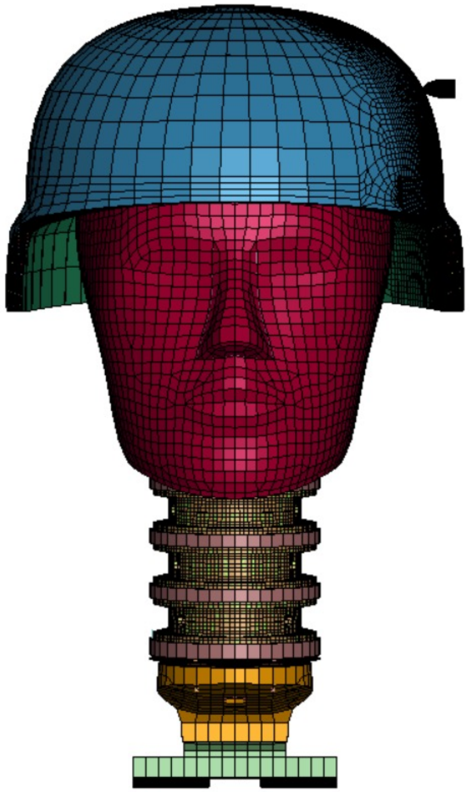
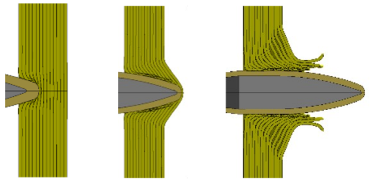


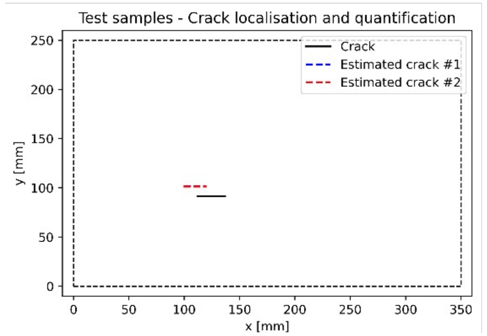
Structural integrity under extreme loads



Topic: High fidelity models and machine learning

•TITLE: Development of machine learning methods to improve the fidelity of numerical models for simulating ultrasonic guided waves in solid media.

RESEARCH BACKGROUND:
Ultrasonic guided waves can be used to characterise structural damage in solid media. To this purpose, dedicated machine learning algorithms may be developed to improve the accuracy and efficiency of state-of-the-art numerical methods.



RESEARCH ACTIVITIES:
1. Experimental tests on composite and/or hybrid plates subjected to low velocity impact.
2. Numerical simulations of the experimental tests.
3. Development of machine learning methods to characterise damage and/or to improve the accuracy and efficiency of numerical methods.

METHODOLOGY: Numerical - Experimental

DURATION: 6-9 months

CONTACTS:

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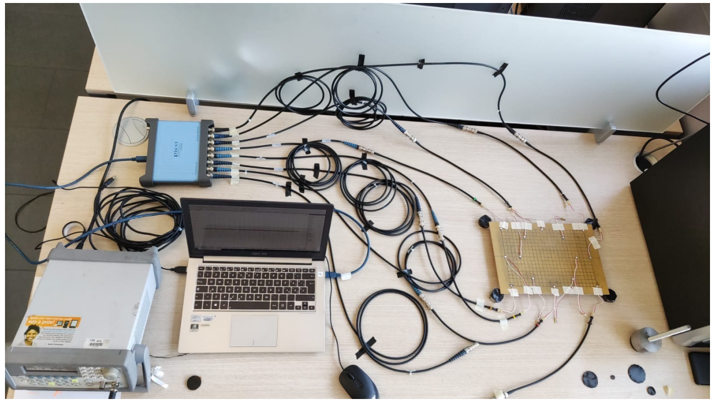
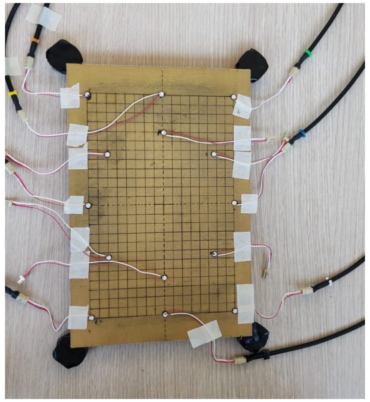




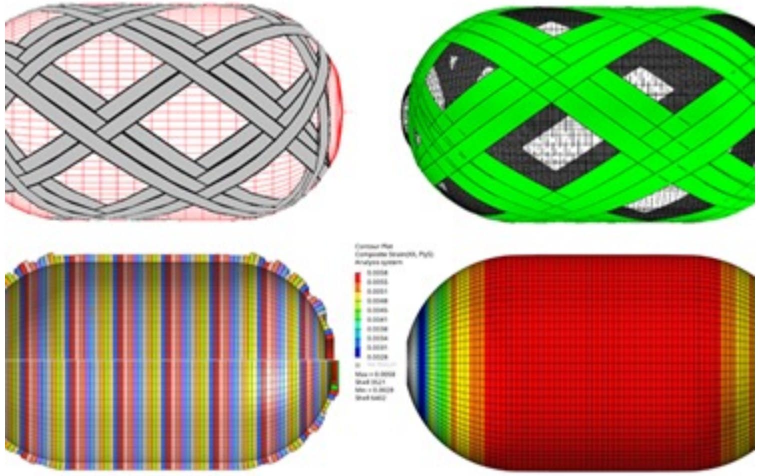
Structural integrity under extreme load

Topic: Hydrogen

•**TITLE: Investigation on the effect of filament winding pattern modelling parameters on the prediction of delamination.**

•**RESEARCH BACKGROUND:** Delamination failure in filament winding composite structures has complex mechanism to investigate. The accuracy in prediction of delamination failure in filament winding composite structures could be increased by considering the filament winding patterns during the numerical modelling.

•**RESEARCH ACTIVITIES:**
1. Investigate the different methods for modelling the filament winding patterns in composite structures.
2. Develop a numerical model to predict the delamination in a filament winding composite structure.
3. Study the effects of modelling parameters on the prediction of delamination.



•**METHODOLOGY:** Numerical

•**DURATION:** 9 months

•**CONTACTS:**
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marco.giglio@polimi.it

Structural integrity under extreme load

Topic: Hydrogen

•**TITLE: Mechanical behaviour of type 4 Hydrogen pressure vessel under random extreme loadings.**

•**RESEARCH BACKGROUND**: In real time the structures could be severely damaged under random and unexpected loadings.

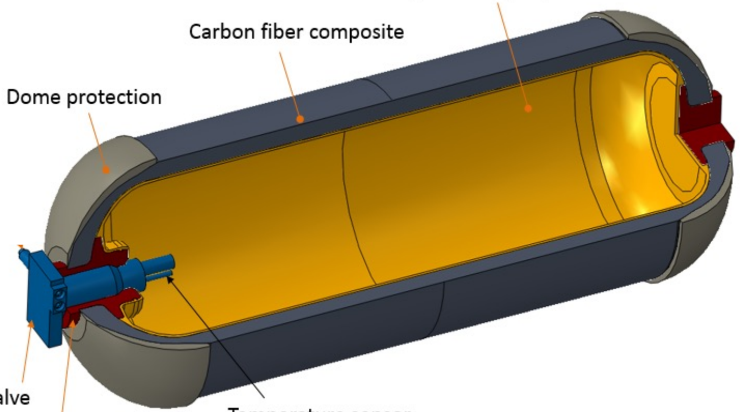
•**RESEARCH ACTIVITIES:**
1. Study the capability of modelling methods for random extreme loadings.
2. Develop a numerical model to investigate the mechanical behaviour of type 4 hydrogen pressure vessel.
3. Study the structural response of pressure vessel under random extreme loadings.

•**METHODOLOGY:** Numerical

•**DURATION:** 9 months

•**CONTACTS:**

andrea.manes@polimi.it
claudio.sbarufatti@polimi.it
marco.giglio@polimi.it



Load monitoring and damage detection

Topic: Hydrogen

•**TITLE: Analysis of Guided waves (GWs) propagation in cylindrical composite vessels**

•**RESEARCH BACKGROUND:** Development of a technique based on GWs requires carful understanding obtained through modelling and analysis of wave propagation.

•**RESEARCH ACTIVITIES:**

1. Investigate the different methods for analysing of GWs propagation in composite structures.
2. Develop a finite element model to model the wave propagation in the composite cylinder.
3. Develop a methodology to analyse the propagation and dispersion of GWs.

•**METHODOLOGY:** Numerical, Programming

•**DURATION:** 9 months

•**CONTACTS:**
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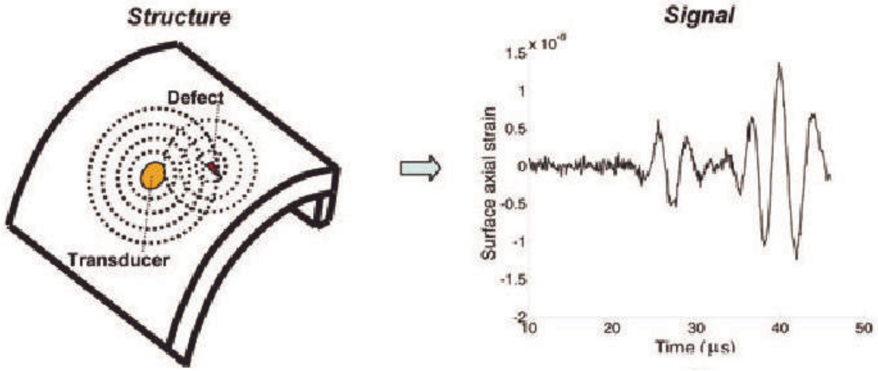
andrea.manes@polimi.it
marco.giglio@polimi.it



Load monitoring and damage detection

Topic: Hydrogen

•TITLE: Model-based structural health monitoring in composite pressure vessels.

•RESEARCH ACTIVITIES:

1. Development of a finite element model to obtain the strain field in composite pressure vessel.
2. Experimental research to measure strain in composite pressure vessel using bucky paper and fibre optic sensors.
3. Validation of FEM results by experimental measurements.

•METHODOLOGY: Numerical, experimental

•DURATION: 9 months

•CONTACTS:

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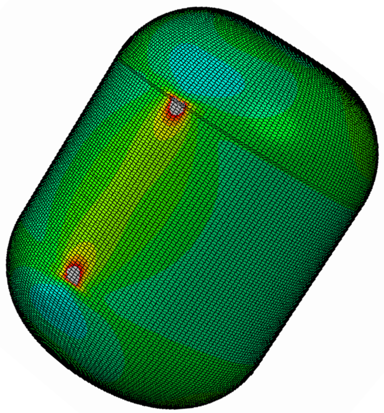
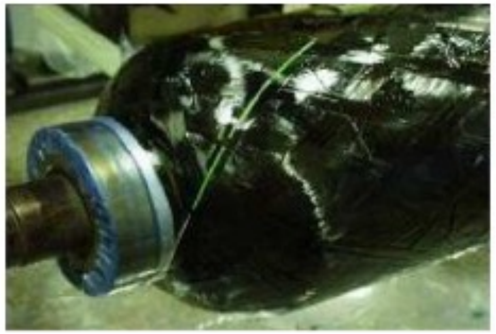
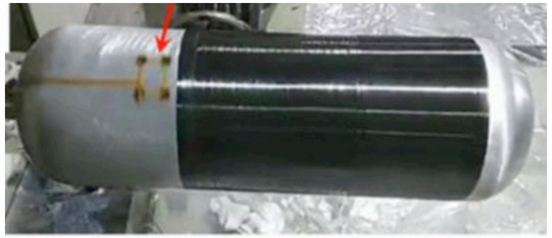
marco.giglio@polimi.it

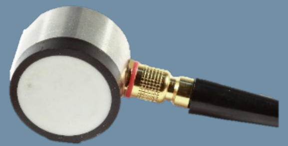






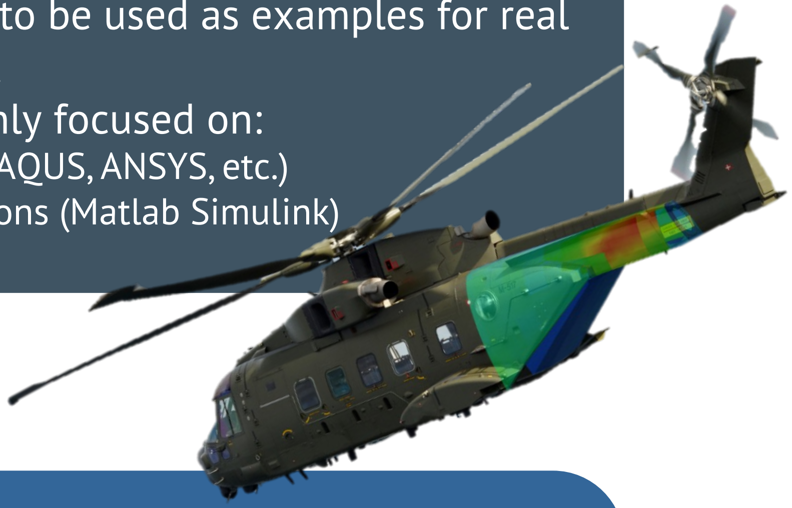
SIGMALab: Health and Usage Monitoring and prognosis for structures and systems subject to degradation

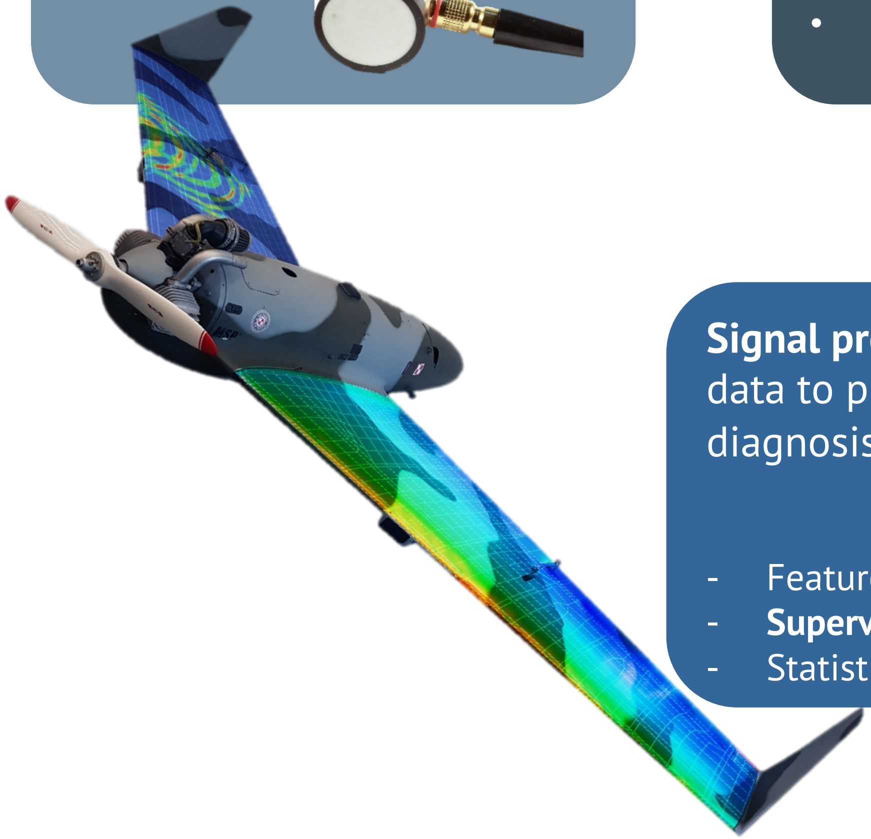
Sensors provide a signal dependent on **damage** that has to be interpreted.



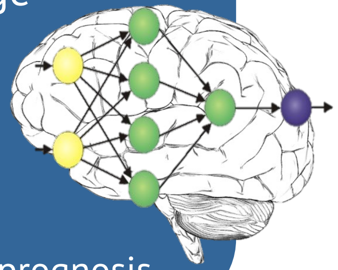
Numerical models provide **simulated signals** in presence of **damage** to be used as examples for real signal interpretation.
Our expertise is mainly focused on:

- Finite Elements (ABAQUS, ANSYS, etc.)
- Multi-body simulations (Matlab Simulink)





Signal processing tools combine numerical and sensor data to provide feature classification and damage diagnosis. Our expertise is focused on:

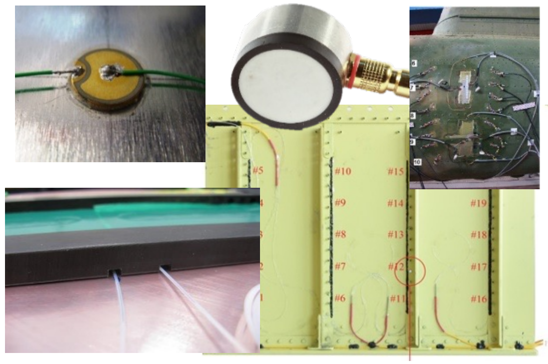


- Feature extraction
- **Supervised** machine learning for diagnosis
- Statistical model-based filtering for diagnosis and prognosis

SIGMALab: Health and Usage Monitoring and prognosis for structures and systems subject to degradation

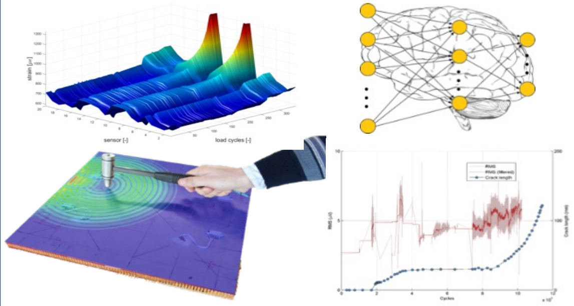
Sensing

- Fiber Bragg Grating (FBG)
- PZT (guided waves)
- Acoustic emission (AE)
- Accelerometers, etc.



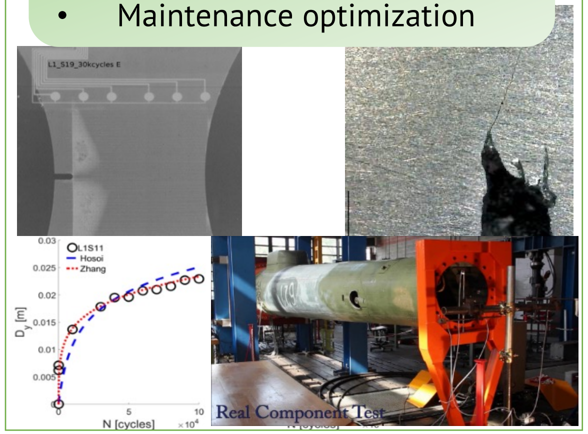
Real-time diagnosis

- Load monitoring
- Anomaly identification
- Fatigue damage monitoring
- Overloads monitoring (impact, harsh landing, etc.)



Real-time prognosis

- Damage growth modeling
- Uncertainty management
- Probabilistic life prediction
- Maintenance optimization



Expertise

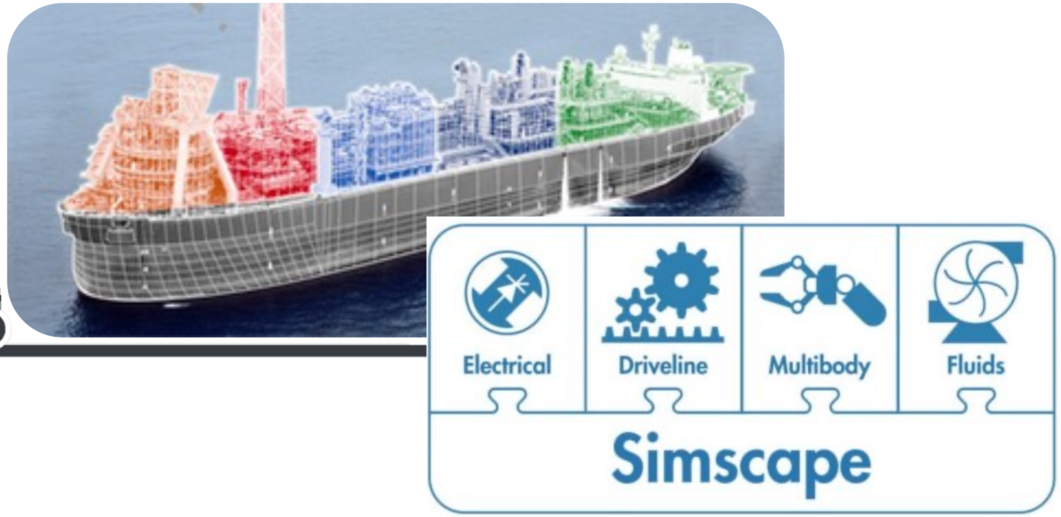
European Defence Agency projects
HECTOR, ASTYANAX SAMAS

- **Full-scale fatigue tests,**
- **Statistical algorithms,**
- **Experimental validation of SHM systems**

SELECTED PAPERS:

- Salvetti, et al; On the performance of a cointegration-based approach for novelty detection in **realistic fatigue** crack growth **scenarios** (2019) MSSP, 123, pp. 84-101.
- Colombo, et al; Definition of a **load adaptive** baseline by inverse finite element method for structural **damage identification** (2019) MSSP, 120, pp. 584-607.
- Sbarufatti, et al; **Adaptive prognosis** of lithium-ion **batteries** based on the combination of particle filters and radial basis function neural networks (2017) JPS, 344, pp. 128-140.
- Corbetta, et al; A Bayesian framework for fatigue life prediction of **composite** laminates under **co-existing matrix cracks and delamination** (2018) COST, 187, pp. 58-70.

THE ROLE OF A DIGITAL-TWIN



Optimisation

Model to assist the SHM designer for sensor network optimisation

Identification

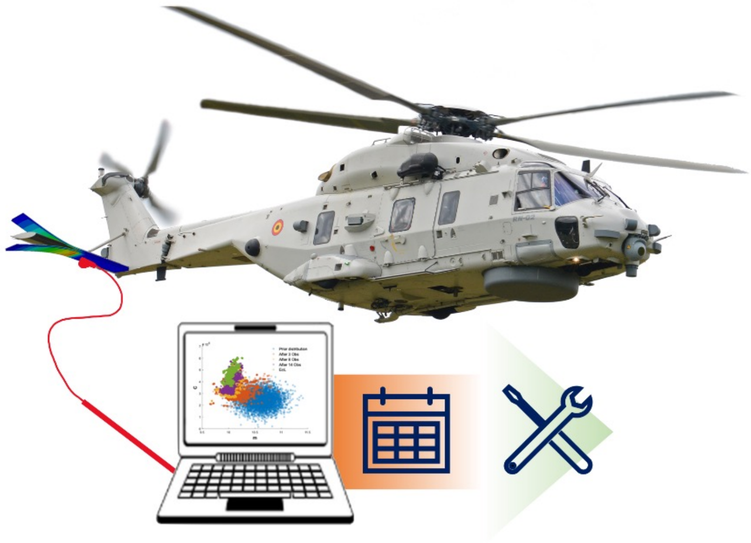
Example data to assist pattern recognition

Prognosis

Damage evolution models to predict material degradation

Decision-making

Modelling of the operative scenario to predict costs, risks and benefits of decisions and configurations



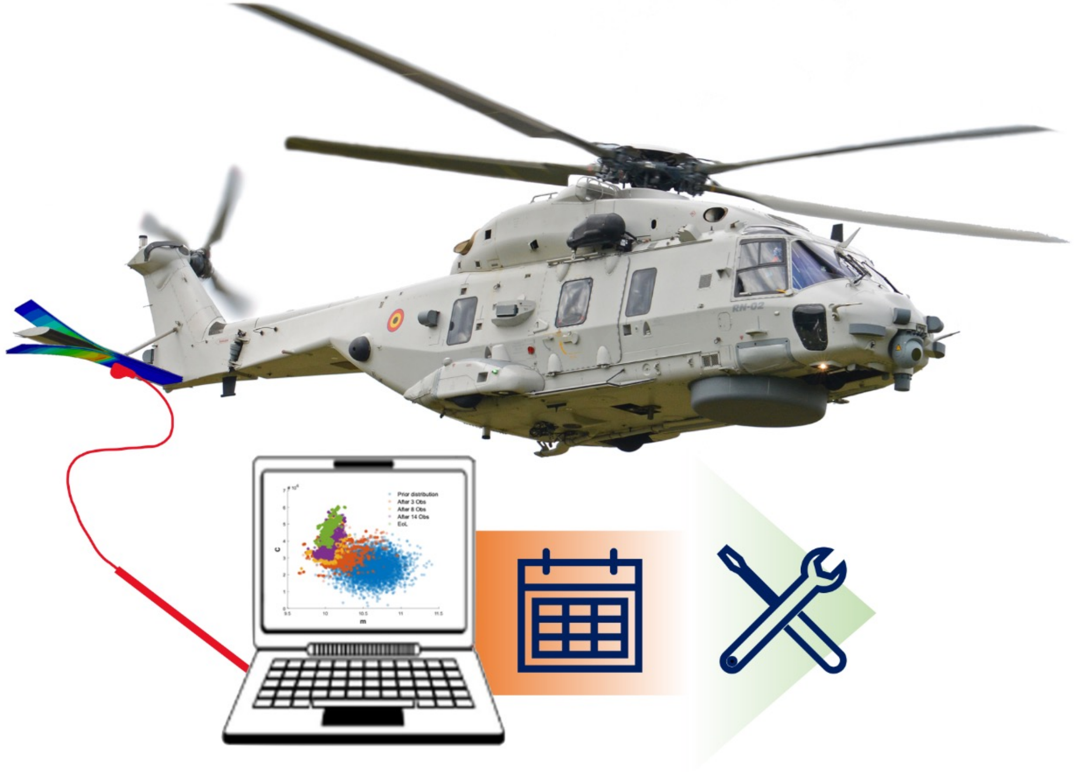
Project overview and related thesis

PATCHBOND II

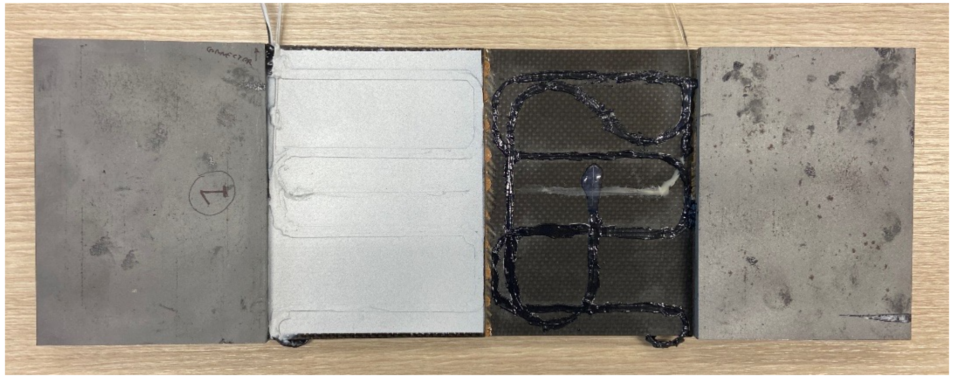
•**RESEARCH BACKGROUND:** Repairing composite structures is more challenging than the traditional metal's structures. The NH90 helicopter is realised with a large use of composites, increasing also the complexity of maintenance and repair operations.

•**PROJECT OVERVIEW:** this project is focused on the realization of a Structural Health Monitoring (SHM) system of a bond repair patch of the NH90 fuselage. Bonded patched are potentially affected by debonding, thus a proper monitoring system can increase the safety of the structure early detecting a anomalies.

•**TESTS:** the SHM methodology is designed on a coupon scale level and then verified with a flight test (incoming tests, 2022-2023)



•**CONTACTS:**
claudio.sbarufatti@polimi.it
marco.giglio@polimi.it

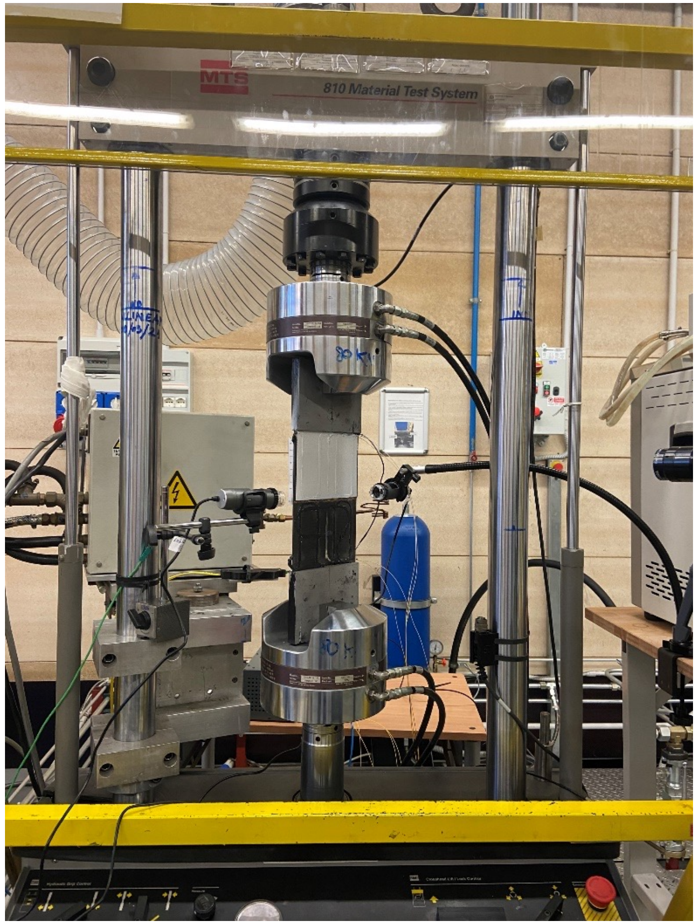


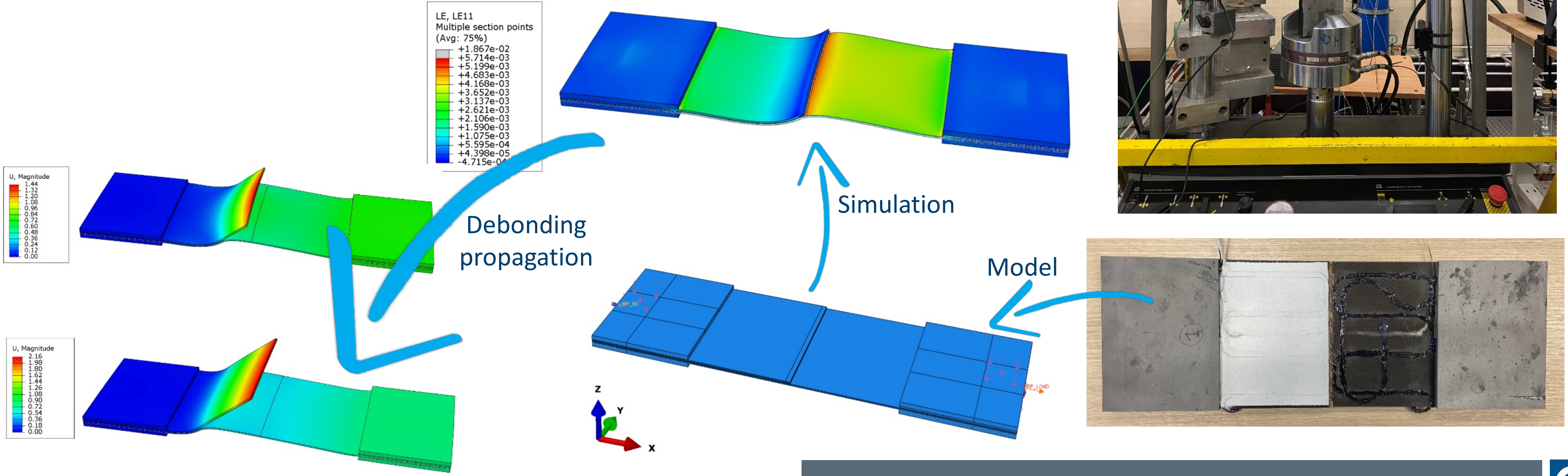
Composite material specimen representative of the NH90 fuselage with strain sensors

PATCHBOND II

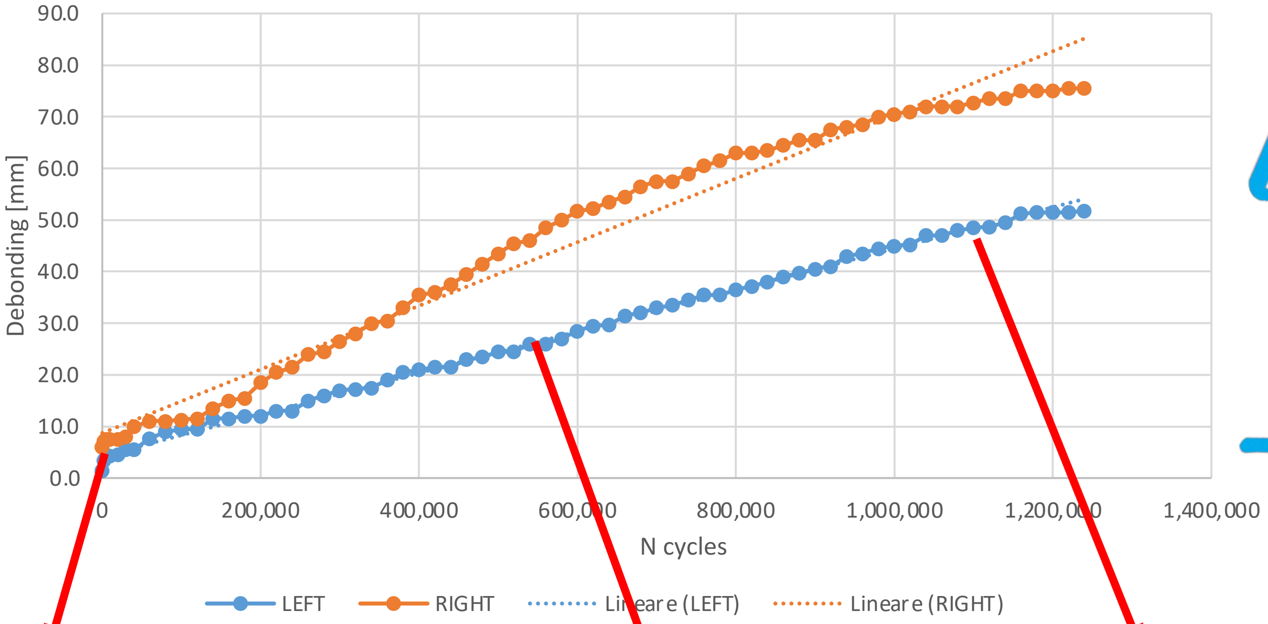
- **MAIN OPEN RESEARCH ACTIVITIES:**
  - Implementation of SHM algorithms for damage diagnosis and prognosis
  - Sensor network optimization and SHM performance evaluation
  - Data analysis
  - Numerical modelling (FEM)
  - Design and realization of experimental tests (incoming flight test, 2022-2023)

Laboratory experimental test

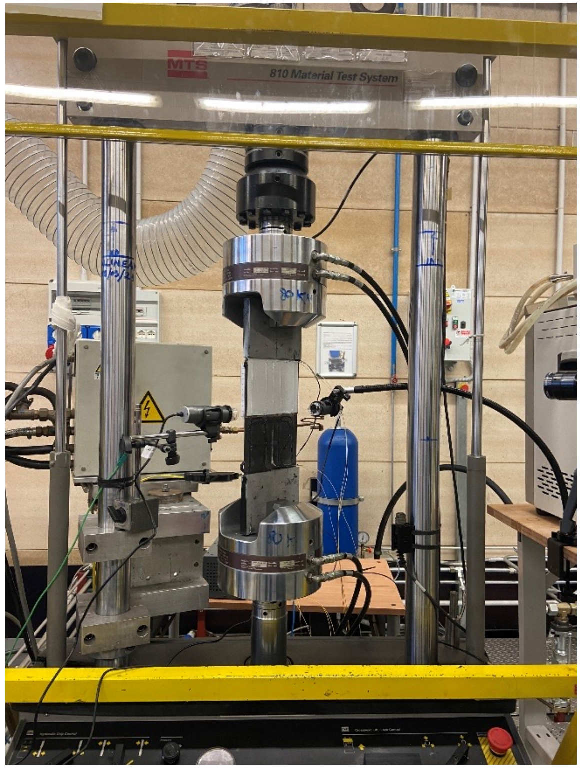


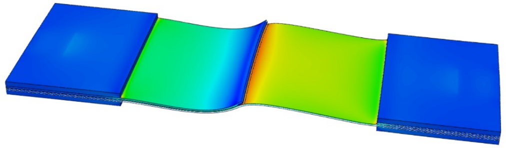


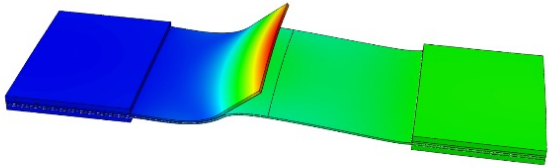
PATCHBOND II

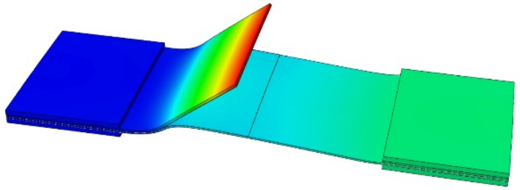


Data acquisition

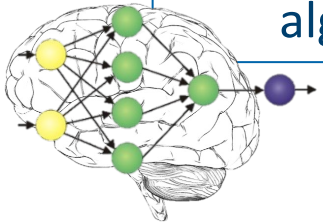








Diagnosis and prognosis algorithms

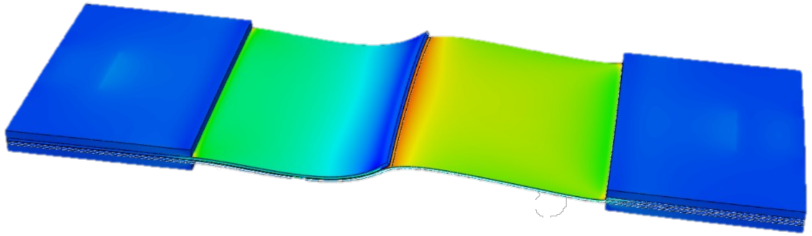


Structural Health Monitoring

TITLE: Sensor network optimization and SHM performance evaluation for the monitoring of a bond repair patch

RESEARCH BACKGROUND: Repairing composite structures is more challenging than the traditional metal's structures. The NH90 helicopter is realised with a large use of composites, increasing also the complexity of maintenance and repair operations. This leads to the development of a dedicated SHM system to early detect the presence of damages.

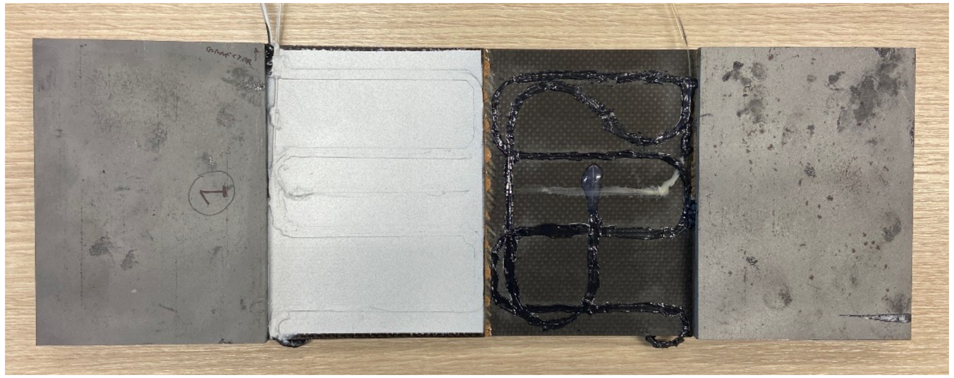
RESEARCH ACTIVITIES:
1. Investigation of the algorithms' performance as a function of the sensor network (number and position)
2. Sensor network optimization
3. Optimization of algorithms' parameters

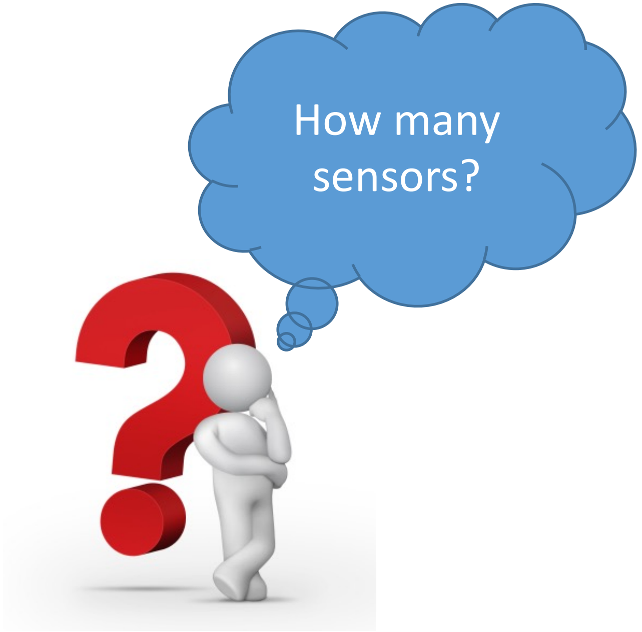


METHODOLOGY: Numerical

DURATION: 6 months

POSSIBLE COLLABORATIONS:
PATCHBOND II partners (Europe)





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marco.giglio@polimi.it

Structural Health Monitoring

TITLE: Design and implementation of an SHM system for an operating helicopter

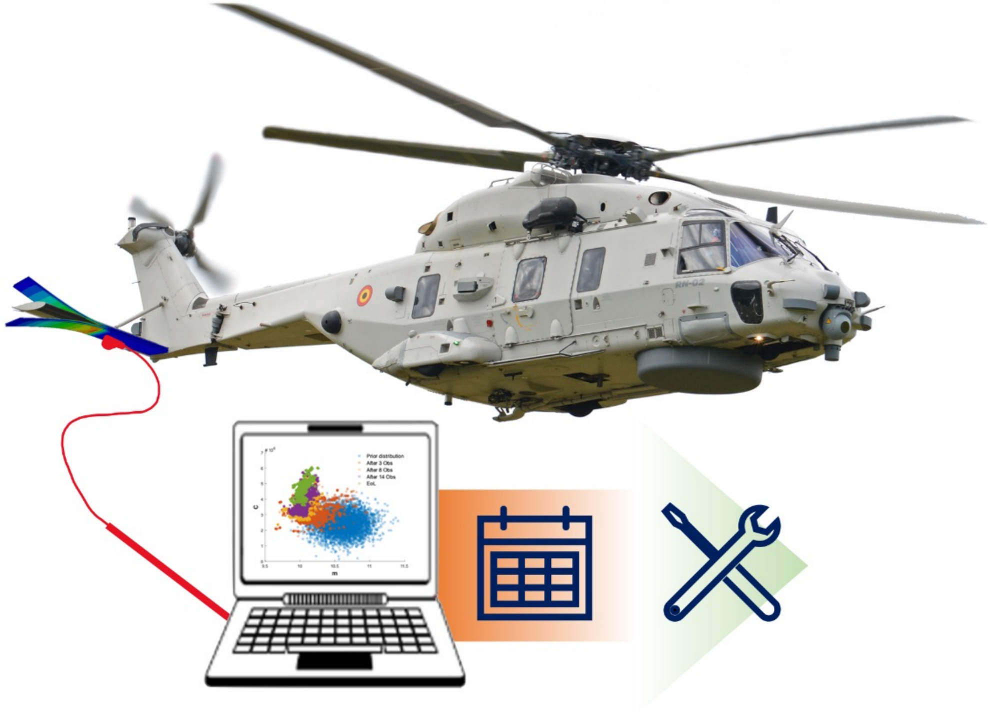
RESEARCH BACKGROUND: Repairing composite structures is more challenging than the traditional metal's structures. The NH90 helicopter is realised with a large use of composites, increasing also the complexity of maintenance and repair operations. This leads to the development of a dedicated SHM system to early detect the presence of damages.

RESEARCH ACTIVITIES:
1. SHM system design
2. In-flight experimental test (2022-2023)
3. Numerical modelling (FEM)
4. Data analysis with SHM algorithms

METHODOLOGY: Numerical, experimental

DURATION: 9 months

POSSIBLE COLLABORATIONS: PATCHBOND II partners (Europe)



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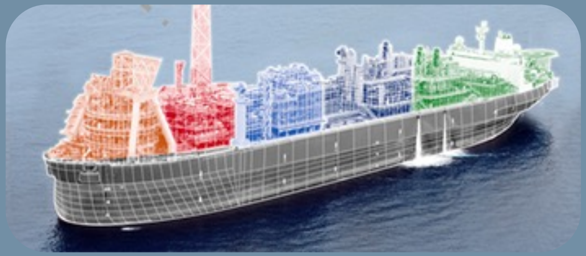
DIGIT-ART: Digital-Twin and Artificial Intelligence for Condition-Based maintenance of a Naval Propulsion System

Digital Twin



Physical Twin

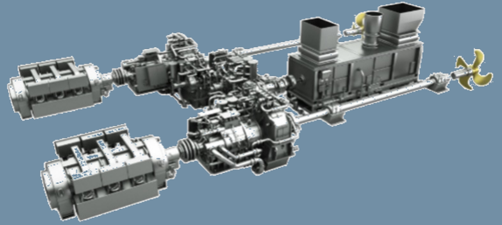
Artificial Intelligence

Condition-Based Maintenance

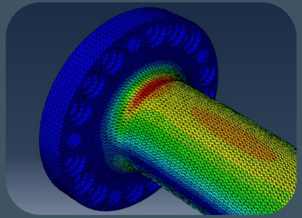
SIGMA Lab

DIGIT-ART: Digital-Twin and Artificial Intelligence for Condition-Based maintenance of a Naval Propulsion System

Propulsion System

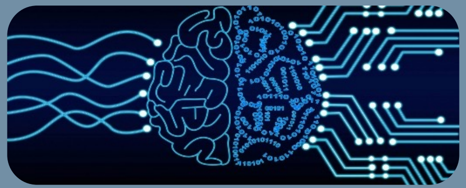


Damage Models



Signal Processing

Artificial Intelligence



Damage Identification & Prognosis

- Anomaly Detection
- Damage Classification
- Damage Localization
- Damage Quantification
- Damage Prognosis

DIGIT-ART: Digital-Twin and Artificial Intelligence for Condition-Based maintenance of a Naval Propulsion System

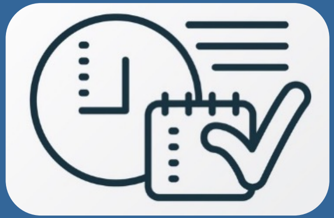
Damage Identification & Prognosis

Remaining Useful Life

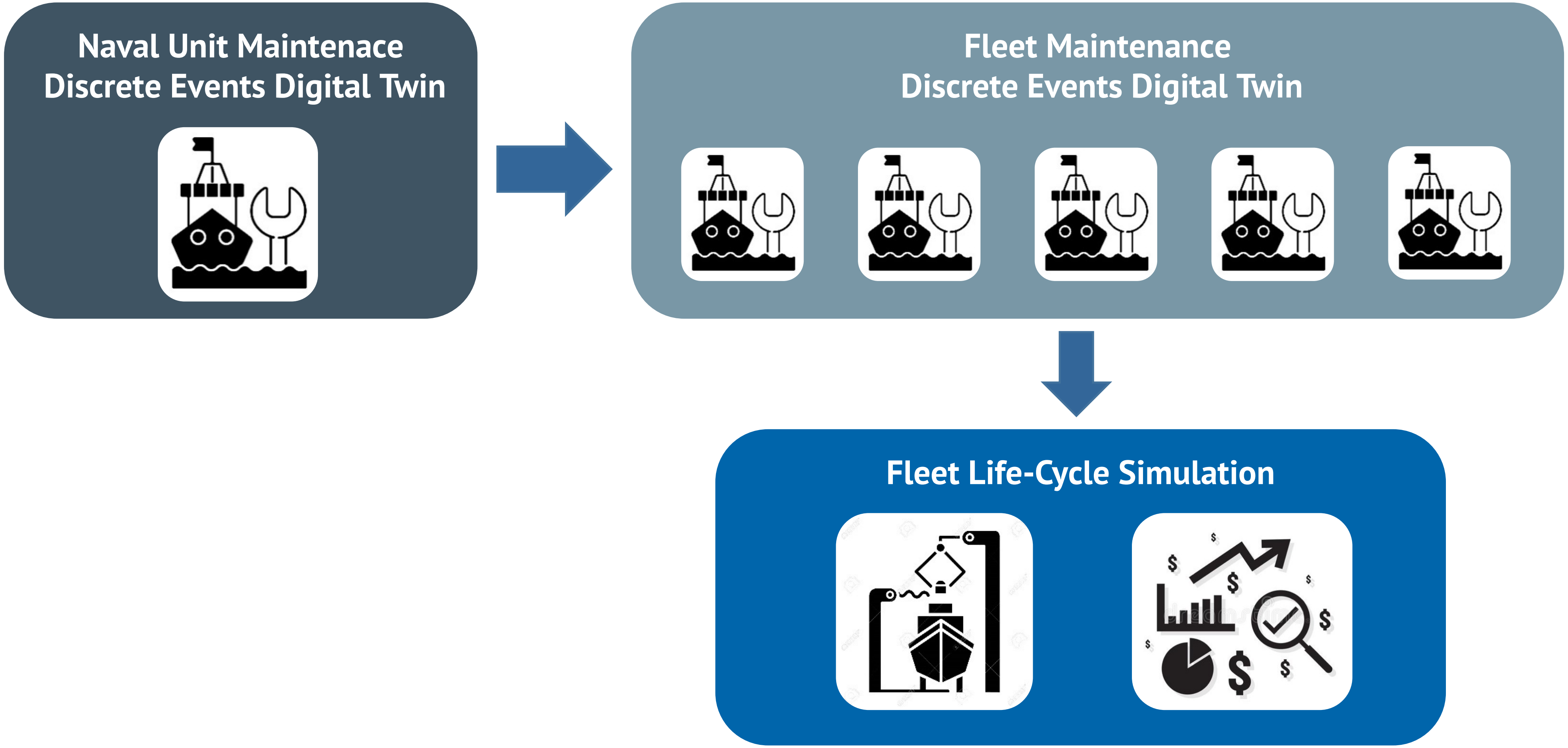
Naval Unit Maintenace Discrete Events Digital Twin

Resource Management & Logistics

Mission Planning & Maintenance Policies



DIGIT-ART: Digital-Twin and Artificial Intelligence for Condition-Based maintenance of a Naval Propulsion System

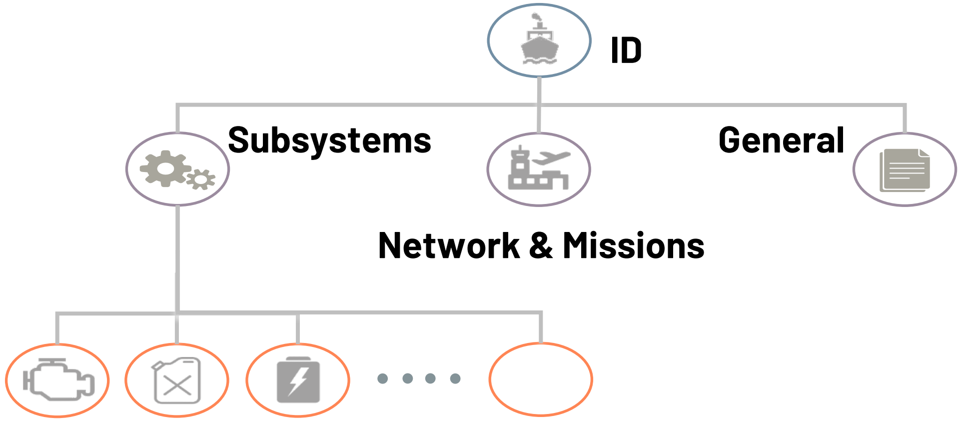


Title: Development of a Discrete Event Digital-Twin of a Naval Fleet for Condition-Based maintenance

RESEARCH BACKGROUND:
Discrete-Event Digital Twins can be used to optmize the assets performance, and to evaluate the cost-effectiveness of different maintenance policies, enabling the shift from programmed maintenance to condition-based maintenance, in an industry 4.0 framework.

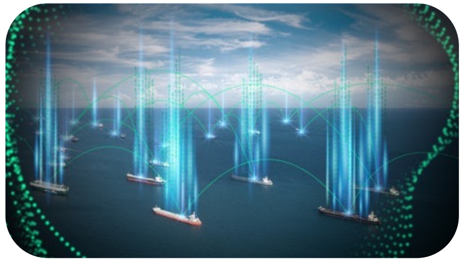
RESEARCH ACTIVITIES:

- Development of a vessel Discrete-Event System in MATLAB-Simulink-SimEvents
- Development of a fleet management system in MATLAB-SimEvents
- Fleet Life-Cycle Analysis by means of Monte Carlo Simulations



METHODOLOGY: numerical – analytical

DURATION: 9 months



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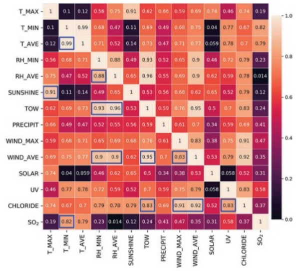
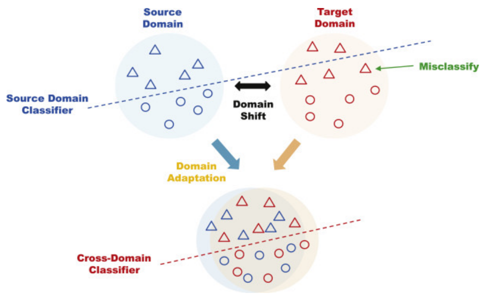
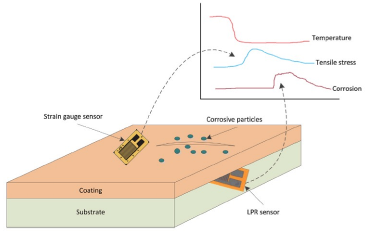
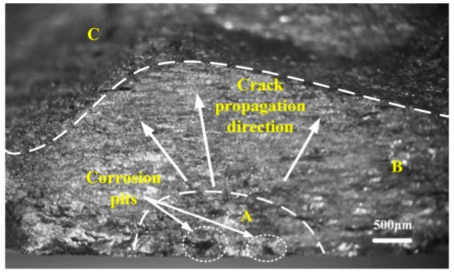
marco.giglio@polimi.it

SAMAS 2: Structural Health and Ballistic Impact Monitoring and Prognosis on a Military Helicopter





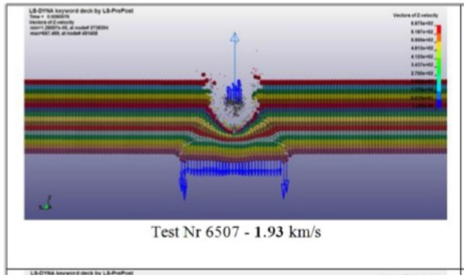


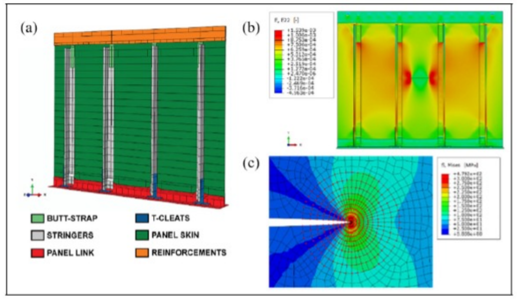


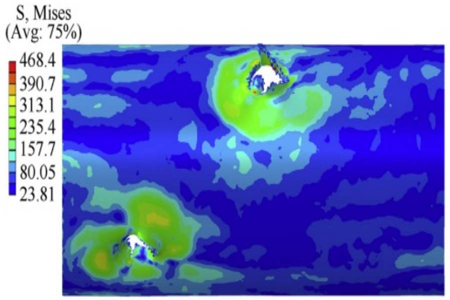
CORROSION MONITORING

IMPACT MONITORING

- WP100 - Management
- WP200 – Preliminary activities and requirements
- WP300 – Structure evaluation for corrosion monitoring
- WP500 – Algorithms for corrosion monitoring
- WP800 – Experimental verification and validation for corrosion monitoring
- WP400 – Creation of the Digital-Twin for impact monitoring
- WP600 – Algorithms for impact and load monitoring
- WP700 – Sensor network design for impact and load monitoring
- WP900 – Experimental verification and validation for impact and load monitoring
- WP1000 – Digital-Twin for LCC, CBA and operational support
- WP1100 – Gap analysis and exploitation roadmap







SIGMA Lab

SAMAS 2: Focus on Corrosion Monitoring

Setup of requirement and target objectives

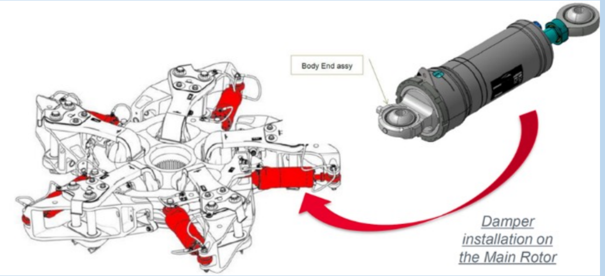
Sensors and algorithms for corrosion detection

Models and algorithms for corrosion rate prediction

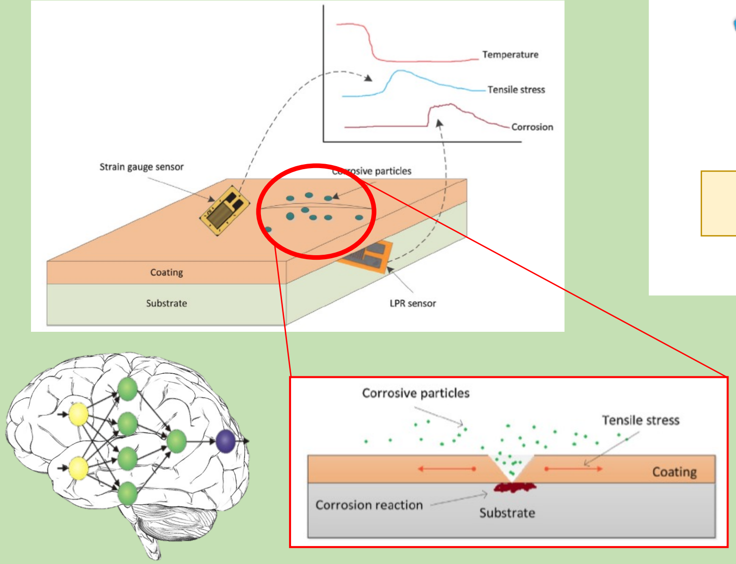
Experimental verification

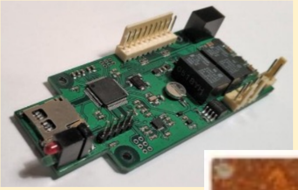
Two helicopter's components provided by LHD have been selected for this task:

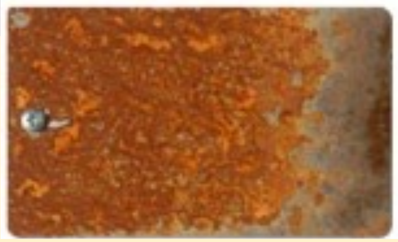
Tail Gear Box Case made of Aluminium Alloy A357

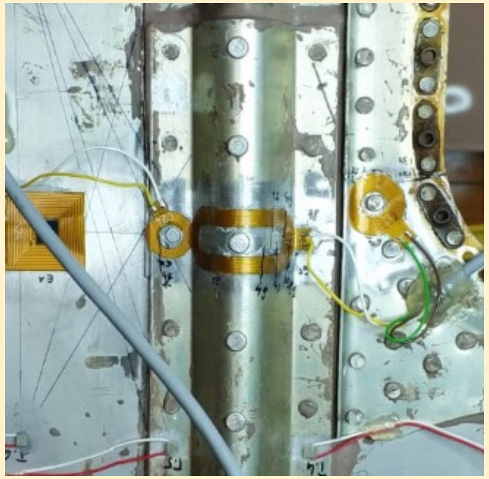


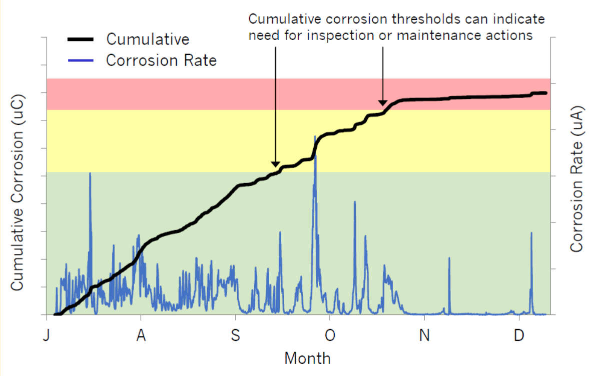
Main Rotor Body-End Damper made of Steel 15-5 PH











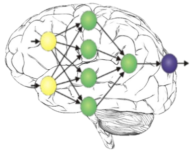
SIGMA Lab

SAMAS 2: Focus on Impact Monitoring

Setup of requirement and target objectives

Creation of a Digital-Twin in healthy and damaged conditions

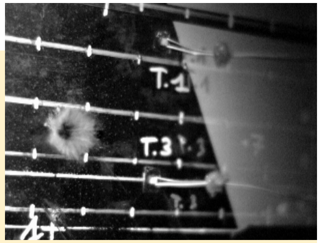
Algorithms for diagnosis and prognosis of impact damage and load monitoring



Methods for sensor network optimization

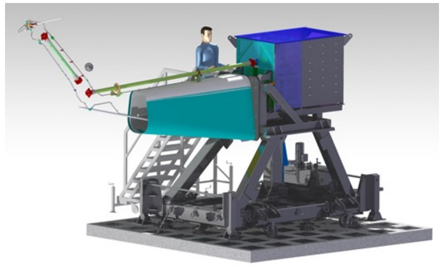
Experimental verification

Test campaign



- Impact TESTS on a component (on laboratory)
- Dynamic GROUND tests on SIMPLIFIED TEST RIG (in healthy and damage condition)
- Dynamic GROUND tests on FULL-SCALE structure
- Technology verification by means of FLIGHT TESTS (fatigue load monitoring)

FULL-SCALE Ground Test of the tail rotor drive (in healthy and damage configurations) in close-to-operative conditions.



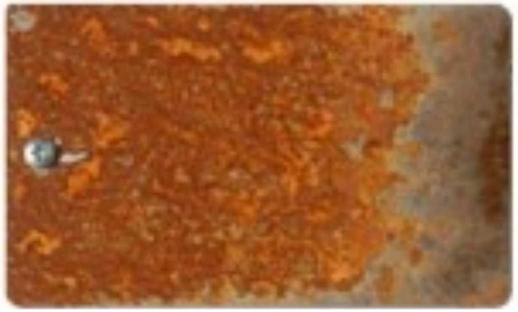
Flight Test on Mil Mi-24 helicopter. HUMS will be installed on representative structures (in healthy configuration) for performance evaluation in real operational condition.

SAMAS 2

Topic: Models for corrosion rate prediction

TITLE: Development of models for corrosion rate prediction

RESEARCH BACKGROUND: Corrosion is a process created by the interaction between a metal or alloy, and its environment that results in degradation. Corrosion is a very important, wide and multi-disciplinary task for structure safety and cost management. Modeling of corrosion processes is a research subject of great interest and has applications in aeronautic, automotive, marine, medical, etc. industries.

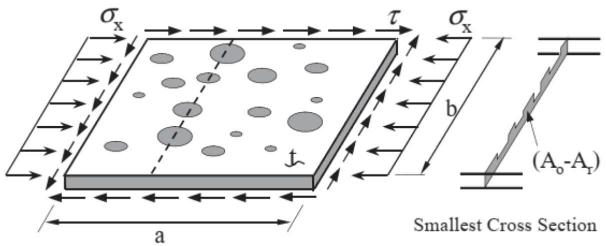


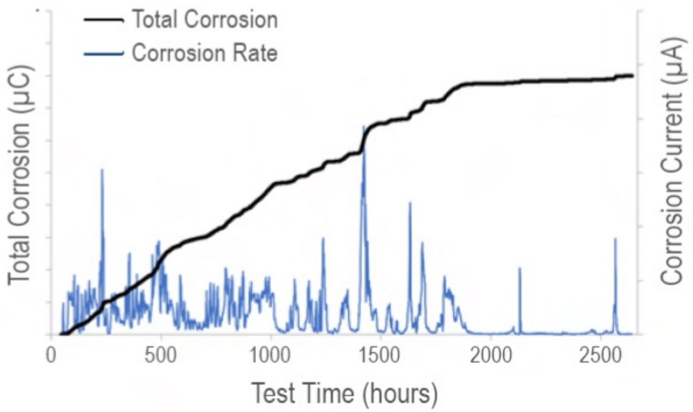
RESEARCH ACTIVITIES:

1. Investigate the different methods for defining an evolution model to correlate the corrosion rate with the ambient parameters (like relative humidity, temperature, etc.).
2. Develop a numerical model to predict the corrosion damage in metals.
3. Study the effects of modelling parameters on the prediction of corrosion damage.

METHODOLOGY: Numerical

DURATION: 6-9 months





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SAMAS 2

Topic: High fidelity models and machine learning

TITLE: Development of models and algorithms for corrosion damage assessment

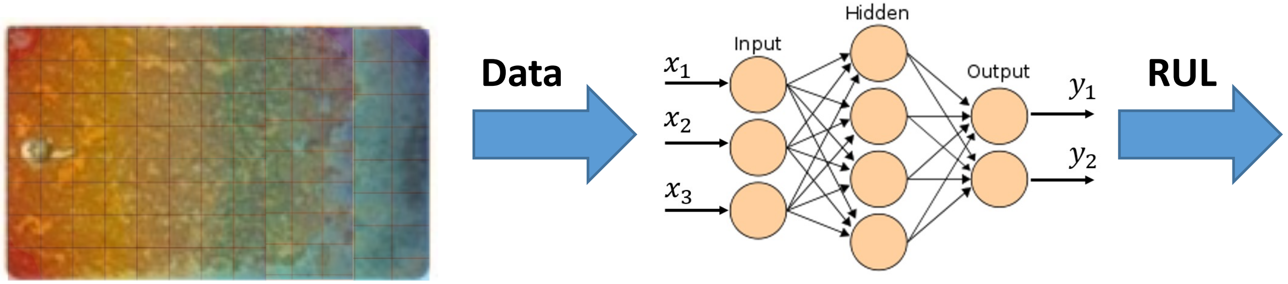
RESEARCH BACKGROUND: Development of a diagnostic tool for corrosion monitoring based on machine learning algorithms (Artificial Neural Networks, Gaussian Processes, Particle Filters) for the identification of the damage state of the component.

RESEARCH ACTIVITIES:

1. Develop a numerical model to predict the corrosion damage in metals (pitting corrosion).
2. Define an algorithm that, given the observations from numerical data, identifies the actual damage state of the component (diagnosis) and predicts its damage evolution and remaining useful life (RUL) (prognosis).

METHODOLOGY: Numerical, Programming

DURATION: 9 months



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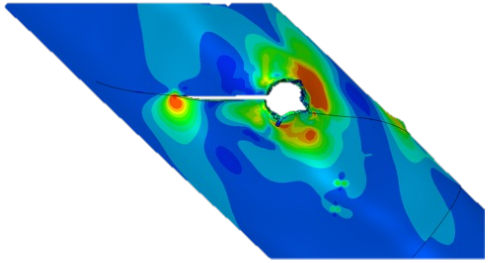
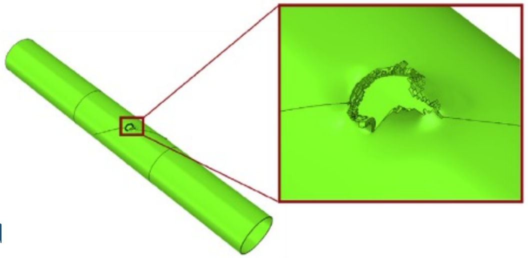
SAMAS 2

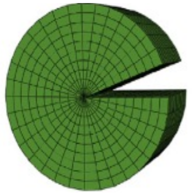


Topic: Models for cracked rotor shaft



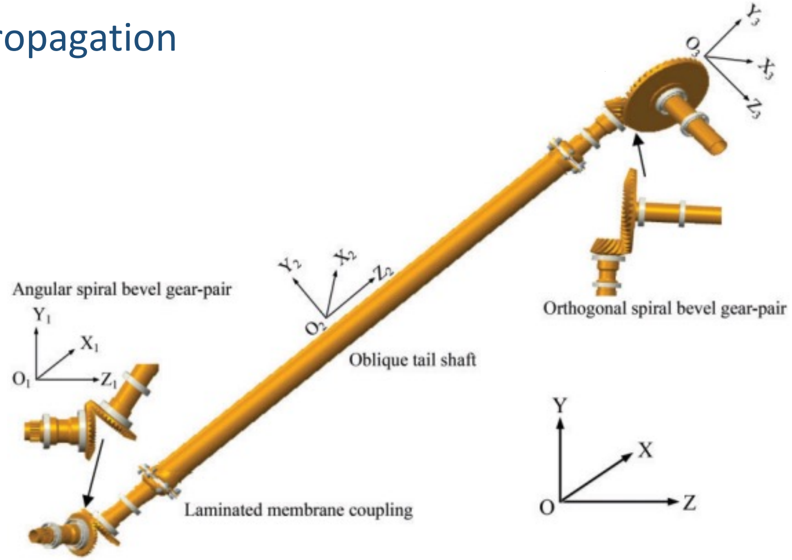
TITLE: Development of models for a cracked rotor shaft

RESEARCH BACKGROUND: The dynamics of a general non-linear, time-varying, damaged structure can be described by the spatially discrete and coupled system including the non-linear equation of motion and the non-linear evolution of damage. Simulating the dynamic behavior of cracked rotating machinery is a vital task for Structural Health Monitoring and Prognosis systems.



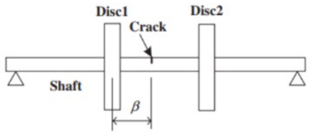
RESEARCH ACTIVITIES:

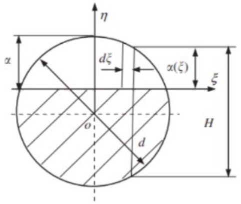
1. Investigate the different methods for defining an evolution model to correlate the crack propagation with the environmental and operational parameters of rotating shafts.
2. Develop a numerical model to predict the crack propagation on rotating shafts.
3. Study the effects of modelling parameters on the prediction of crack propagation.

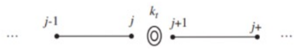


METHODOLOGY: Numerical

DURATION: 6-9 months







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SAMAS 2

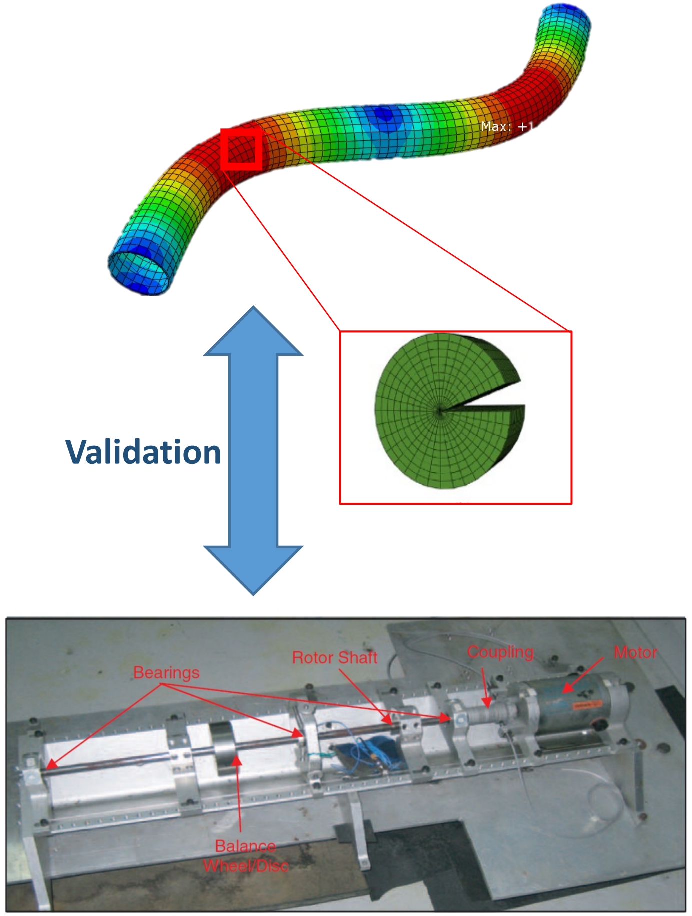
Topic: High fidelity models

TITLE: Model-based structural health monitoring in transmission shaft.

RESEARCH BACKGROUND: Model-based methods rely on the availability of a reliable system's dynamic model of fatigue and fault progression, which is derived by using principles of physics.

RESEARCH ACTIVITIES:

1. Development of a finite element model of the cracked rotor shaft and obtain the frequency responses.
2. Experimental research to measure phase and amplitude change due to the presence of crack, using accelerometers mounted on the supports.
3. Validation of FEM results by experimental measurements.



METHODOLOGY: Numerical, Experimental

DURATION: 6-9 months

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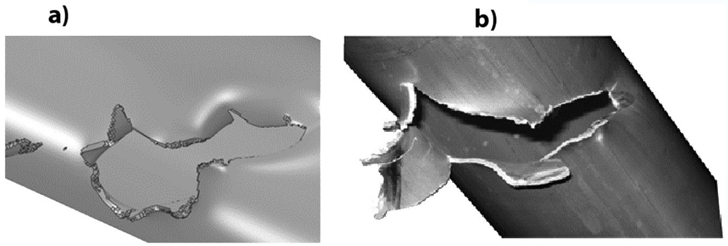
SAMAS 2

Topic: High fidelity models and machine learning

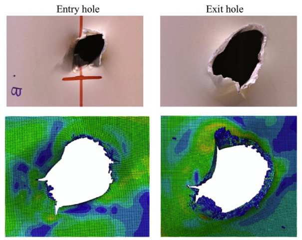
TITLE: Development of models and algorithms for impact damage assessment

RESEARCH BACKGROUND: Development of a diagnostic tool for damage monitoring after impact occurrence based on Artificial Intelligence algorithms and thus detecting the damage state of the component.



RESEARCH ACTIVITIES:

1. Experimental tests on rotor shaft subjected to ballistic impact.
2. Numerical simulations of the experimental tests.
3. Development of machine learning methods to characterise damage and/or to improve the accuracy and efficiency of numerical methods.



METHODOLOGY: Numerical, Experimental

DURATION: 9 months

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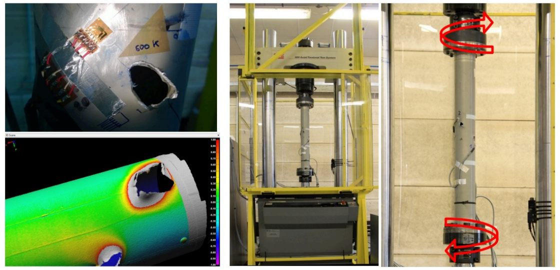
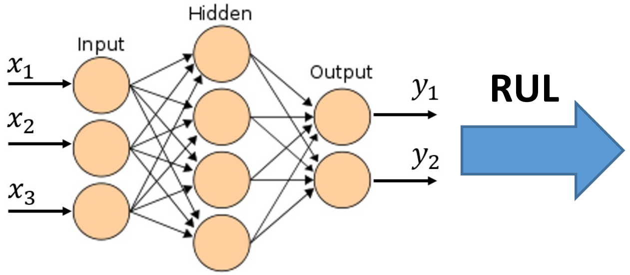


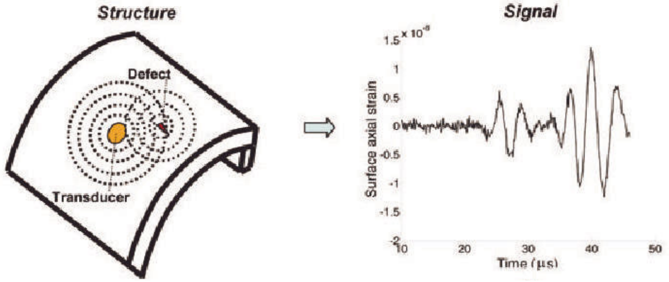


Frequency feature
Rotor imbalance
Rotor lateral crack
Rotor misalignment
Oil film whirl
Rotating stall
Breathing vibration
Rub between rotor and stationary
Rotor less surplus
Loose rotating parts
Fluid-induced instabilities

SAMAS 2

Topic: Signal Processing and Data Analysis

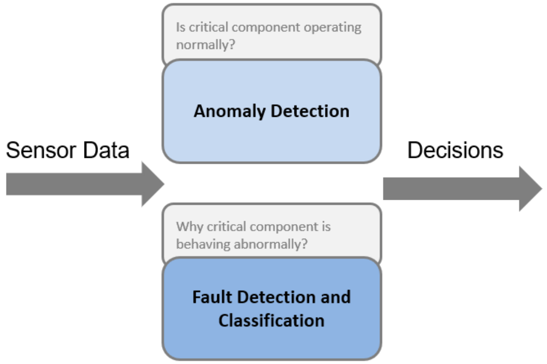
TITLE: Signal processing and data analysis for impact damage assessment

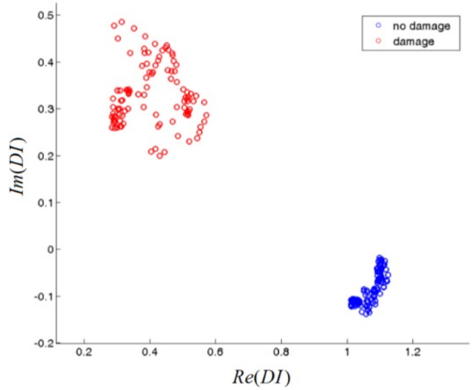


RESEARCH BACKGROUND: Signal processing is of vital importance for an efficient fault monitoring system. It reflects the intermediate step between the occurrence of the ballistic impact and the task of feature extraction, and it is required in order to convert raw signal data into editable signal information.

RESEARCH ACTIVITIES:

1. Experimental tests on rotor shaft subjected to ballistic impact.
2. Perform signal preprocessing to facilitate the efficient extraction of indicators of the condition of the failing component.
3. Perform vibration signal processing consisting of data collection, information extraction and knowledge gaining in time, frequency or wavelet domain.





METHODOLOGY: Numerical, Experimental

DURATION: 9 months

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Other research activities

inverse Finite Element Method (iFEM)

Load
Material
BC
Geometry

FEM → U → ε

Strain
BC
Geometry

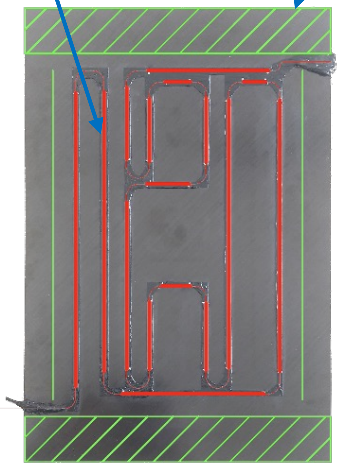
iFEM → U → ε

NO Load & Material properties

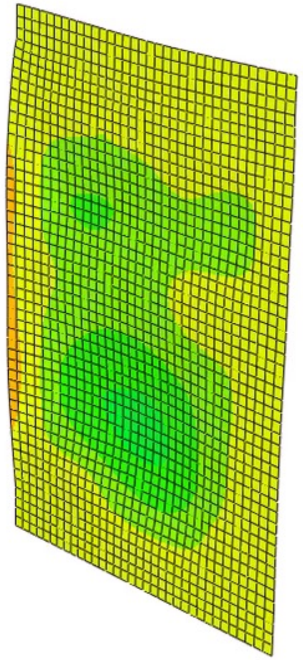
Possibility to compare the experimental and numerical strain (iFEM reconstruction) to perform **damage identification** and localization.

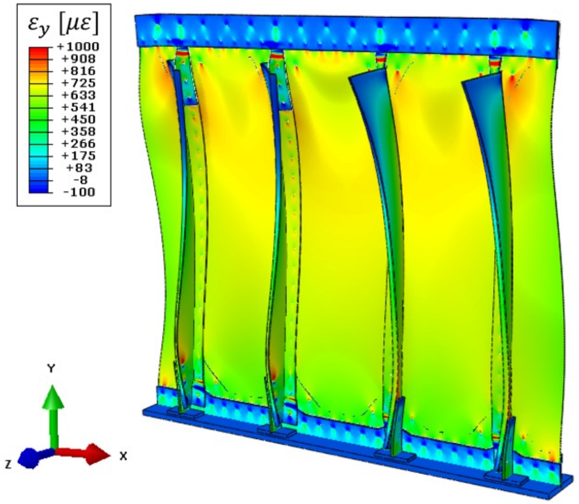
Strain sensor

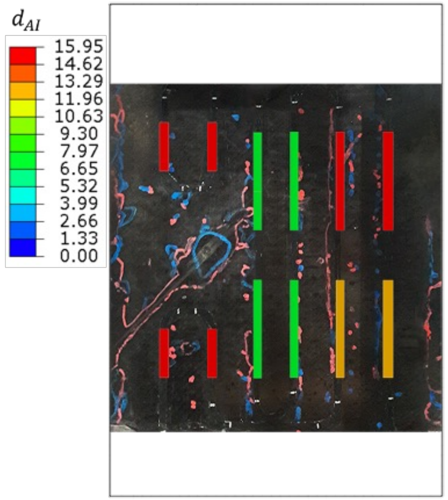
BC



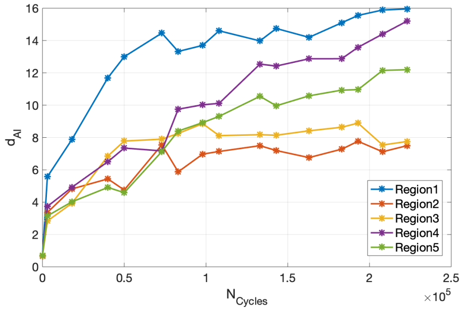
Shape sensing

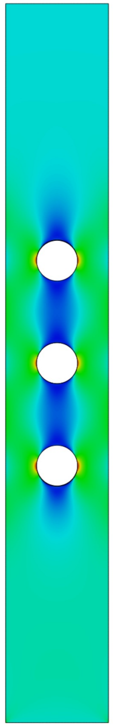






Damage identification & Localization





iFEM for SHM

TITLE: Inverse FEM and Smoothing Element Analysis (SEA) performance optimization for shape sensing

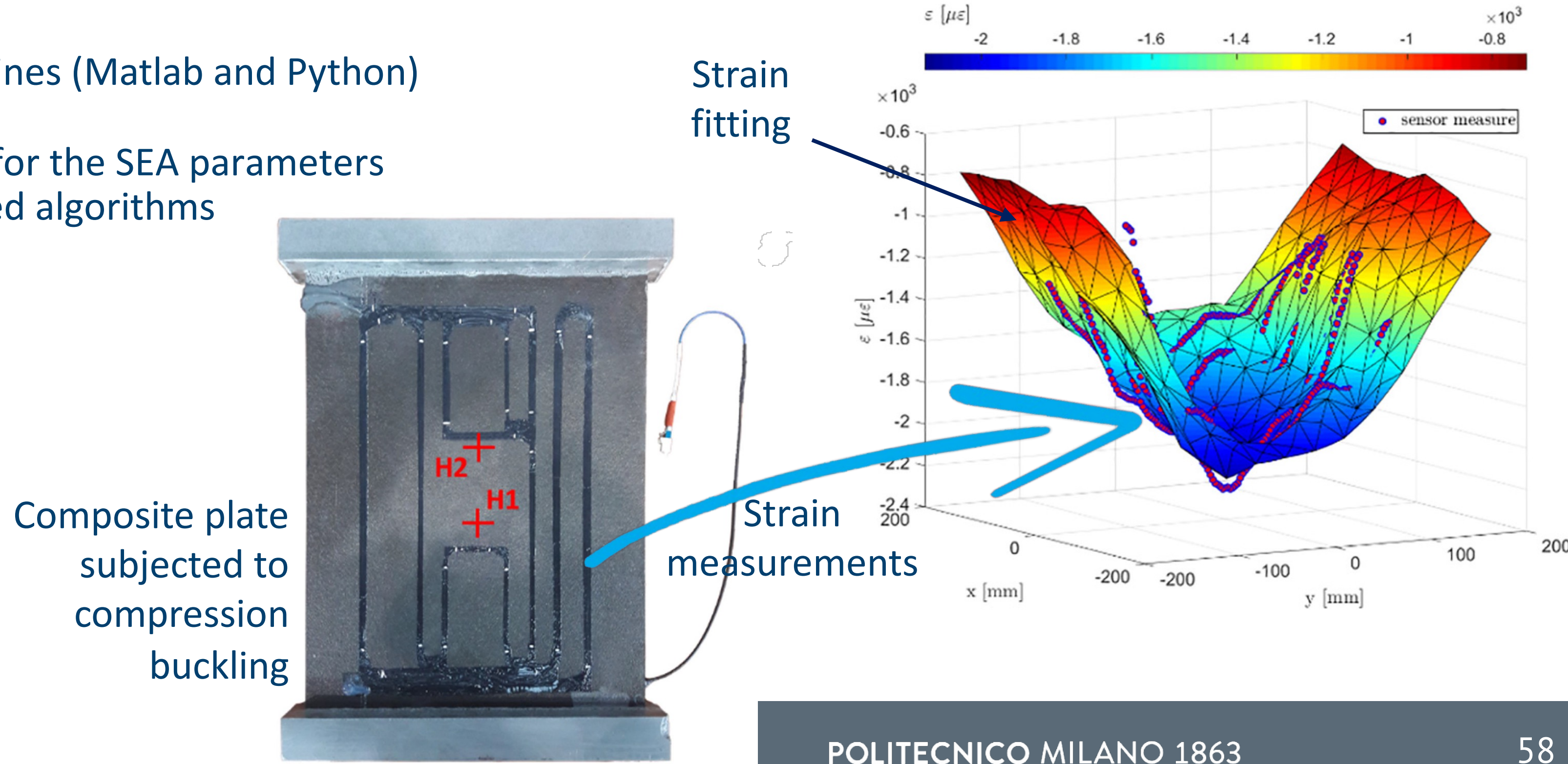
RESEARCH BACKGROUND: The inverse Finite Element Method (iFEM) is a model-based technique to compute the displacement field of a structure from experimental strain measurements. A proper displacement reconstruction requires a large number of sensors, which is not feasible in many real applications due to constraints and cost limitations. For this reason, strain pre-extrapolation techniques (like the SEA) helps in defining the input strain field on the whole structure, also where physical sensors are not available. However, the SEA results are affected by several parameters that have to be optimized for each case study. This work is aimed to develop a systematic optimization process with specific indicators to highlight the quality of the obtained results.

RESEARCH ACTIVITIES:

1. Implementation of iFEM and SEA routines (Matlab and Python)
2. Finite Element Analysis (Abaqus)
3. Definition of an optimization process for the SEA parameters
4. Testing and validation of the developed algorithms

METHODOLOGY: Numerical

DURATION: 9 months



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iFEM for SHM

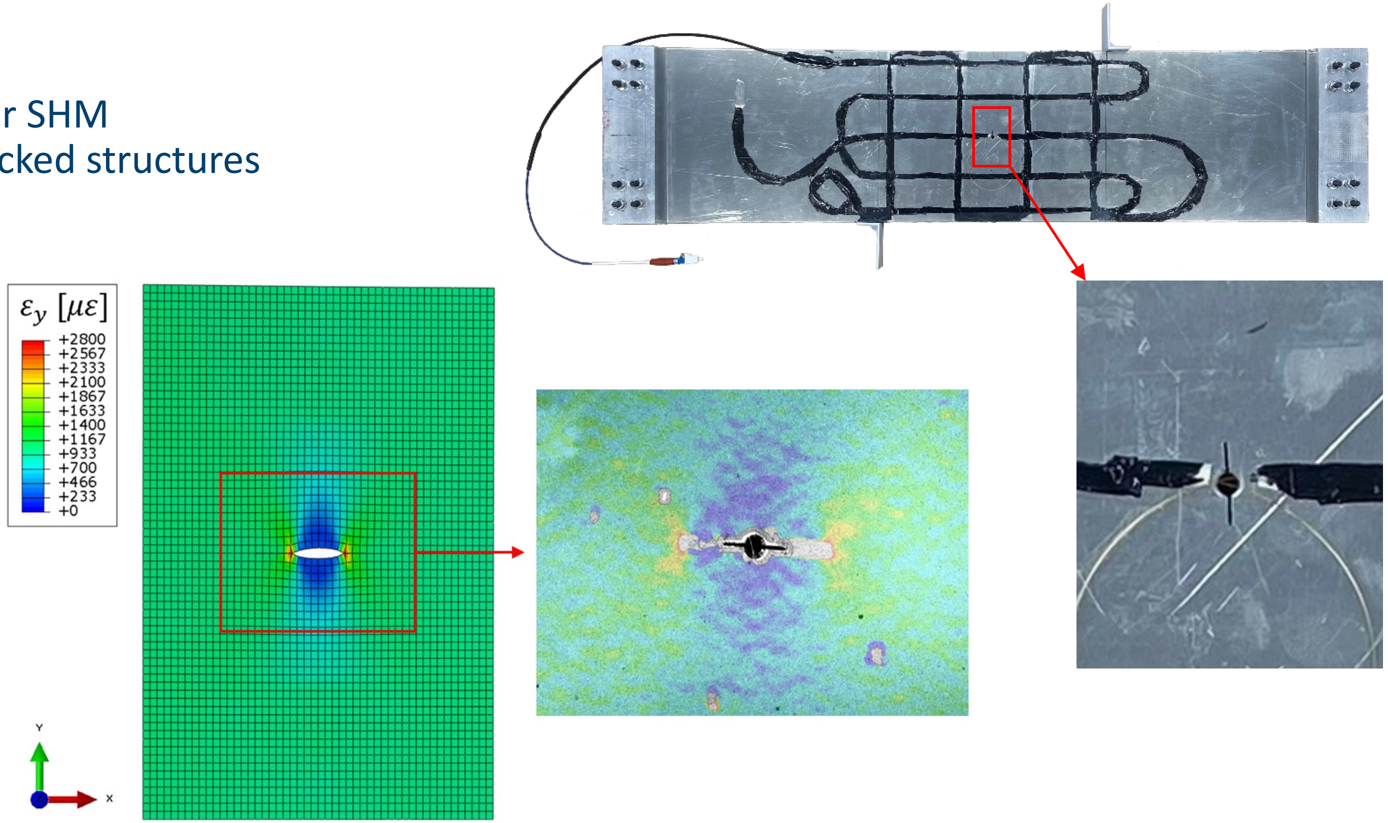
TITLE: Statistical damage diagnosis and prognosis of a cracked structure with inverse FEM

RESEARCH BACKGROUND: The inverse Finite Element Method (iFEM) is a model-based technique to compute the displacement field of a structure from experimental strain measurements. Nowadays, it can be used also is a SHM framework to perform damage detection, however, a proper damage localization and size estimation is still not fully developed. This work aims to extend the iFEM to crack localization and size estimation with statistical approaches.

RESEARCH ACTIVITIES:
1. Implementation of iFEM routines (Matlab and Python) for SHM
2. Finite Element Analysis (Abaqus) for the modelling of cracked structures
3. Testing and validation of the developed algorithms

METHODOLOGY: Numerical, experimental

DURATION: 9 months



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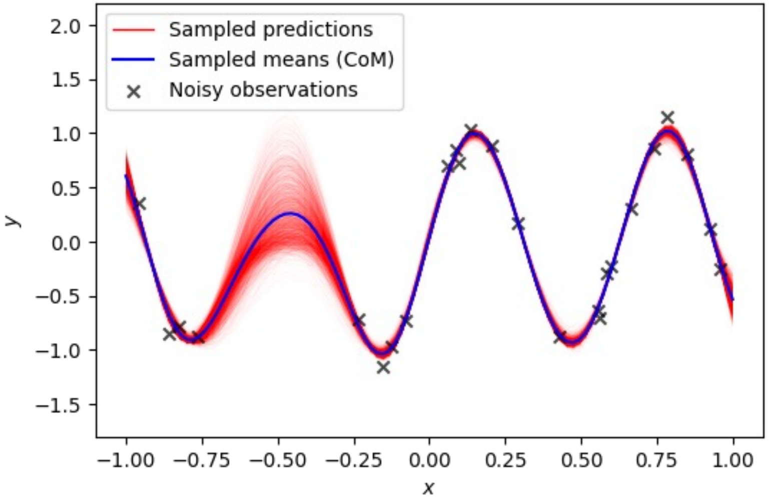
Title: Censored Gaussian Process Regression for non-parametric Bayesian Fatigue Life Estimation

RESEARCH BACKGROUND:
Existing fatigue life prediction model are usually empirical or semi-empirical. Gaussian Process have been proposed as a non-parametric and probabilistic tool to estimate the fatigue life of materials. Censored GP regression should improve fatigue life prediction in the transition region between «finite»-fatigue life and «infinite» fatigue life.



RESEARCH ACTIVITIES:

- Application of Censored Gaussian Process Regression to fatigue-life data with python
- Comparison with state-of-the-art parametric approaches

METHODOLOGY: numerical – analytical

DURATION: 9 months

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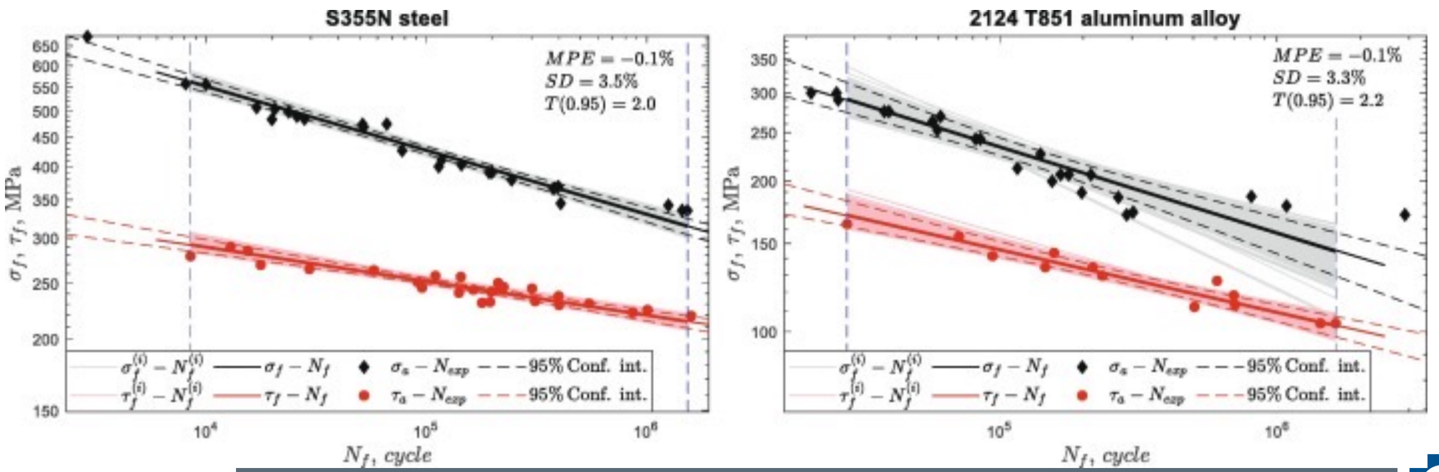
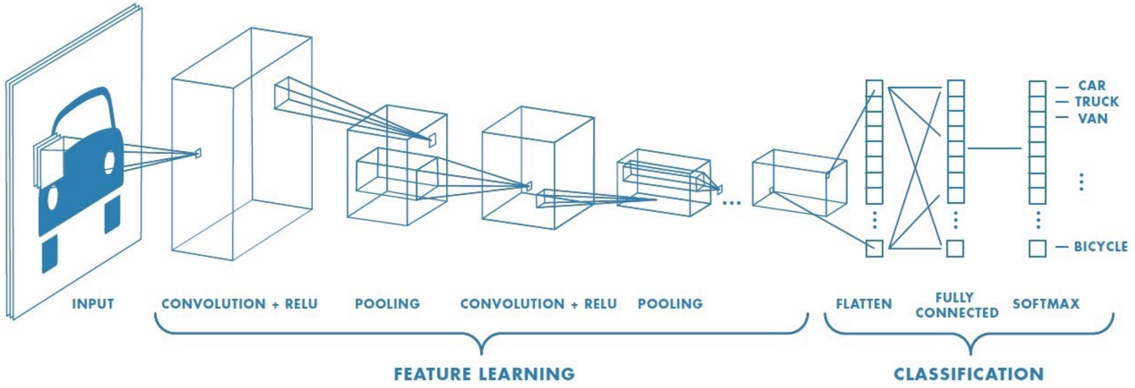


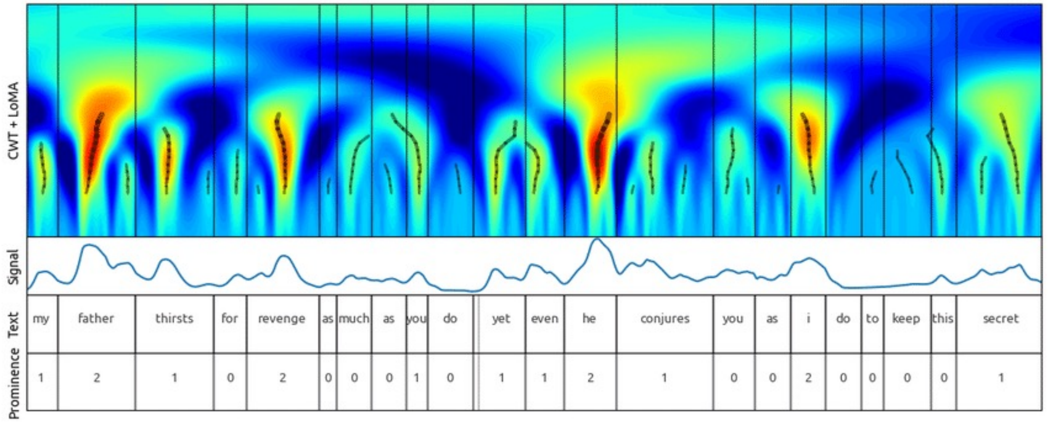
Title: Manoeuver classification and clustering from experimental strain data using Convolutional Neural Networks and Wavelet Transforms

RESEARCH BACKGROUND:
Automatic maneuver classification in aircrafts from strain data is a little researched area which can be useful for classifying operational loads according to the maneuver type, improving the design phylosophy, and for limiting the flight envelope of a damaged aircraft on-line.



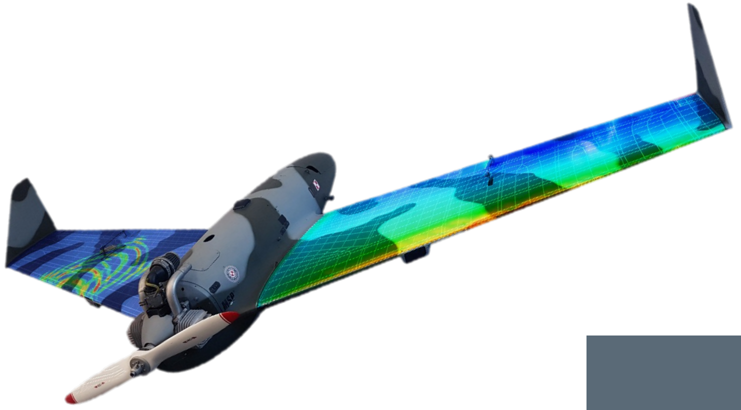
RESEARCH ACTIVITIES:

- Application of Wavelet Transforms to experimental strain data
- Application of a CNN to classify maneuver data



METHODOLOGY: numerical – analytical

DURATION: 9 months



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Title: Probabilistic force localization and reconstruction using a Reversible Jump Markov-Chain Monte Carlo Method

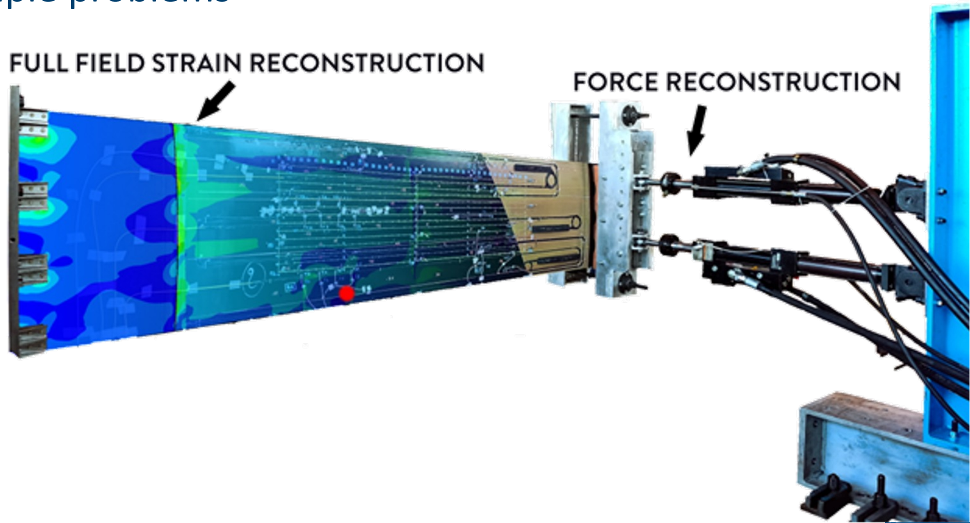
RESEARCH BACKGROUND:
Mechanical and aeronautical structures could experience unexpected loads during operation, potentially reducing their operability. Strain-based load monitoring systems enable the reconstruction of the real load spectra of a structure, providing an estimate of the Residual Usage Life (RUL). Using a RJMCMC, the number of forces, their locations and their magnitude may be estimated in a probabilistic fashion, providing the uncertainties on the RUL. Such monitoring algorithm may also be employed to track objects and events in structures.

RESEARCH ACTIVITIES:

- Application of Reversible-Jump Markov-Chain Monte Carlo Method to naive sample problems
- Application of the RJMCMC to force reconstruction in beams

METHODOLOGY: numerical – analytical

DURATION: 9 months



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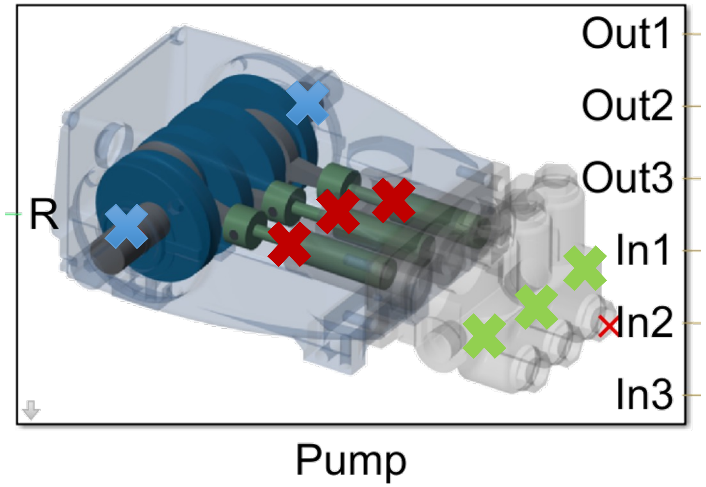
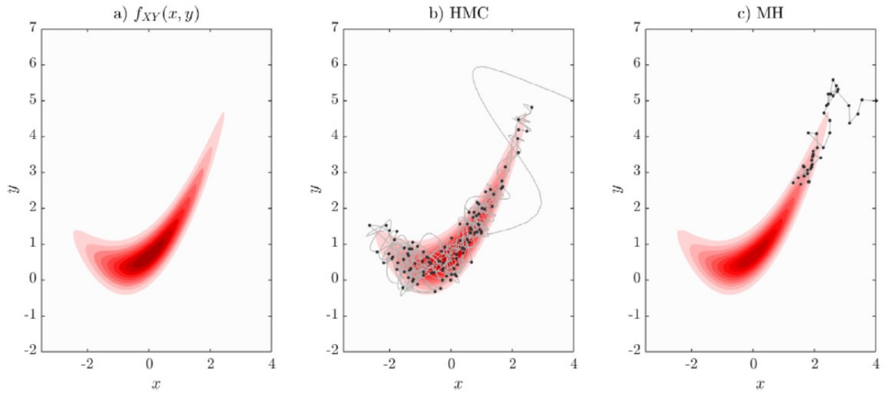
Title: Scalable Hamiltonian Monte Carlo via Surrogate Methods for Digital-Twins



RESEARCH BACKGROUND:
Hamiltonian Monte Carlo coupled with surrogate modelling and random bases may prove to be one of the leading algorithm for uncertainty quantification for models with a large number of parameters. However, so far its application has been limited to some sample problems: hence the need to prove its effectiveness with real-world probability distributions, such as the ones that may arise from a complex Digital-Twin.

RESEARCH ACTIVITIES:

- Application of Hamiltonian Monte Carlo to sample problems
- Application of HMC coupled with surrogate models to estimate complex multi-dimensional distributions with data generated from numerical Digital-Twin for da estimation



METHODOLOGY: numerical – analytical

DURATION: 9 months

CONTACTS:
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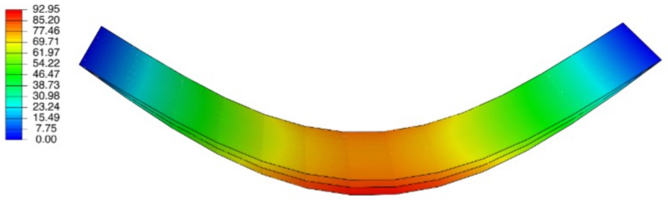
Title: Multivariate Gaussian Process strain extrapolation for iFEM uncertainty quantification

RESEARCH BACKGROUND:

The Inverse Finite Element method (iFEM) employing a network of strain sensors reconstructs the full-field displacement on beam or shell structures, independently of the loading conditions and of the material properties. Current research at SigmaLab is involved in quantifying the uncertainty in the iFEM-reconstructed displacement field, and a Multivariate GP regression may further enhance the sensor network design and reduce the output uncertainty.

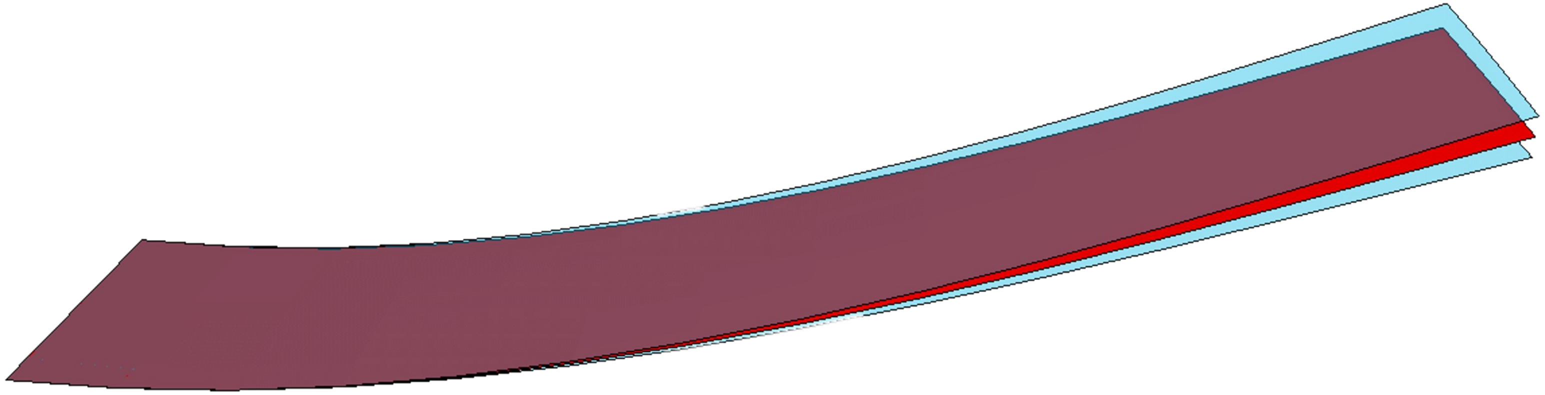


RESEARCH ACTIVITIES:

- Application of a Multivariate Gaussian Process in Python to extrapolate strains in simple shell structures for uncertainty qunatification in iFEM
- Comparison of the proposed technique with the state of the art

METHODOLOGY: numerical – analytical

DURATION: 9 months



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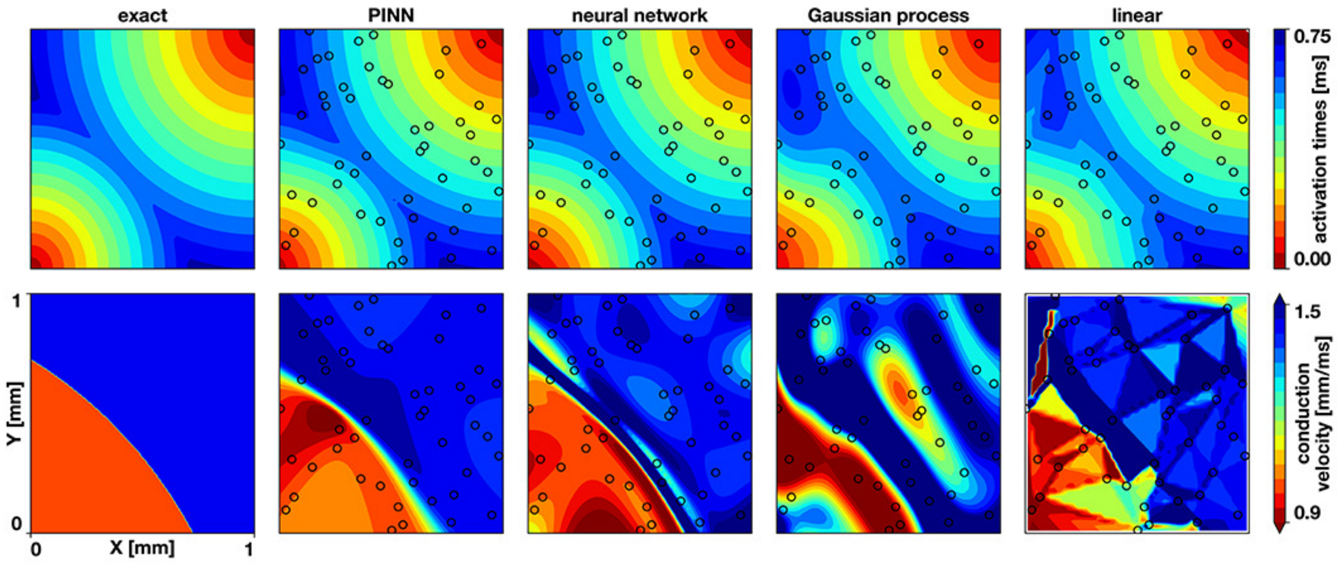
Title: Physics-Constrained nonstationary Gaussian Process

RESEARCH BACKGROUND:
Gaussian process regression has been a well-known machine learning method for various applications such as uncertainty quantifications. Incorporating physics-based constraint in the Gaussian Process kernel should improve state-of-the-art surrogate modelling techniques and may reduce the computational size and time required to solve Partial Differential Equations problems, e.g. improving the well-known Finite Element Method.

RESEARCH ACTIVITIES:

- Literature research on state-of-the-art techniques
- Application of Physics-Constrained nonstationary Gaussian Processes to analytic functions to improve surrogate modeling techniques



METHODOLOGY: numerical – analytical

DURATION: 9 months

CONTACTS:
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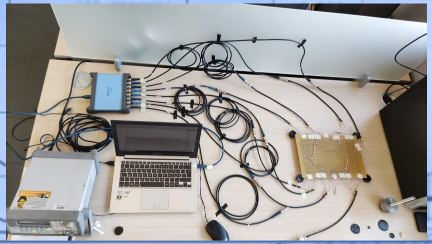
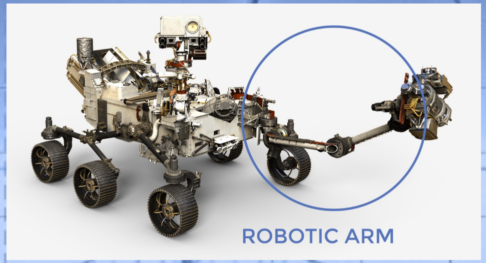
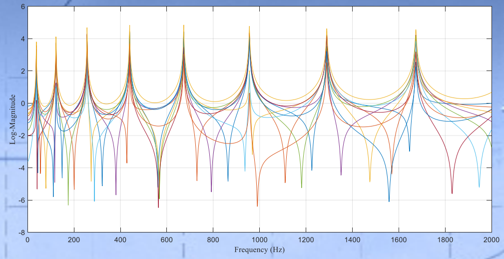
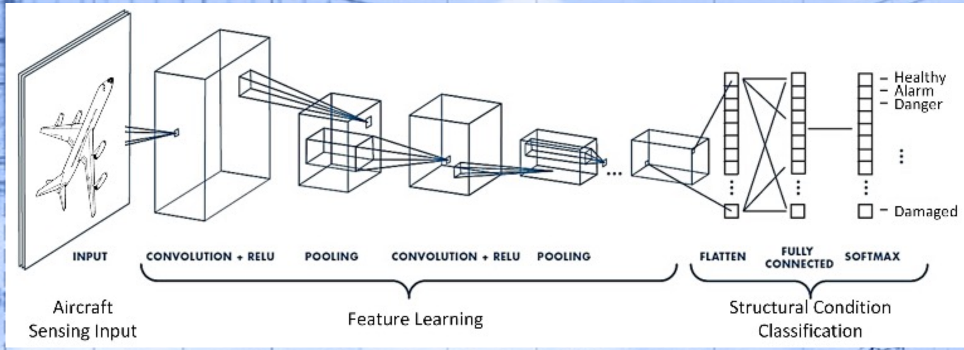
dario.poloni@polimi.it
marco.giglio@polimi.it

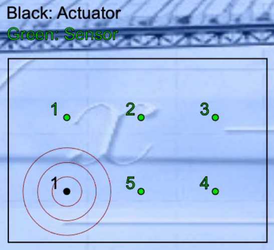
Artificial intelligence and machine learning for system integrity

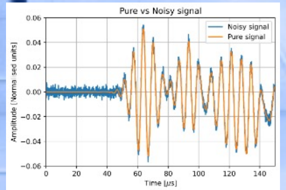


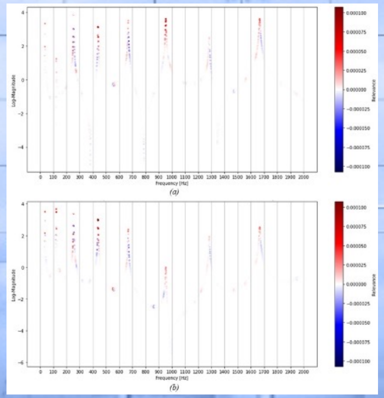












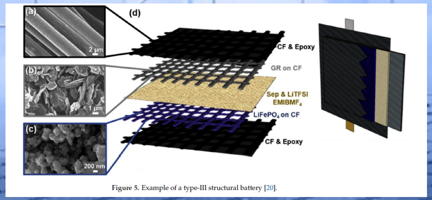
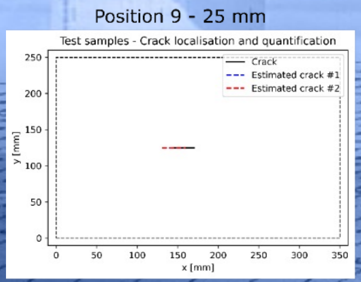
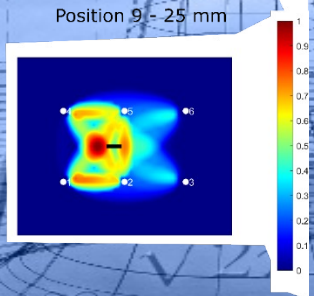
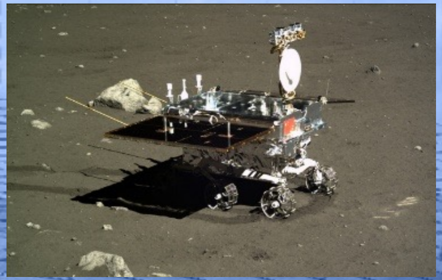


Figure 5. Example of a type-III structural battery [20].







Research lines and projects

- **Artificial intelligence** and **Machine Learning** for Structural Health Monitoring (**SHM**)

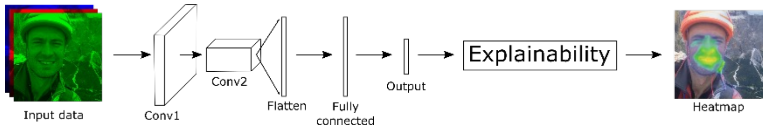
- **Projects**: combination of **digital twin** modeling and machine learning for prognostics and health management (**PHM**)

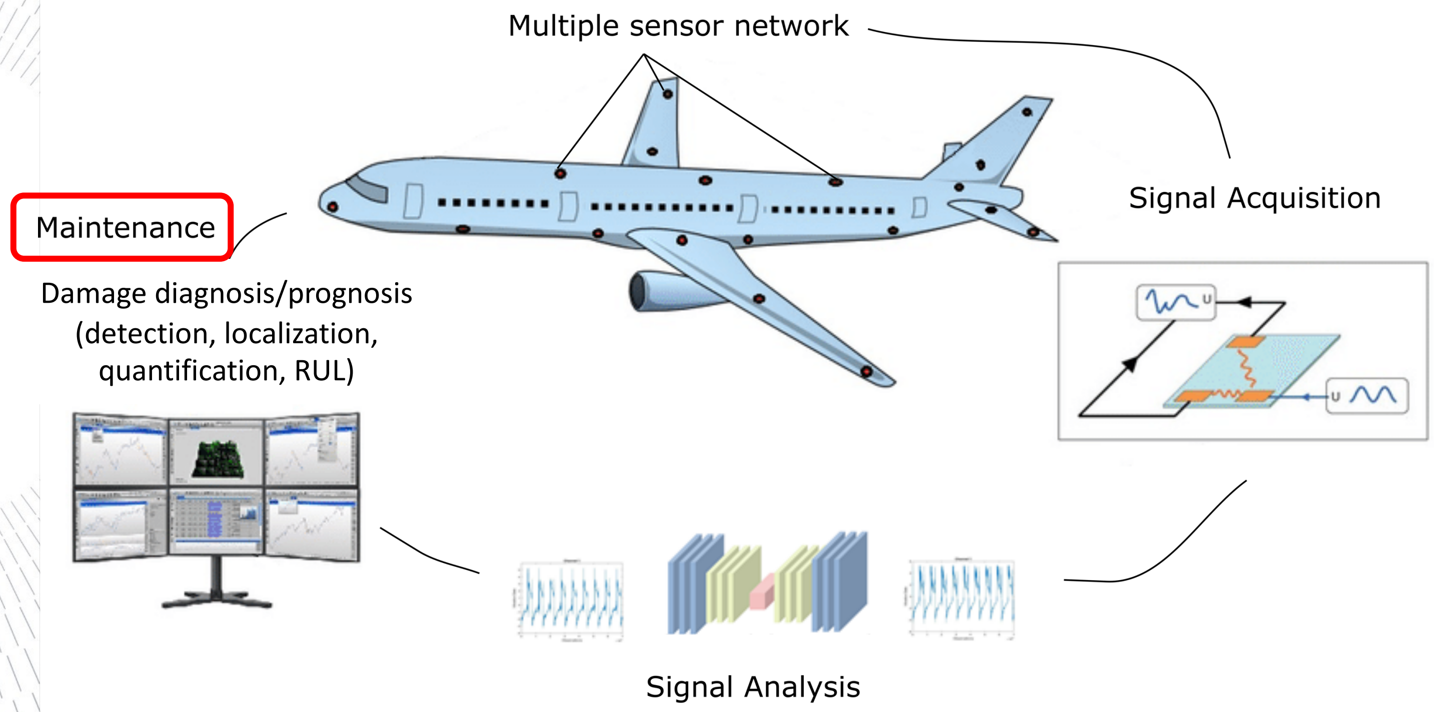
Research lines and projects

- **Artificial intelligence** and **Machine Learning** for Structural Health Monitoring (**SHM**)

- **Projects**: combination of **digital twin** modeling and machine learning for prognostics and health management (**PHM**)

Deep Learning for Structural Health Monitoring (SHM)





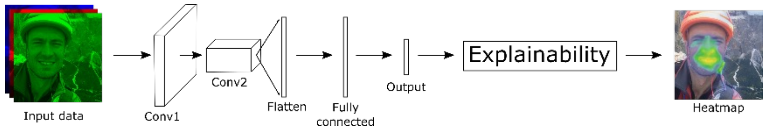
Sense signals

Process signals

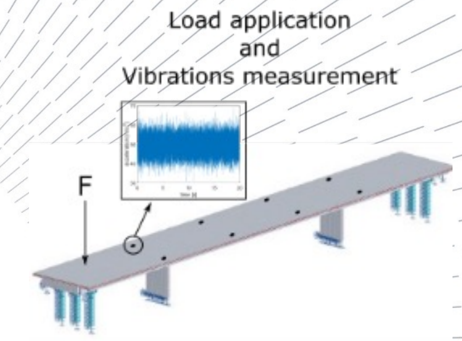
AI driven damage diagnosis/prognosis

Explain!

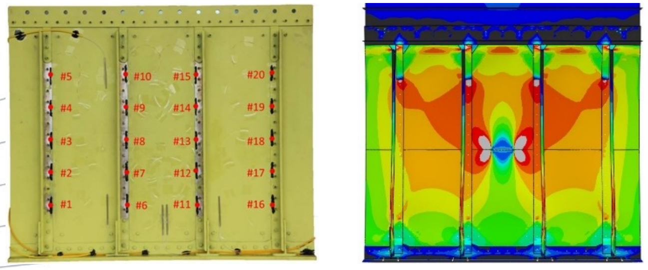
Deep Learning for Structural Health Monitoring (SHM)



Structural vibrations

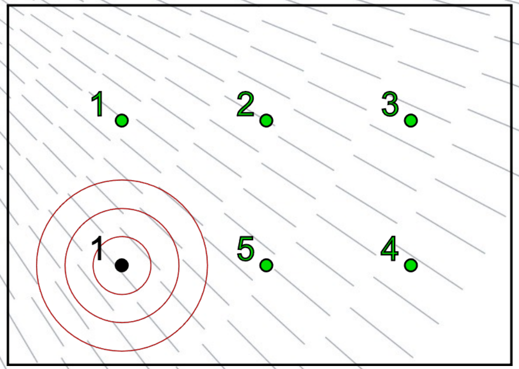


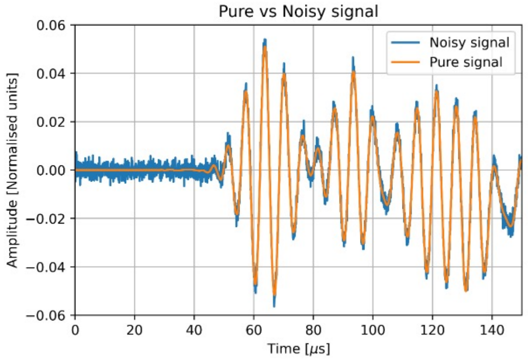
Strain field



Elastic waves

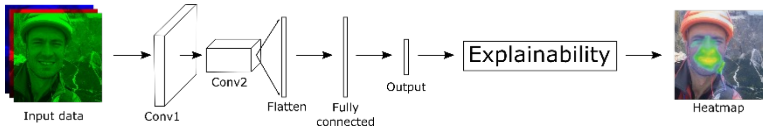
Black: Actuator
Green: Sensor



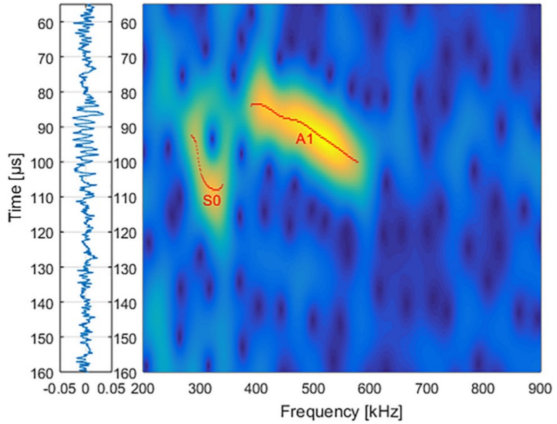


Sense signals → Process signals → AI driven damage diagnosis/prognosis → **Explain!**

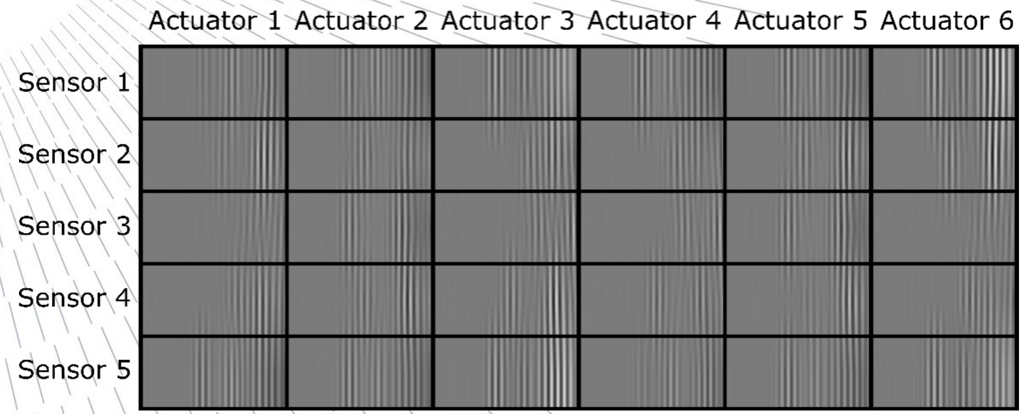
Deep Learning for Structural Health Monitoring (SHM)



Time and/or frequency domain



Prepare data for ML



Sense signals

↓

Process signals

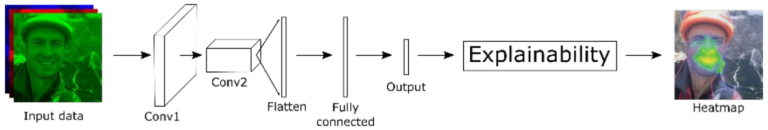
↓

AI driven damage diagnosis/prognosis

↓

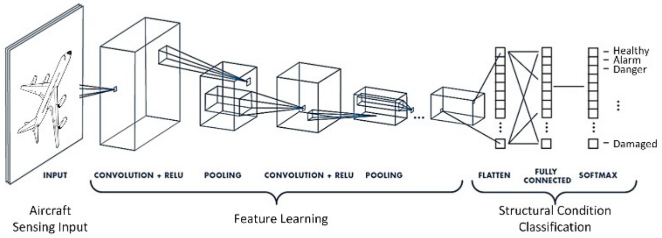
Explain!

Deep Learning for Structural Health Monitoring (SHM)



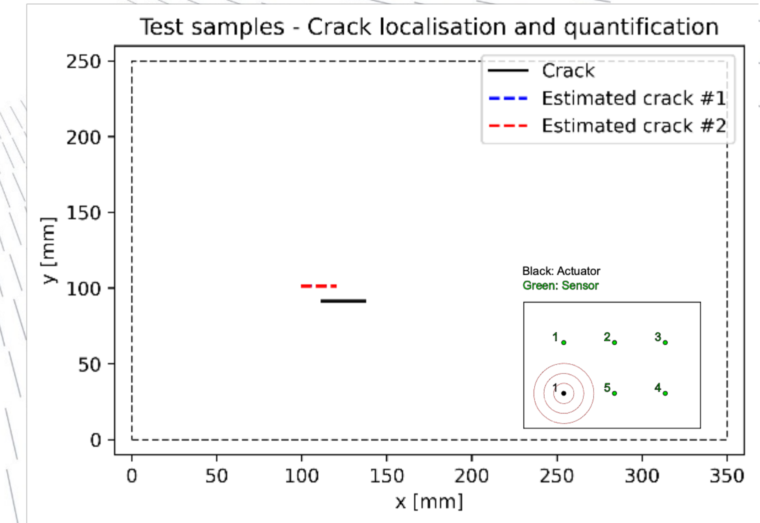
Deep Neural networks

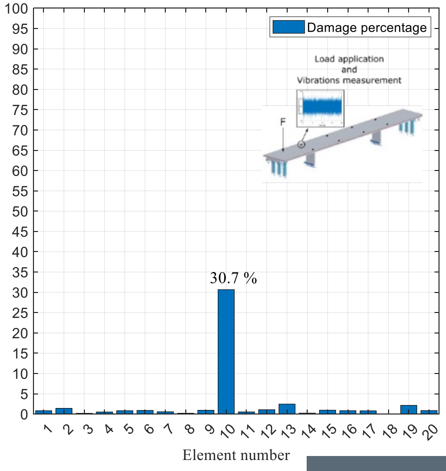
Convolutional Neural Networks (CNNs), Autoencoders, etc.



Detection, localisation and quantification

Position 2 - 25 mm





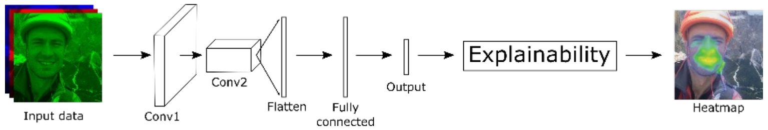
Sense signals

Process signals

AI driven damage diagnosis/prognosis

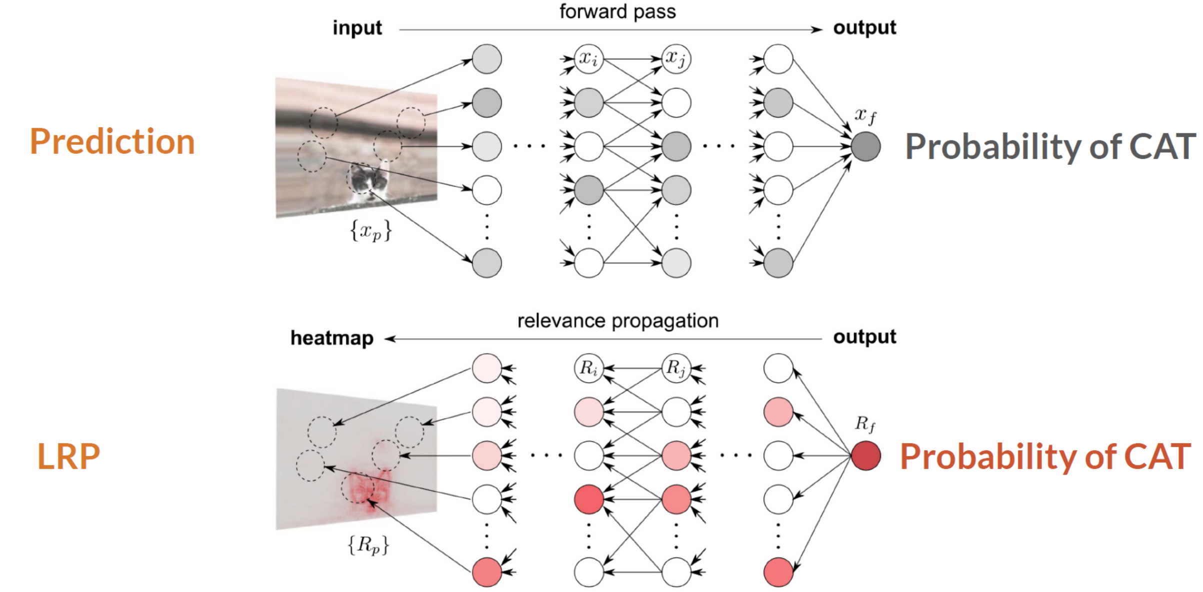
Explain!

Deep Learning for Structural Health Monitoring (SHM)



1. Pure signals are considered, no feature extraction
2. Intelligent unique framework for damage diagnosis
3. **Explainability** of the artificial intelligence methods involved (LRP algorithm)

Layer-wise Relevance Propagation [LRP]



Sense signals

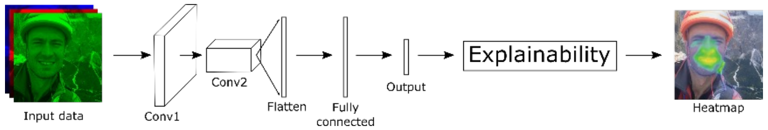
Process signals

AI driven damage diagnosis/prognosis

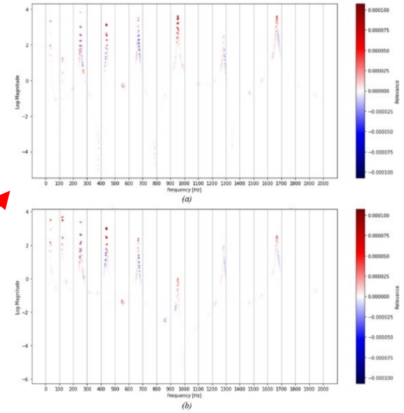
Explain!

SIGMA Lab

Deep learning in SHM and beyond



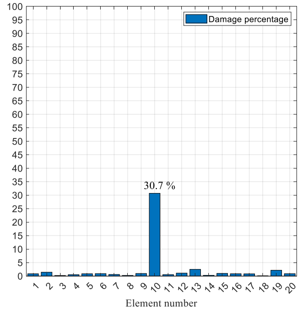
Topic: Deep learning for transmissibility-based SHM



TITLE: Development of a supervised and/or unsupervised deep learning-based framework to perform damage diagnosis based on vibration measurements (transmissibilities)

RESEARCH BACKGROUND:

Supervised machine learning methods are currently used to process vibration measurements for damage diagnosis with satisfactory performance. However, additional research is required to decrease the level of supervision (the amount of training data) required by deep learning approaches to achieve more sophisticated diagnosis goals (such as localization and quantification)



RESEARCH ACTIVITIES:

1. Deep learning techniques to process vibrational data
2. Development of a smart SHM framework for damage diagnosis
3. **Explainability** algorithms

METHODOLOGY: analytical - numerical

DURATION: 7-9 months

CONTACTS:

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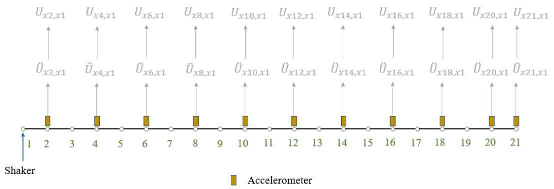
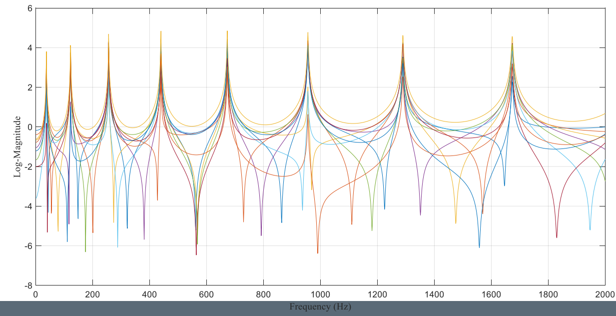
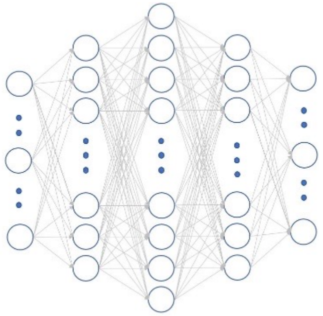
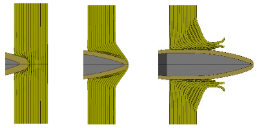
marco.giglio@polimi.it

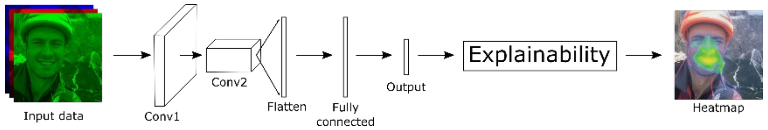






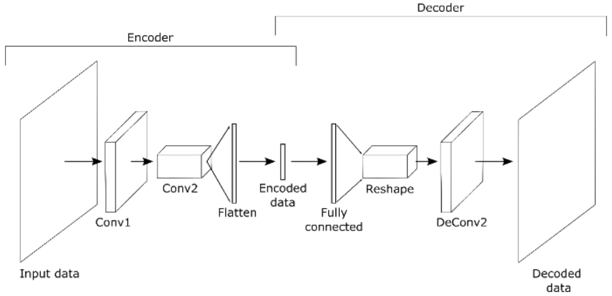
Deep learning in SHM and beyond





Topic: Deep learning for ultrasonic guided waves processing in composites

TITLE: Development of supervised deep learning-based methods for damage diagnosis on composite and hybrid plates



RESEARCH BACKGROUND:

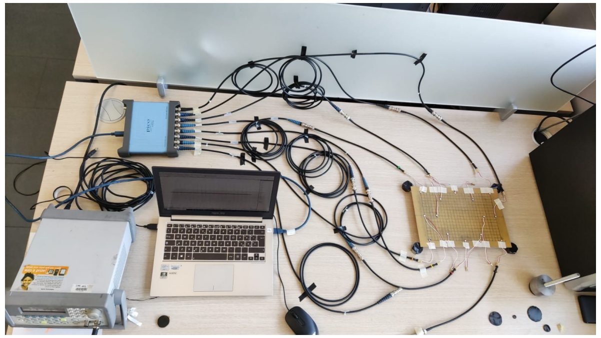
Supervised machine learning methods are currently used to process ultrasonic guided waves for damage diagnosis with satisfactory performance. Testing some of these methods, including in-house algorithms, on experimental databases represents the next step towards their large-scale deployment

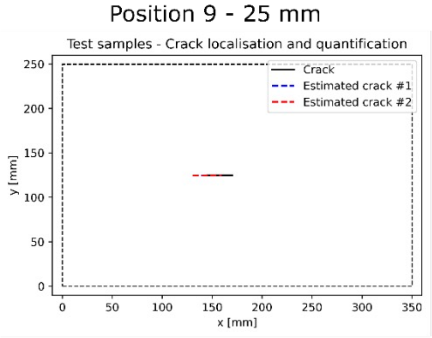
RESEARCH ACTIVITIES:

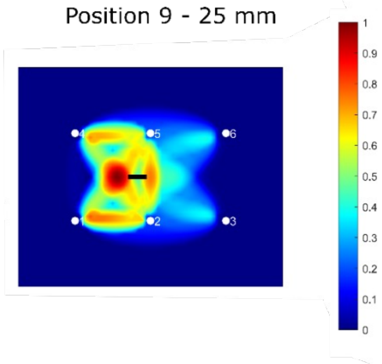
1. Experimental tests on composite and/or hybrid plates subjected to low velocity impact
2. Development of a **supervised (num. and/or exp.)** framework for damage diagnosis
3. Test of the supervised framework on the experimental data acquired in task 1
4. Comparison **num. and/or exp.**
5. **Explainability** algorithms

METHODOLOGY: Experimental – Numerical

DURATION: 7-9 months







CONTACTS:

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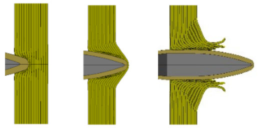
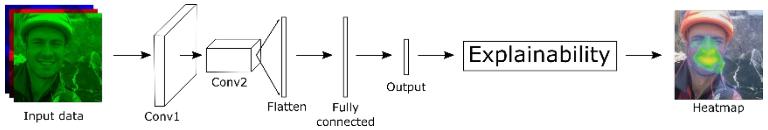
andrea.manes@polimi.it

Deep learning in SHM and beyond

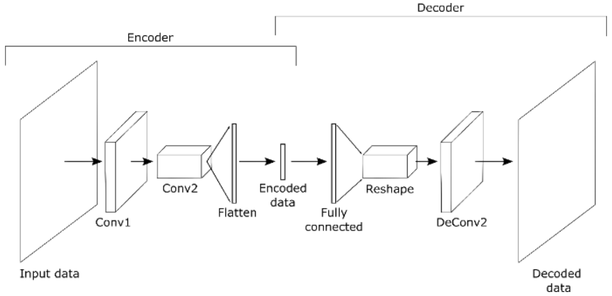




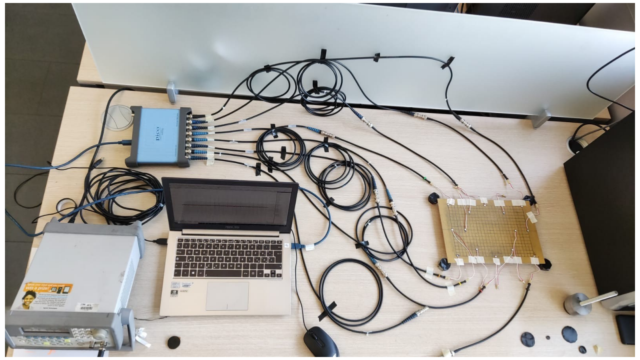
Topic: Deep learning for ultrasonic guided waves processing in composites

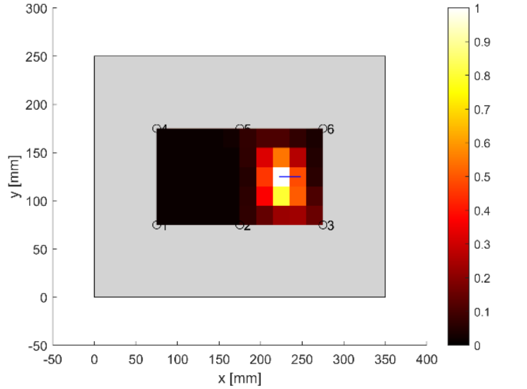
TITLE: Development of unsupervised deep learning methods for damage diagnosis on composite and hybrid plates

RESEARCH BACKGROUND:
Unsupervised machine learning methods are typically employed to overcome limitations of supervised approaches. In the field of ultrasonic guided wave-based damage diagnosis, an in-house unsupervised algorithm has been developed. Testing this method on experimental databases would allow proving and further improving its capabilities.



RESEARCH ACTIVITIES:
1. Experimental tests on composite and/or hybrid plates subjected to low velocity impact
2. Development of an **unsupervised** framework for damage diagnosis
3. Test of the unsupervised framework on the experimental data acquired in task 1
4. **Comparison with supervised approaches**
5. **Explainability** algorithms



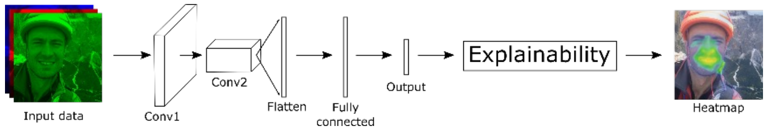


METHODOLOGY: Experimental – Numerical

DURATION: 7-9 months

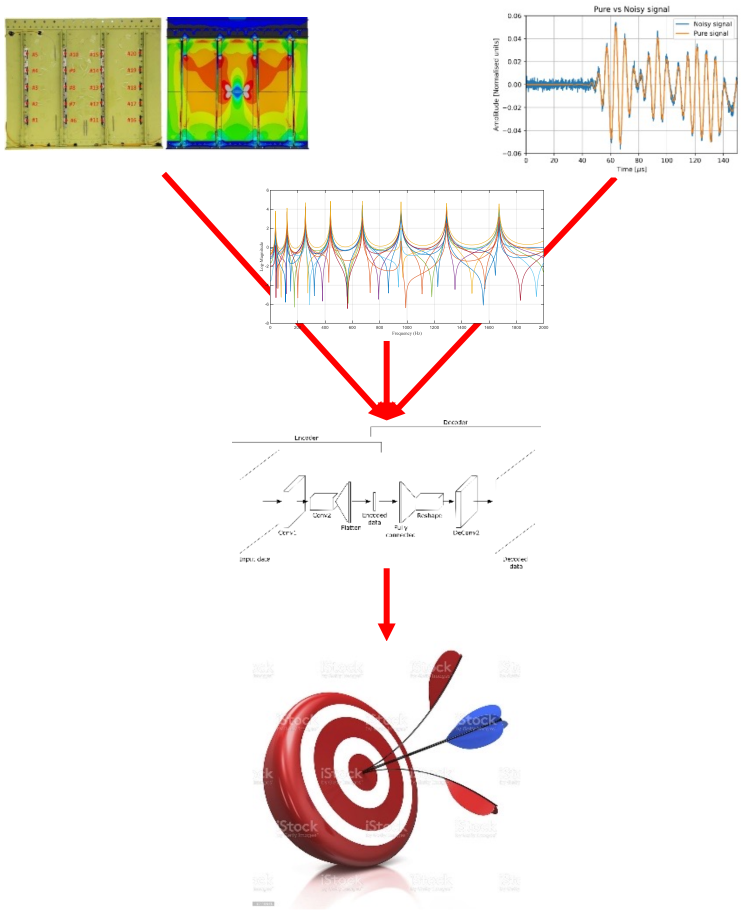
CONTACTS:
francesco.cadini@polimi.it
andrea.manes@polimi.it

Deep learning in SHM and beyond



Topic: Data fusion and deep learning

TITLE: Development of deep learning methods for damage diagnosis exploiting data fusion techniques



RESEARCH BACKGROUND:
Often, deep learning approaches for SHM and PHM in general stems from a single measurement type (either strains, or Lamb waves, or vibrations, etc.). Data fusion is actually expected to improve accuracy and precision of predictions

RESEARCH ACTIVITIES:
1. Experimental tests on composite
2. Development of **data fusion deep learning** frameworks for damage diagnosis
3. **Comparison with mono-measurement approaches**
4. **Explainability** algorithms

METHODOLOGY: Experimental – Numerical

DURATION: 7-9 months

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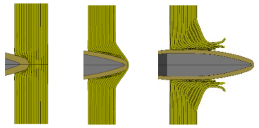
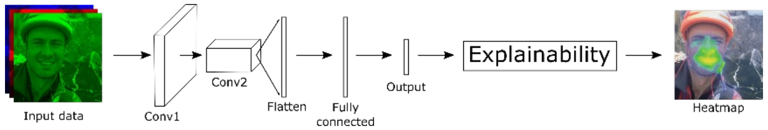
Deep learning in SHM and beyond

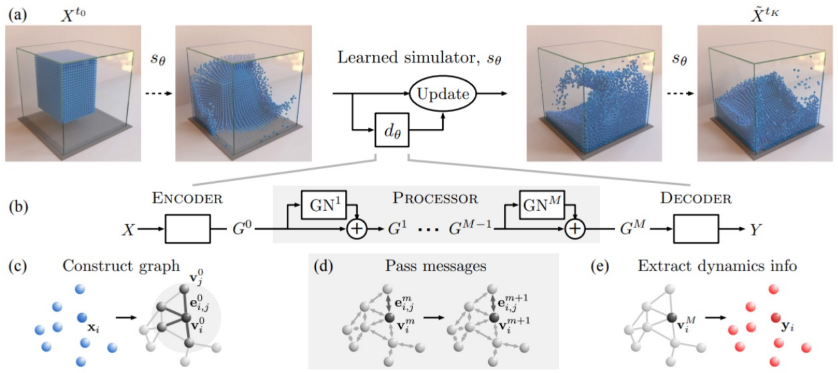




Topic: Efficient and Explainable deep learning

TITLE: Efficient and explainable <u>deep graph neural networks</u> to numerically simulate complex phenomena

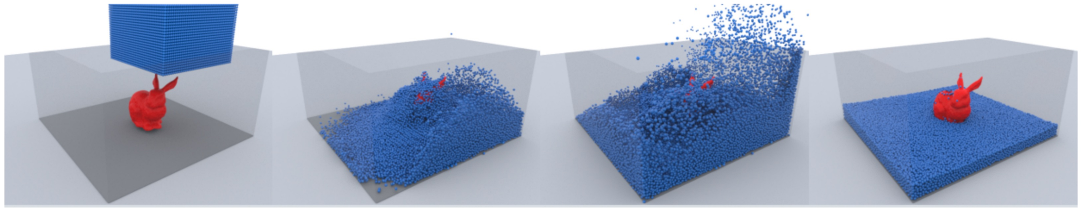
RESEARCH BACKGROUND:
Simulating complex phenomena such as structural and fluid dynamics requires expensive simulations. State-of-the-art machine learning methods may be used to create faster, yet accurate, simulation methods.



RESEARCH ACTIVITIES:
1. Introduction to ***graph neural networks*** (GNNs)
2. Application of GNNs to simple case studies
3. Development of GNNs to simulate the propagation of ***ultrasonic guided waves in solid media***

METHODOLOGY: Analytical – Numerical

DURATION: 7-9 months



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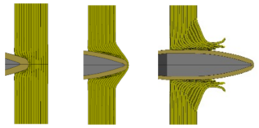
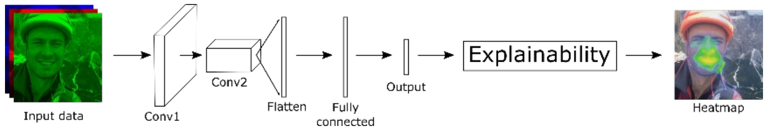
marco.giglio@polimi.it

Deep learning in SHM and beyond



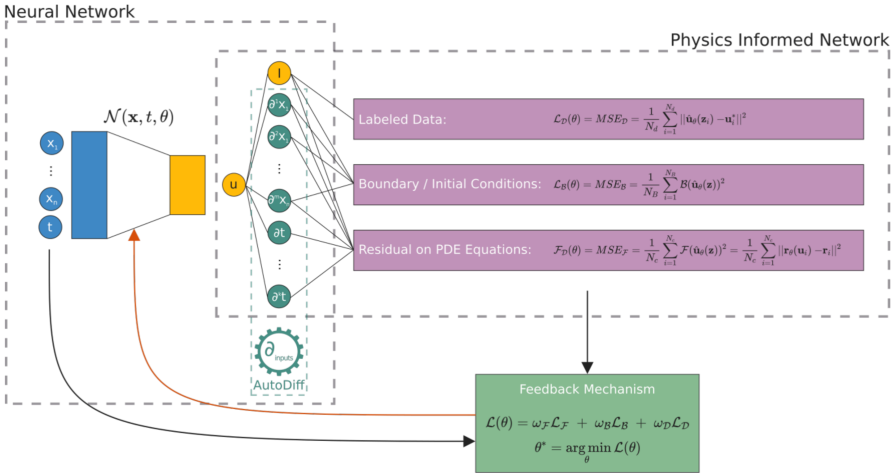


Topic: Efficient and Explainable deep learning

TITLE: Physics-informed deep neural networks to account for the physics governing ultrasonic guided waves propagation and interaction with damage

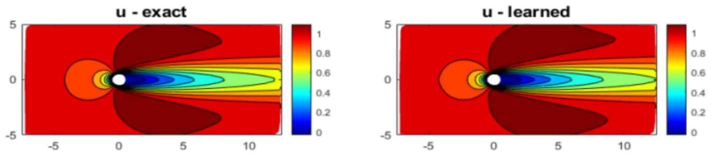
RESEARCH BACKGROUND:

Machine learning methods usually fully rely on data to provide outputs, thus not necessarily sticking to the physics underlying complex phenomena. However, in case governing equations of problems of interest are known, these may be exploited to improve the performance of machine learning methods



RESEARCH ACTIVITIES:

1. Introduction to ***physics-informed neural networks*** (PINNs)
2. Application of PINNs to simple case studies
3. Development of PINNs to describe ***ultrasonic guided waves*** propagation and interaction with damage



METHODOLOGY: Analytical – Numerical

DURATION: 7-9 months

CONTACTS:

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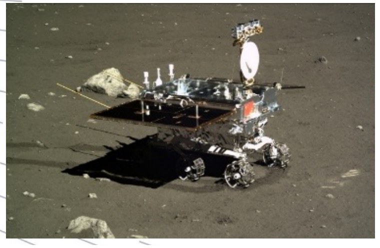
andrea.manes@polimi.it
marco.giglio@polimi.it

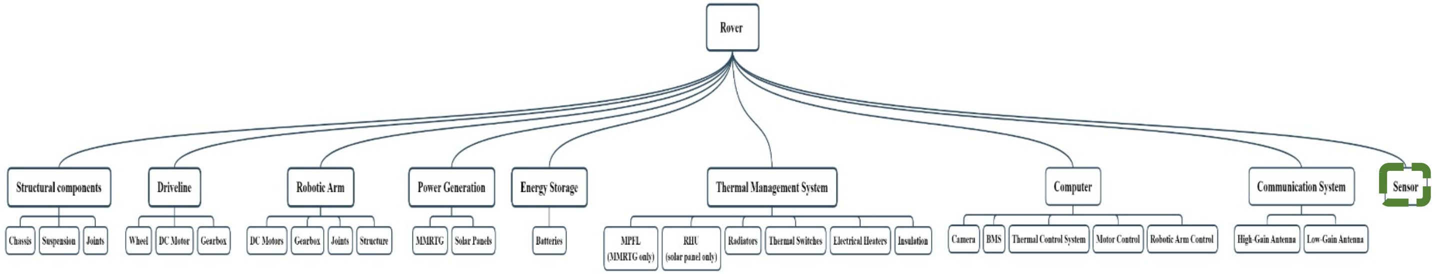
- **Artificial intelligence** and **Machine Learning** for Structural Health Monitoring (**SHM**)

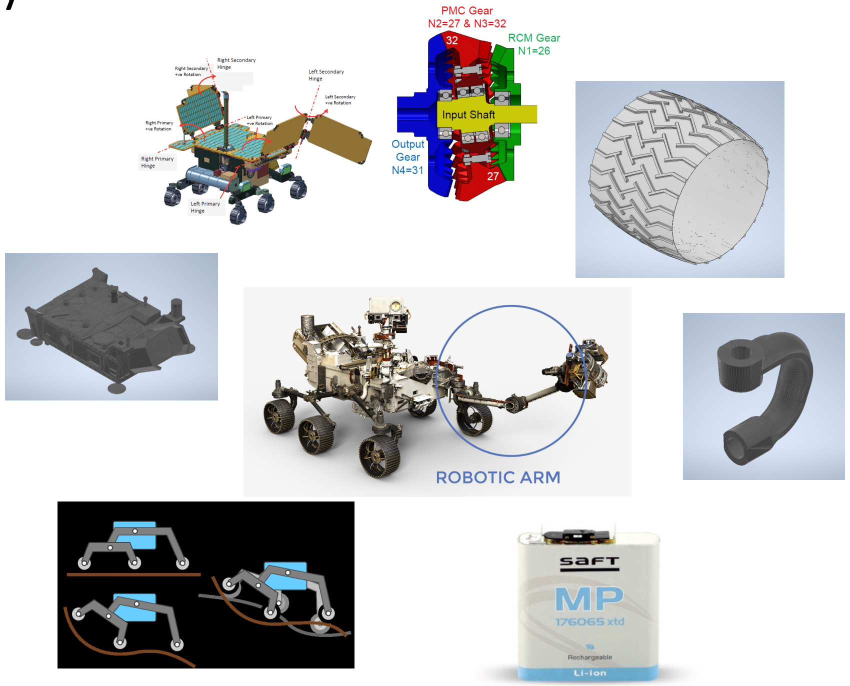
- **Projects**: combination of **digital twin** modeling and machine learning for prognostics and health management (**PHM**)

DIGES - DIGital twin di sistemi di ESplorazione lunare (DIGES)

- **Objective**: development of an efficient HUMS strategy for a potential **rover for Lunar exploration** based on
  - ✓ **Digital twin (DT) multi-physics** modelling (healthy and anomalous conditions)
  - ✓ **Surrogate modeling** (machine learning-based) for DT efficiency
  - ✓ **Machine learning** for signal processing (SHM oriented)







SIGMA Lab

DIGES

Topic: Machine learning-based efficient digital twin modelling for faster

TITLE: Surrogate modelling of a lunar rover **Digital Twin** for **real-time operations**

RESEARCH BACKGROUND:

Surface exploration of planets and satellites with rovers is the trending topic of space exploration. Rovers' complexity and costs require high reliability since anomalies or component degradation may compromise the mission. In this framework, it is possible to develop a Digital Twin (DT) of the rover to simulate its behaviour and its subsystems.

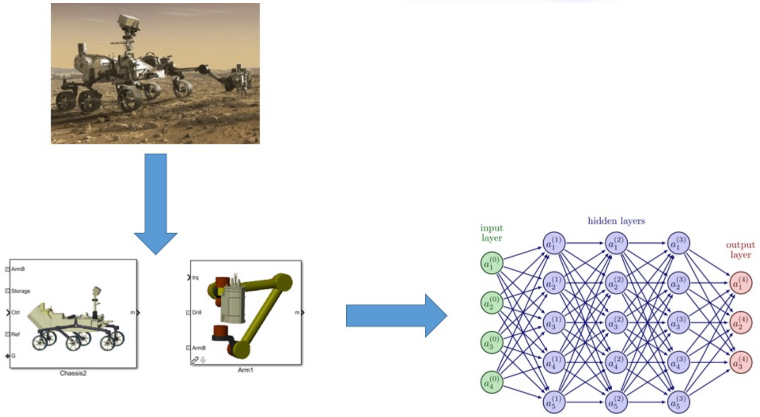
A continuous and real-time comparison between the DT model and the real system will allow a more efficient operational management of the space system, coupling the models with artificial intelligence algorithms. The DT must be characterized by a relatively low computational weight, allowing its real-time usability. This can be achieved by exploiting the potential of machine learning-based surrogate models.

RESEARCH ACTIVITIES:

1. Bibliographic analysis of state-of-art of rovers, DT and surrogate modelling
2. System modelling on **Simulink-Simscape**
3. Choice and optimization of Machine Learning algorithms for surrogate modelling
4. Development of a simplified scenarios to test the developed framework

METHODOLOGY: Numerical – Experimental

DURATION: 7-9 months



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POSSIBLE COLLABORATIONS: ASI

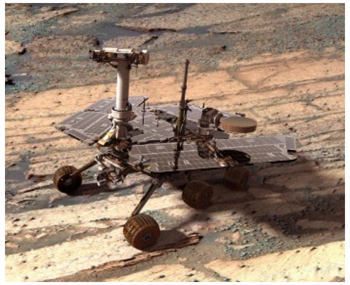
DIGES

Topic: Healthy and damaged conditions modelling and simulation

TITLE: Integration of **anomalies** and **degradations** in a lunar rover **Digital Twin** for performing **damage diagnosis**

RESEARCH BACKGROUND:

Surface exploration of planets and satellites with rovers is the trending topic of space exploration. Rovers' complexity and costs require high reliability since anomalies or component degradation may compromise the mission. In this framework, it is possible to develop a Digital Twin (DT) of the rover to simulate its behaviour and its subsystems. The implementation of anomalies in the DT, before the real-time operations, allows for creating a database of defects and their consequences. This can be used during the mission to perform a diagnosis of the rover, that is the identification of defects and their position and extent. The following step can be the prognosis. The latter estimates the Residual Useful Life (RUL) and the implementation of actions to address or mitigate the anomaly relying upon damage evolution collected data and physics-based damage evolution model



RESEARCH ACTIVITIES:

1. Bibliographic analysis of state-of-art of rovers, DT and damage implementation
2. DT modelling Simulink-Simscape and damage implementation
3. Development of a simplified scenarios to generate datasets

METHODOLOGY: Numerical – Experimental

DURATION: 7-9 months

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POSSIBLE COLLABORATIONS: ASI

DIGES

Topic: Heat rejection system modelling and analysis

TITLE: Development of a **Digital Twin** of a lunar rover **Heat Rejection System** for performing **damage diagnosis**

RESEARCH BACKGROUND:

Surface exploration of planets and satellites with rovers is the trending topic of space exploration. Rovers' complexity and costs require high reliability since anomalies or component degradation may compromise the mission. In this framework, it is possible to develop a Digital Twin (DT) of the rover to simulate its behaviour and its subsystems.

Among the latter, the heating/cooling system (Heat Rejection System, HRS) is crucial for the completion of the mission due to the extreme temperatures of the working environment concerning the working temperature range of electronics, motors, batteries, etc. Therefore, the development of a DT will allow a more efficient thermal management of the rover itself, avoiding reaching extreme working temperatures that will cause the mission failure.

RESEARCH ACTIVITIES:

1. Bibliographic analysis of state-of-art of rover HRS, DT and damage implementation
2. Lunar rover HRS modelling on **Simulink-Simscape** and **damage implementation**
3. Development of simplified scenarios to generate datasets

METHODOLOGY: Numerical – Experimental

DURATION: 7-9 months

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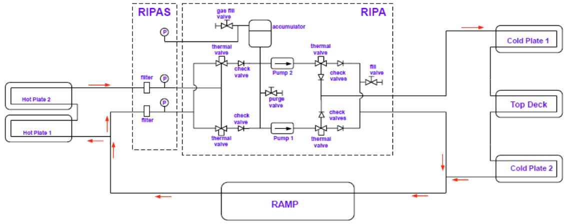
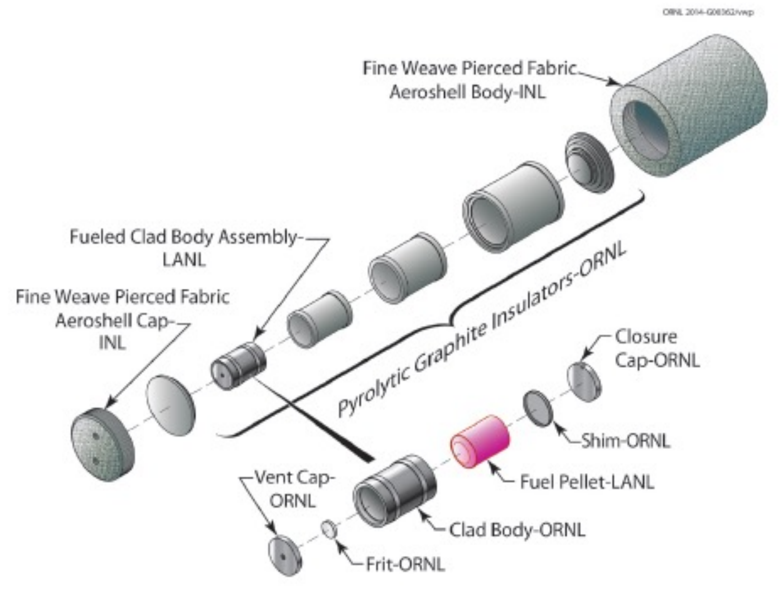
POSSIBLE COLLABORATIONS: ASI





DIGES

Topic: Power harvesting and storage systems modelling and analysis

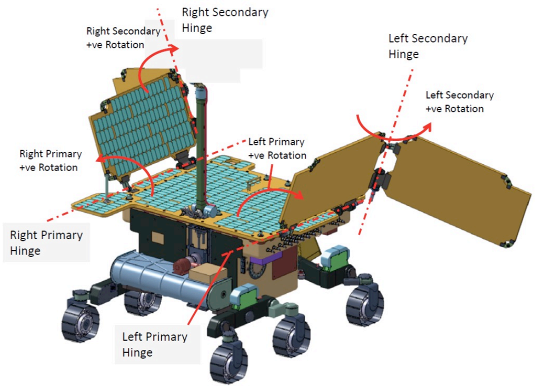
TITLE: Development of a **Digital Twin** of a lunar rover **power harvesting and storage system**

RESEARCH BACKGROUND:

Surface exploration of planets and satellites with rovers is the trending topic of space exploration. Rovers' complexity and costs require high reliability since anomalies or component degradation may compromise the mission. In this framework, it is possible to develop a Digital Twin (DT) of the rover to simulate its behaviour and its subsystems. The heart of the rover is the power harvesting and storage system. Considering a rover with solar arrays, the latter generates the electric power needed for the rover while the batteries are necessary when the sunlight can't provide the energy required by the payloads. However, both batteries and solar array performances are well known to decay with time and for this reason, a diagnosis system is fundamental to maximize the rover's life.

RESEARCH ACTIVITIES:

1. Bibliographic analysis of state-of-art of rover solar array and batteries, DT and damage implementation
2. Solar array and batteries modelling in Simulink-Simscape, including their interactions and Battery Thermal Management System (BTMS)
3. Development of simplified scenarios in various working conditions (temperature/irradiance/payloads)
4. Detection of battery damages (ISC/over-discharging)



METHODOLOGY: Numerical – Experimental

DURATION: 7-9 months

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POSSIBLE COLLABORATIONS: ASI

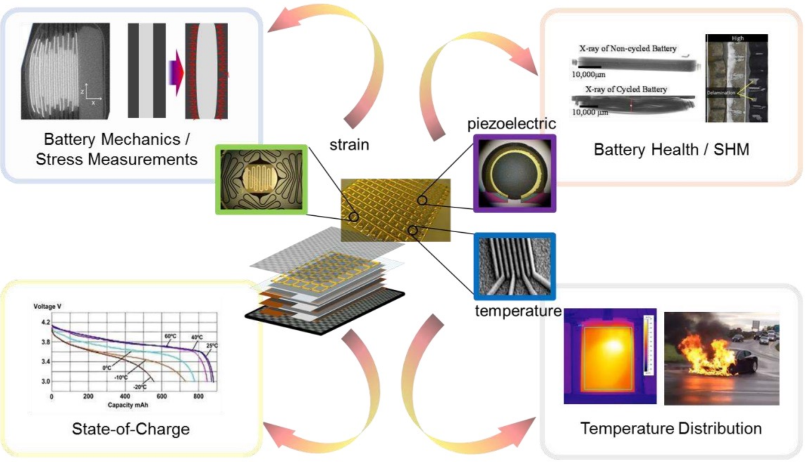
SIGMA Lab

Improving PHM methods for Li-Ion batteries

- **Objective**: development of an efficient PHM strategies for Li-Ion batteries, possibly **structural batteries**, for automotive/aeronautical applications

  ✓ **Digital twin (DT) multi-physics** modelling (healthy and anomalous conditions)
  ✓ **Surrogate modeling** (machine learning-based) for DT efficiency
  ✓ **Machine learning** for signal processing (SHM oriented)

Fusion with mechanical measurement for SOC and SOH estimation



Structural batteries

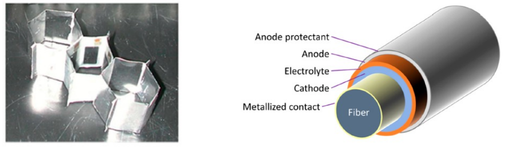


Figure 4. Examples of type-II structural batteries: planar [49] (left) and coaxial configurations, after [50] (right).

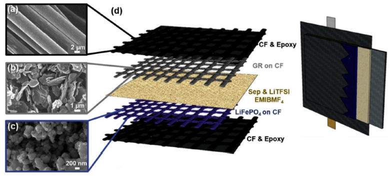


Figure 5. Example of a type-III structural battery [20].

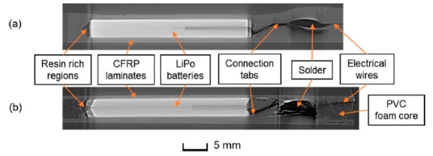


Figure 3. Examples of integrated conventional storage: cross-sectional X-ray CT images of an embedded LiPo pouch cell in (a) CFRP laminate and (b) sandwich composite [38].

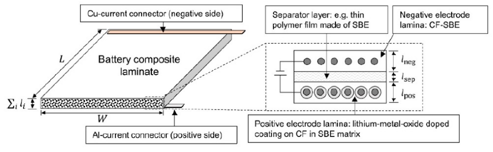


Figure 6. Example of a type-IV structural battery concept [66].

Why resorting to Mechanical Methods of State Estimation of LIB?

- Common practice is that the BMSs perform health estimation (SOC, SOH, etc.) relying only on measurements of **terminal voltage**, **current** and cell **temperature**
- The information provided by traditional electrical signals tend to be somewhat limited: demonstrated **slower response** than mechanical-based or temperature-based in detecting **thermal runaway**, for example
- Also, the stress can instantly respond to Lithium content in electrodes -> effective as a SOC estimator
- For a more complete diagnosis and prognosis, mechanical measurements should be exploited by the estimation tools, for more effective battery management and safety

SOX estimation by **fusing multiple signals** is likely to become a research hotspot in the future*

*Yang S. et al., Review on state-of-health of lithium-ion batteries: Characterizations, estimations and applications, Journal of Cleaner Production, 314 (2021)

Li-Ion batteries for lightweight applications

- Radical innovations for all aircraft power systems and subsystems are needed for:

    - Realizing **future carbon-neutral aircraft**, with hybrid-electric aircraft due to be delivered after 2035
    - Sustaining the steady and **diversified** development of unmanned aerial vehicle (**UAV**) applications, especially in the defence field

- Electrical energy storage is one key element, demanding **safe**, **energy-dense**, **lightweight** technologies, for both non-propulsive (e.g., secondary systems) and propulsive purposes

- **However, due to the limited energy and power density of current battery technologies, the application of electric aircraft might offer a substantial weight penalty**

One possible approach to storing electrical energy as well as reducing weight in the aircraft is to **combine energy storage and load-bearing capabilities in structural batteries (SB)**

Improving PHM methods for Li-Ion batteries

Topic: Model-based PHM for Li-ion batteries

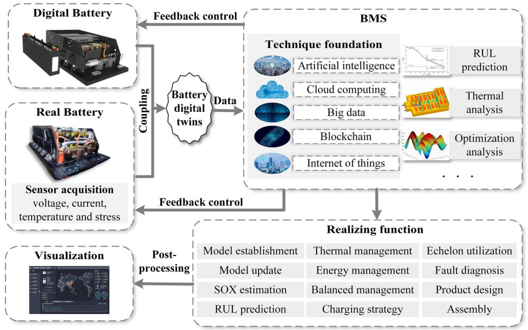
TITLE: Lithium-ion batteries PHM by exploiting **mechanical-based measurements** and **machine learning**

RESEARCH BACKGROUND:
To ensure safe and efficient operation, the power batteries of EVs should be controlled on a suitable operative environment, which includes temperature and pressure as well. Therefore, an accurate battery management system (BMS) which mainly rely on the estimation of battery health states including SOC, SOH, RUL and ISC early occurrence is highly required which means, an efficient prognostics and health management (PHM) system

RESEARCH ACTIVITIES:
1. Implementation and development of a **multi-physics digital twin** (DT) of a Li-Ion battery, at increasing levels of detail, including electrochemical, thermal and mechanical dynamics
2. Modelling of main **degradation and ageing process** and implementation in the DT
3. Processing of **thermal, electrical and mechanical signals** with **machine learning** for Li-ion battery diagnosis and prognosis

METHODOLOGY: Numerical – (Experimental)

DURATION: 7-9 months



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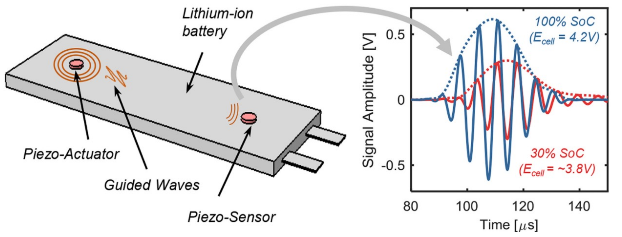

POSSIBLE COLLABORATIONS:
To be defined

Improving PHM methods for Li-Ion batteries

Topic: Application of PHM approaches to structural batteries

TITLE: Offering an achievable and advanced **health monitoring strategy** for **structural batteries**

RESEARCH BACKGROUND:
With the higher demands of performances in the **automotive** and **aeronautical** fields, more battery cells are required for the higher power and energy of the pack. The trade-off between the **power and weight** is an open research problem. Structural battery packs potentially offer a compromise whose multifunctional materials serve both for energy storage and load bearing. However, for SB on aeronautic applications, the maintenance and replacement are complex, which might rely more on an efficient PHM system

RESEARCH ACTIVITIES:
1. Implementation and development of a **multi-physics digital twin** (DT) of a Li-Ion battery, at increasing levels of detail, including electrochemical, thermal and mechanical dynamics
2. Modelling of main **degradation and ageing process** and implementation in the DT
3. Processing of **thermal, electrical and mechanical signals** with **machine learning** for Li-ion battery diagnosis and prognosis
4. Additionally, more detailed combined electrical and structural assessments (numerical/experimental) will be required

METHODOLOGY: Numerical – (Experimental)

DURATION: 7-9 months

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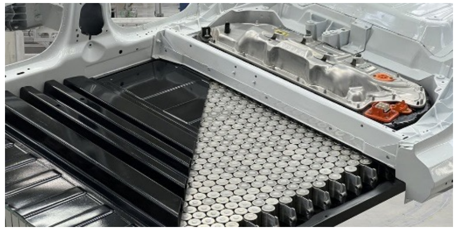
POSSIBLE COLLABORATIONS:
To be defined



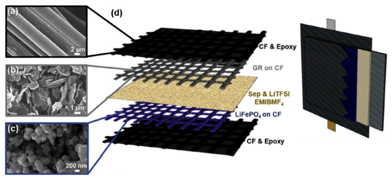
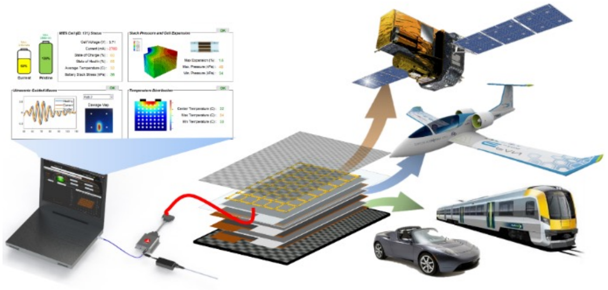


Figure 5. Example of a type-III structural battery [20].

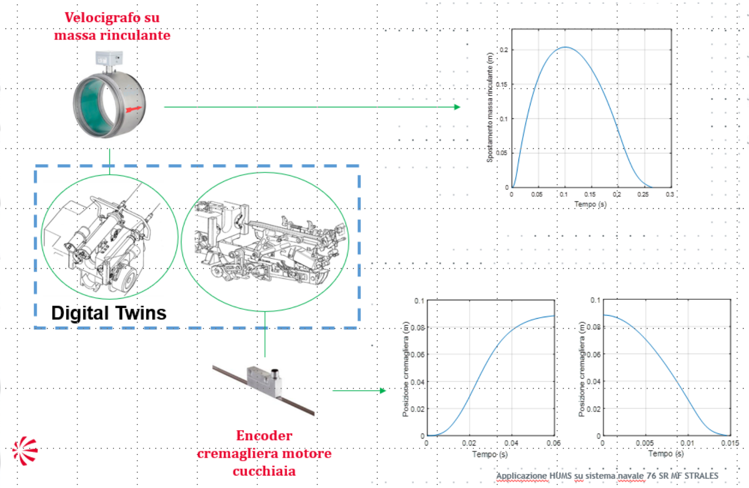


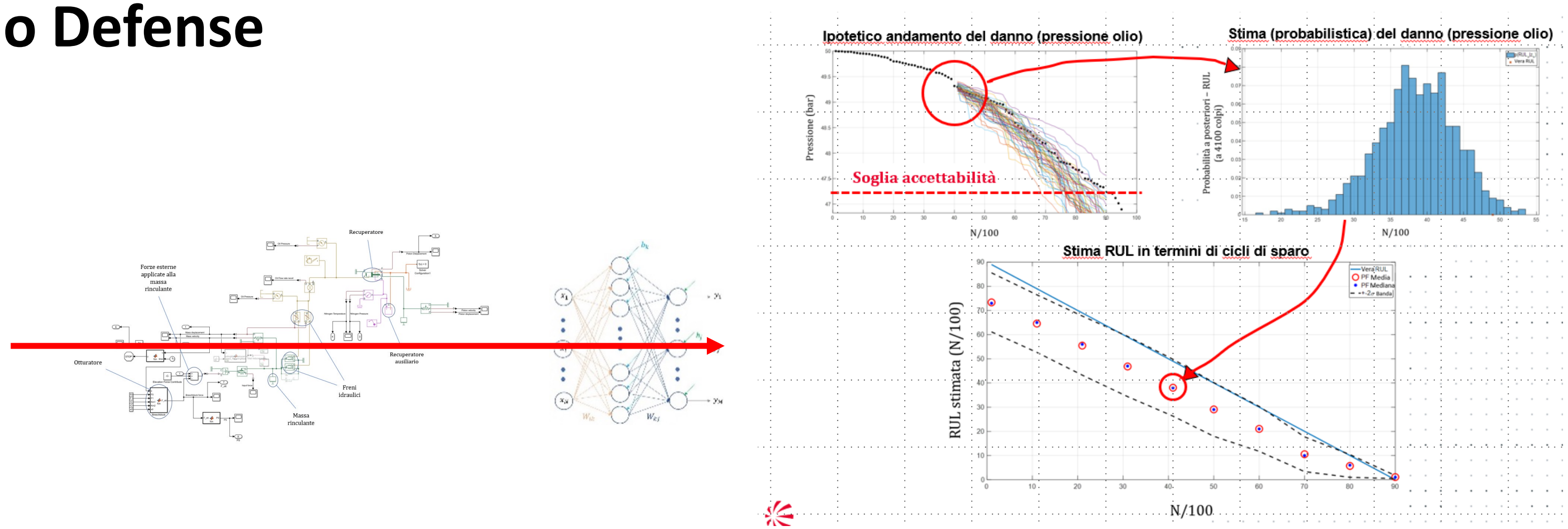
HUMS for naval defense systems

- **Objective**: development of an efficient HUMS strategy for diagnosis and prognosis of several important subsystems of naval defense systems

  - ✓ **Digital twin (DT) multi-physics** modelling (healthy and anomalous conditions)
  - ✓ **Machine learning** for signal processing (SHM oriented)

- Two projects for two different systems (traditional and evolutive)
- Collaboration with **Leonardo Defense**





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DIPARTIMENTO DI ECCELLENZA
MIUR 2018-2022

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