POLITECNICO
MILANO 1863

DIPARTIMENTO DI MECCANICA
Department of Mechanical Engineering

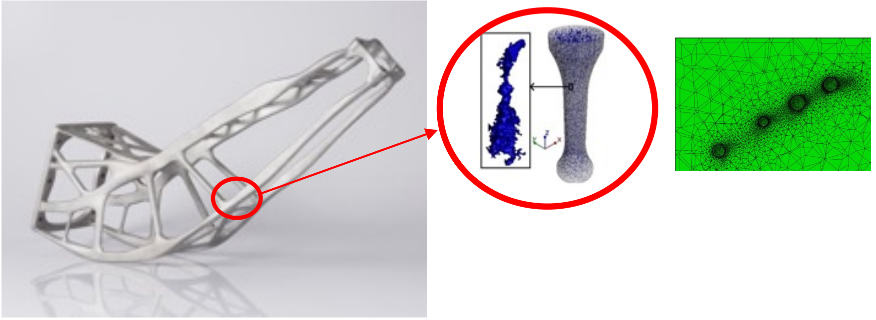
Track CM3
Computational Mechanical Design

Prof. Stefano Beretta

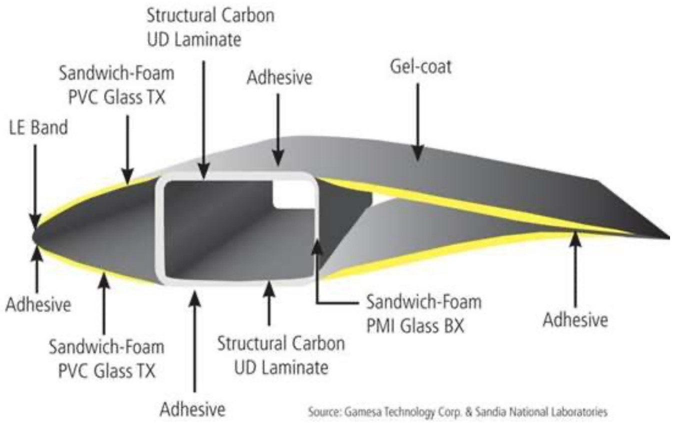
May 2023

Computational Mechanical Design: an overview

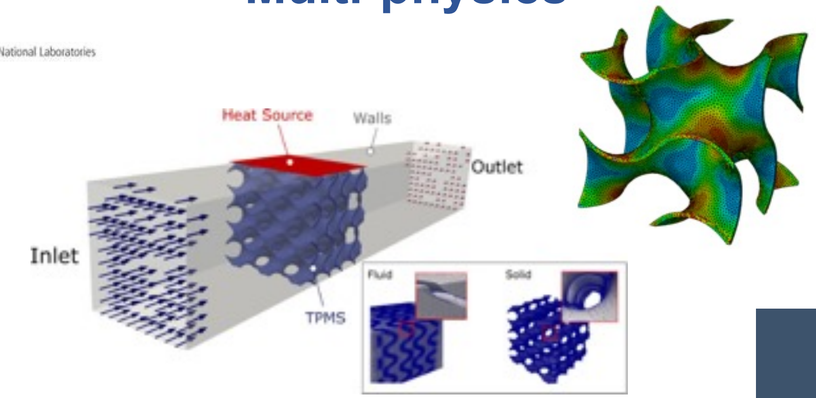
Multi-scale



Multi-material



Multi-physics



Emerging technologies, such as **topology optimization and multi-material additive manufacturing**, are opening new possibilities in terms of mechanical design of **lightweight and high-performance components/systems**.

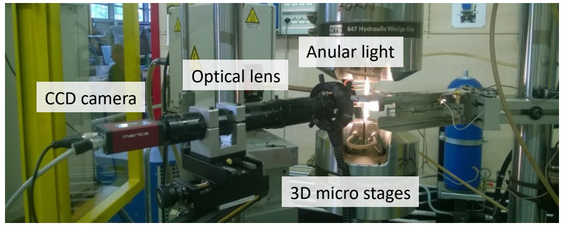
Simulation is becoming vital: **effective modelling** can help drive the design, speed up time to production and eliminate costly design mistakes.

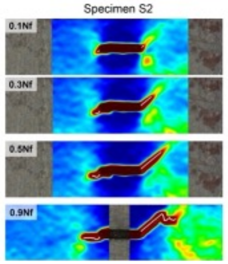
By attending the *Computational Mechanical Design* track, students will acquire the technical skills, methods and principles to **design disruptive mechanical systems and their components by using:**

- **advanced multi-scale;**
- **multi-material;**
- **multi-physics approaches**.

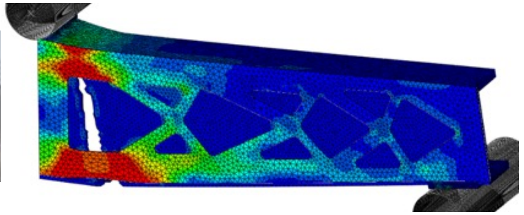
CM3: Skills you will acquire...

Advanced materials tests

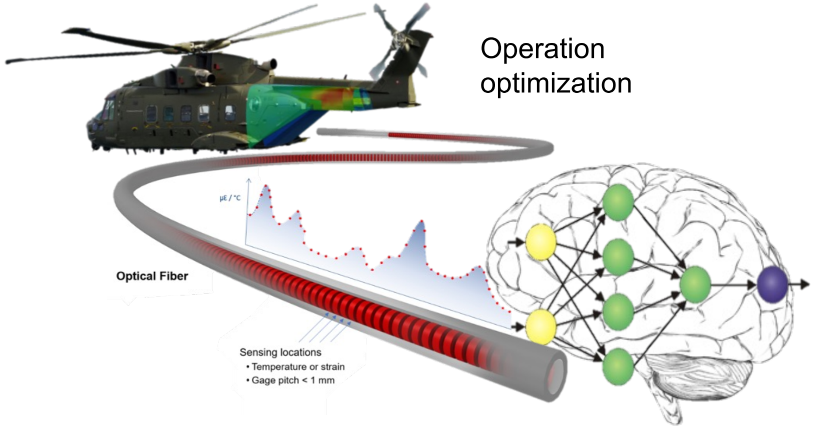




Damage & material models



Sensors & life analysis



Students will learn how to:

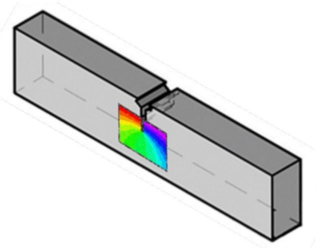
- **manage and master multi-scale multi-physics modelling** (FEM, CFD, …) **of components** and systems
- **plan lab experiments for the testing and modelling of material behaviour** in complex working conditions
- **design** innovative components **combining structural (topology) optimization** and **innovative multi-material solutions**
- **process real-life sensor data** from components/systems through suited models

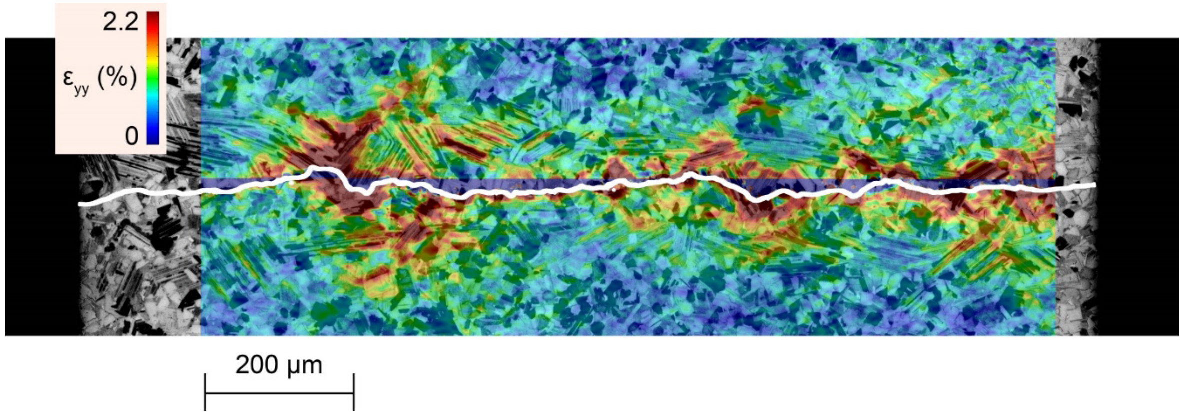
The Application of Computational Mechanical Design

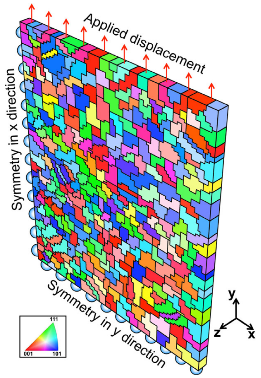
Dr. Marco Allara (GEAvio)

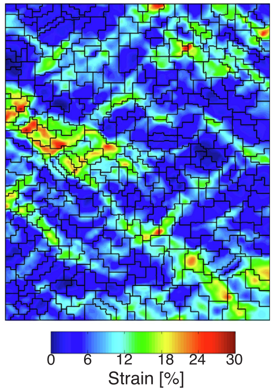
CM3: Core Courses

COURSE TITLE	YEAR	SEM	ECTS	ECTS group
Energy Technologies for Efficient and Decarbonized Industry	1	1	10	10
Advanced Dynamics of Mechanical Systems	1	2	10	10
Advanced Machine Design	1	2	10	10
Advanced Manufacturing Processes B	1	1	5	5
Production Management	1	2	5	5
Advanced Materials for Mechanical Engineering	1	1	5	5









CM3: Track Specific Courses

COURSE TITLE	YEAR	SEM	ECTS	ECTS group
Mechanical Behaviour of Materials and Finite Element Simulation	1	1	10	10
Computational Fluid Dynamics - Fundamentals	1	2	5	5
Measurements for Mechanical Engineering	2	2	5	20
Machine Learning and Model Identification for Mechanical Systems	2	2	5	
Digital Twin for Health and Usage Monitoring	2	1	5	
Topology Optimisation	2	1	5	
Surface Modeling for Engineering Applications	2	2	5	
Additive Manufacturing B	2	1	5	
Simulation Tools for Materials and Processes	2	1	5	
Elective courses (Computational Fluid Dynamics - Advanced Methods and Applications, Computational Fluid Dynamics - Experimental Assessment, Advanced Design of Machine Elements, Impact Engineering)	2	1-2	5	10
Lab course (Metamaterials and Metastructures, Structural Health and Usage Monitoring in Action, Structural Integrity of Aerospace and Mechanical Components, Prototyping of Bioinspired Solutions, Destructive and Non-Destructive Testing of Composite Materials and Structures)	2	2	5	5

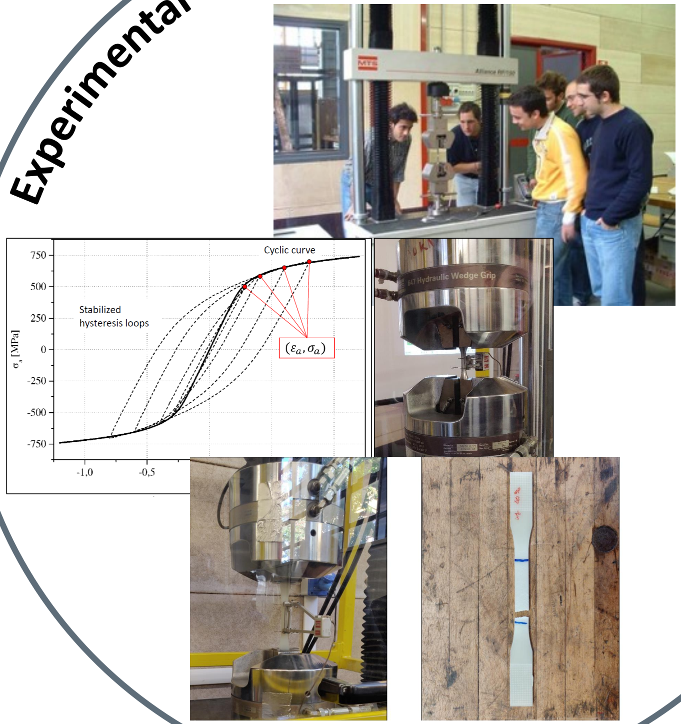
CM3: Modelling of Mechanical behaviour of materials

1st Year - 1st Semester

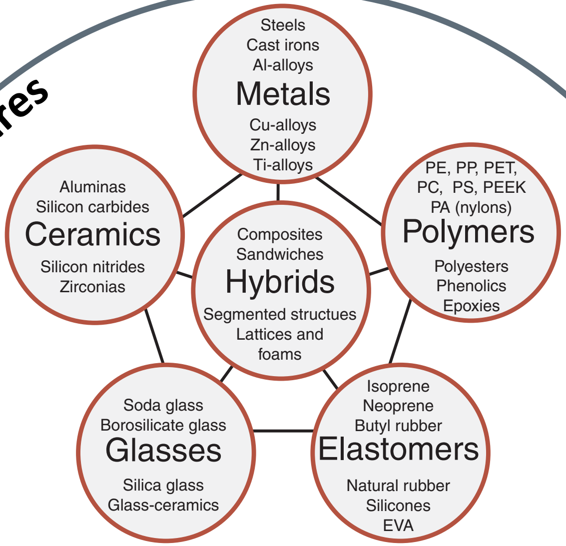
Elastic Mechanical Properties Linear elasticity, hyperelasticity, viscoelasticity

Inelastic Mechanical Properties Metal plasticity, models for metals subjected to cyclic loading, Johnson-Cook Plasticity, Porous metal plasticity

Experimental Labs



Lectures



$$G_R(t)=G_0\left(1-\sum_{k=1}^{N}\bar{g}_k^P\left(1-e^{-t/\tau_k}\right)\right)$$

$$W=\sum_{i+j=1}^{N}C_{ij}(I_1-3)^i(I_2-3)^j$$

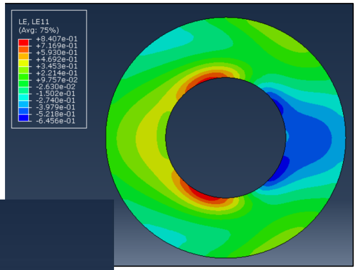
$$\left(\frac{\sigma_{11}}{S_L}\right)^2+\left(\frac{\sigma_{22}}{S_T}\right)^2-\frac{\sigma_{11}\sigma_{22}}{S_L^2}+\left(\frac{\sigma_{12}}{S_{LT}}\right)^2\leq 1$$

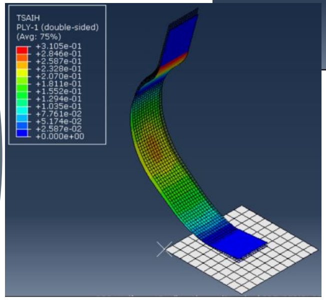
$$\sigma^0=\sigma|_0+Q_\infty\left(1-e^{-b\varepsilon^{pl}}\right)$$

$$d\underline{\alpha}^{(k)}=\frac{2}{3}C^{(k)}d\underline{\varepsilon}_{pl}-\gamma^{(k)}\underline{\alpha}dp$$

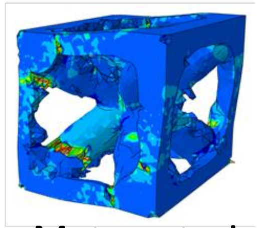
Numerical Labs

Elastomers

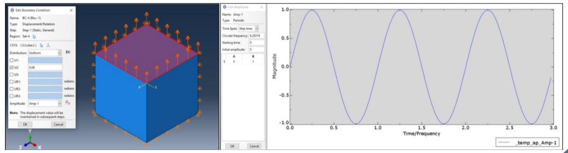




Composites



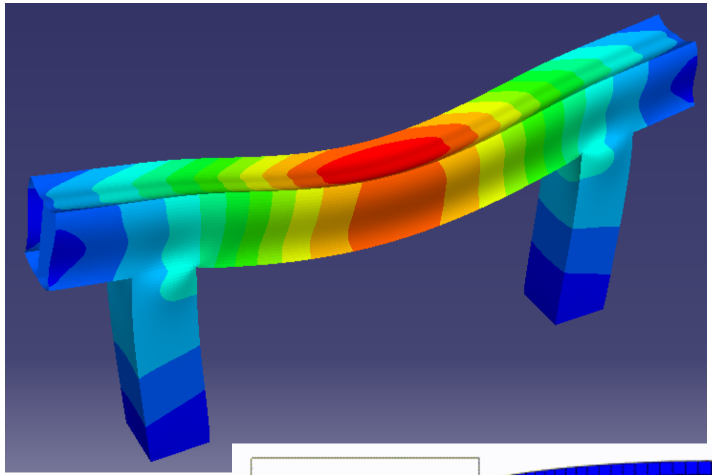
Metamaterials

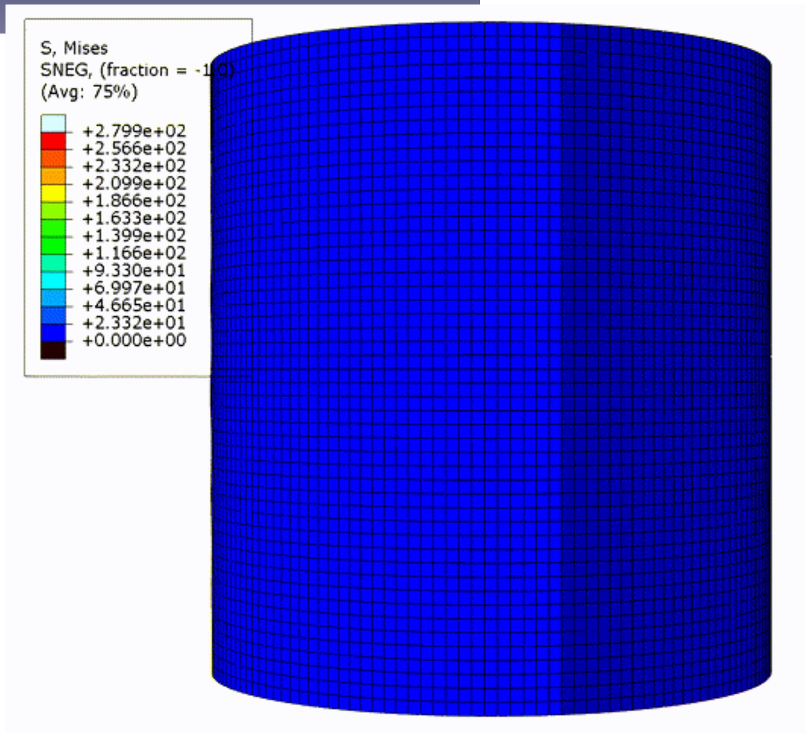


Cyclic plasticity

CM3: Finite element simulation for mechanical design

1st Year - 1st Semester





Main topics:

- **Theory and methods for linear FE simulations**
- **Advanced linear analyses: dynamic and buckling simulations**
- **Non-linear analyses: large displacements, contact and plasticity**

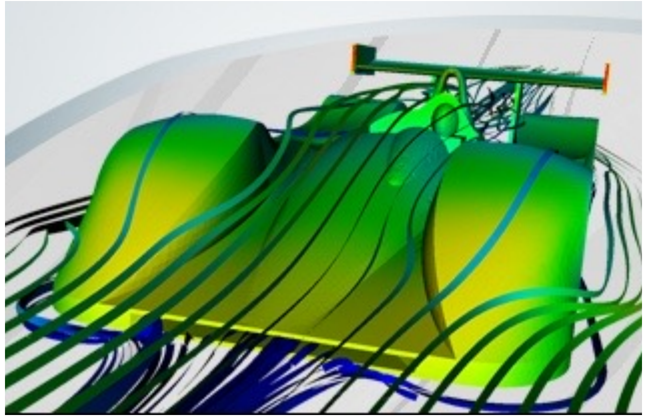
Students will learn how to:

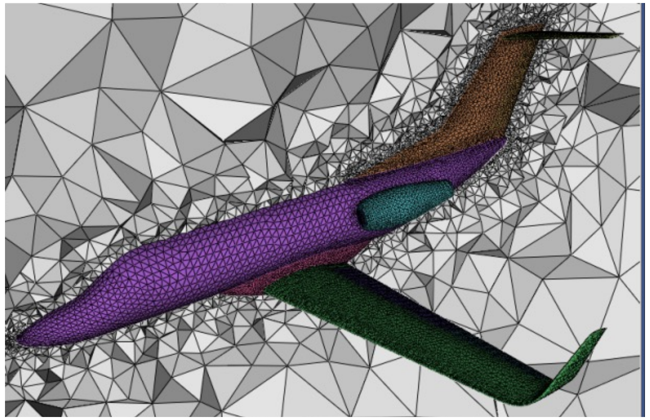
- simulate **real-life scenarios** of structures subjected to **static loadings**
- extract the proper **modes of vibration** or the **buckling loads of mechanical components and structures**
- simulate the **mechanical response** of parts made with **different materials**
- adopt **advanced FE simulation techniques** to model **highly non-linear phenomena** (contact, buckling, large displacements, etc…)

CM3: Computational Fluid Dynamics - Fundamentals

1st Year – 2nd Semester

Aim: to introduce the basics of CFD and to teach how to correctly apply it to simulate simple fluid flows relevant for mechanical engineering, using open-source CFD tool

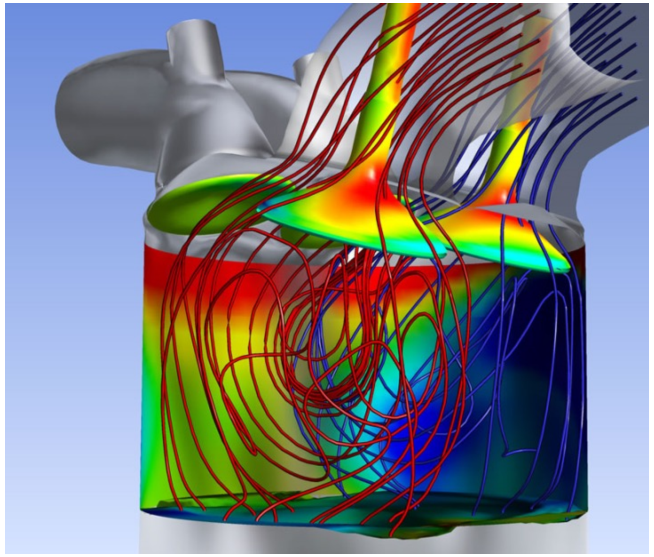


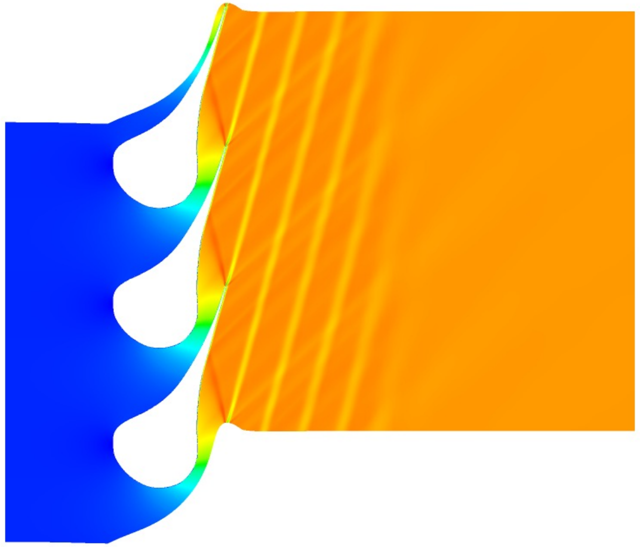


1. **Equations of fluid motion**
2. **Turbulence and its modeling**
3. **Space discretization and meshing**
4. **Finite volume schemes and systems**
5. **Solvers and solution strategies**
6. **Examples:**

   Internal flow in pipes

   External flow around airfoils

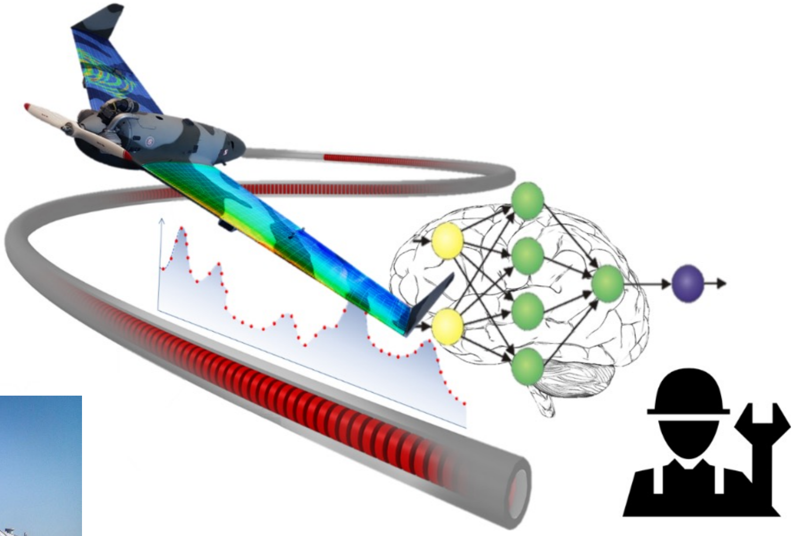




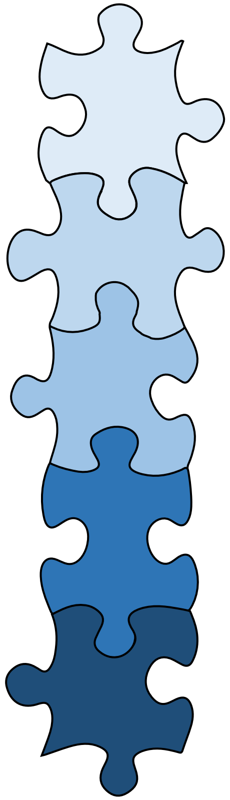
CM3: Digital Twin for Health and Usage Monitoring

2nd Year - 1st Semester

- Digital-twin is a **virtual replica** of a real platform
- It is generally used for **Operation and Maintenance** optimization of high value systems to reduce downtime **costs** and increase **safety**



Course Sillabus



Parametric Multiphysical Model (the master)

Damages are included in the master (additional parameters)

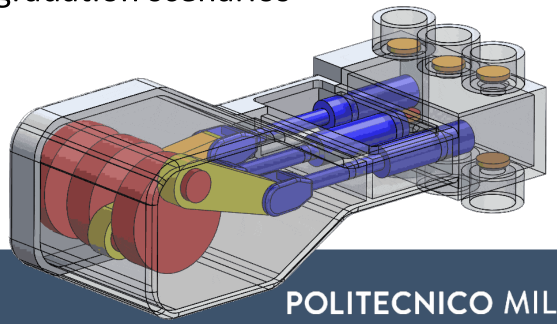
Surrogate modelling (e.g. by machine learning)

Stochastic Model Updating (Bayesian Inference)

Diagnostic and prognostic capability (artificial intelligence)

Digital twin of a pressure vessel in operation

Diagnostic Digital twin of a pump subject to multiple degradation scenarios

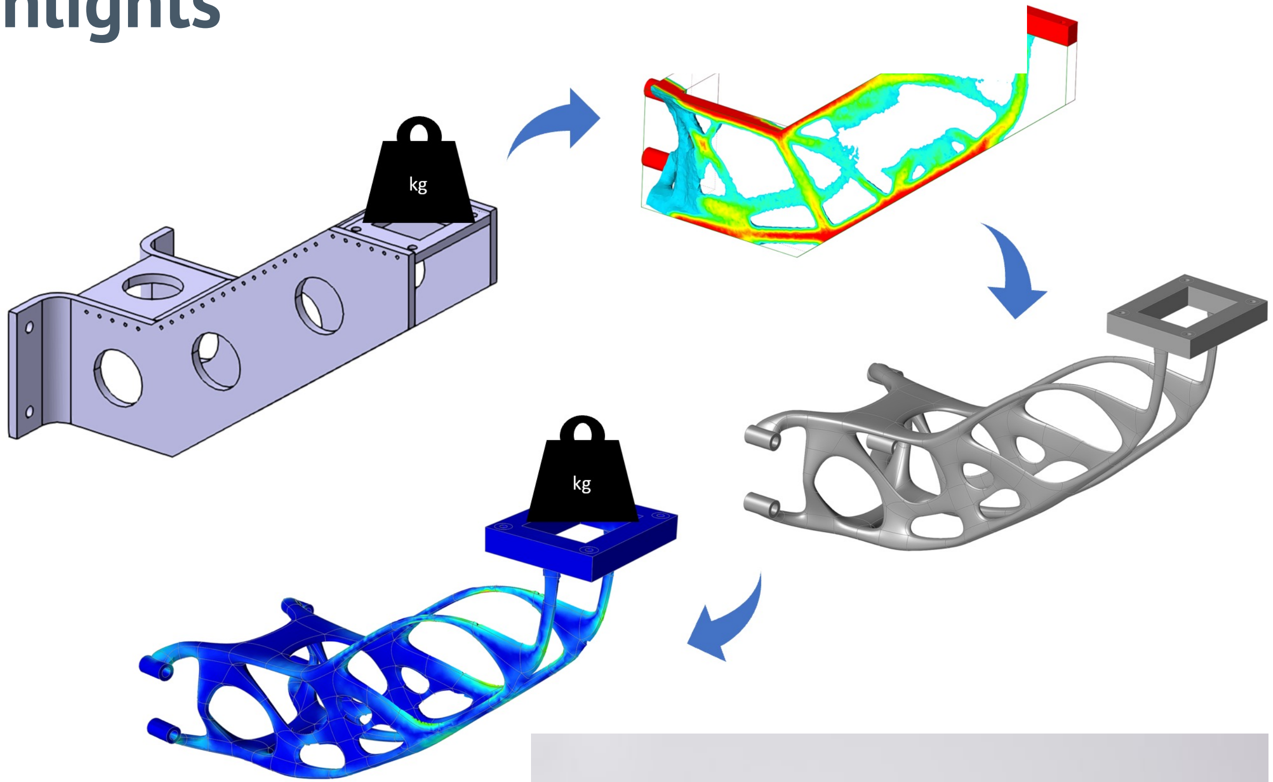


Prognostic Digital twin for Battery Management

CM3: Topology Optimisation - Highlights

2nd Year - 1st Semester

The course aims to introduce the basic concepts of structural topology optimization with particular reference to lightweight design.



Students will deal with:

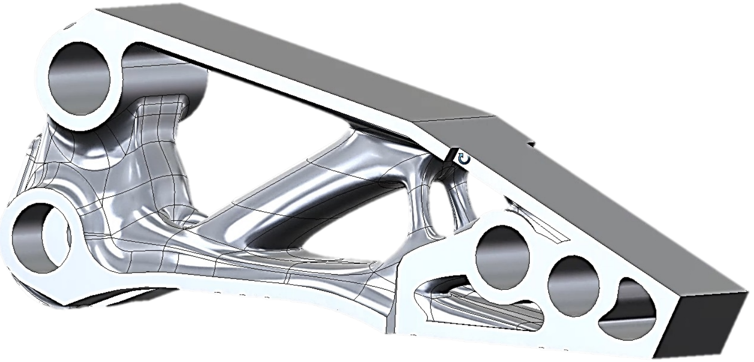
- Computational schemes for solving topology optimization problems
- Topology optimization of frame structures
- Design parametrization and material interpolation schemes for solving general 3D discretized (Finite Element) topology optimization problems
- Actual engineering applications, solved with commercial software and handwritten codes

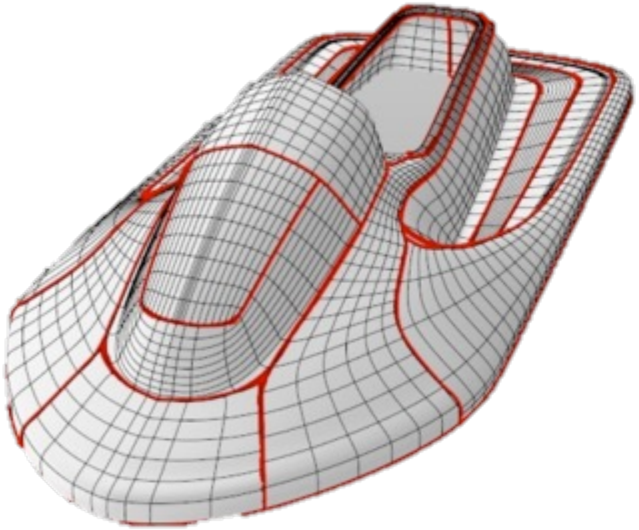
CM3: Surface modeling for engineering applications

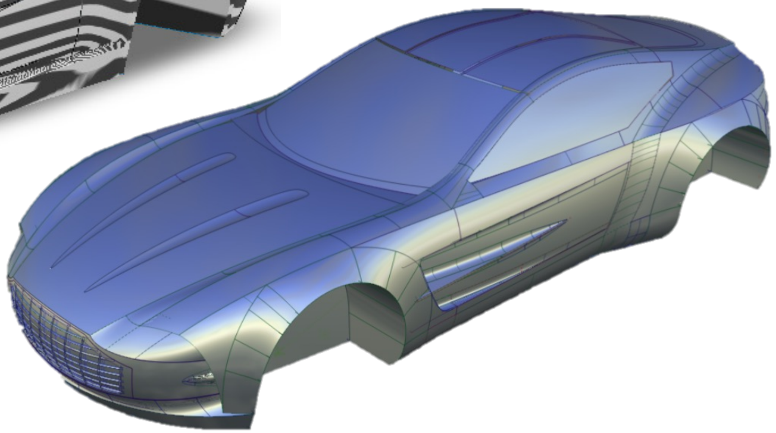
2nd Year – 2nd Semester

The course aims at giving knowledge about surface modeling **theory and practice**.

By the end of the course, the students will be able to **make 3D models of complex shapes**.







Main topics:

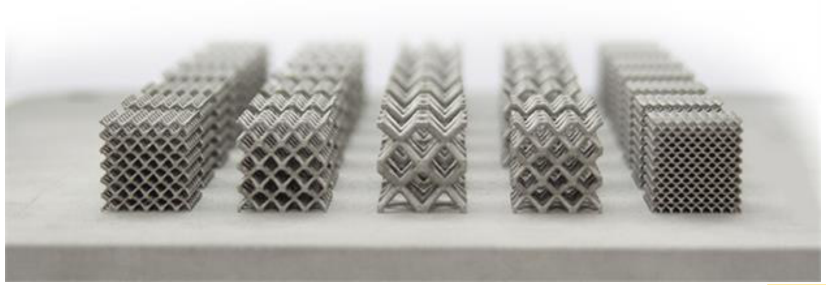
- Brief mathematical foundation of curves and surfaces,
- 3D surface modeling techniques,
- Diagnostic shading techniques,
- Applications in Engineering (products, hulls, airfoils, aesthetic, etc.),
- From surfaces to computational grids,
- From tessellated to parametric surfaces.

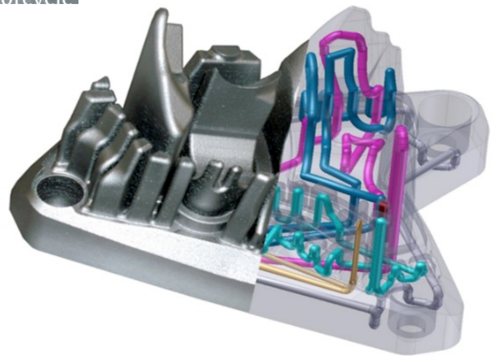
Additive Manufacturing B

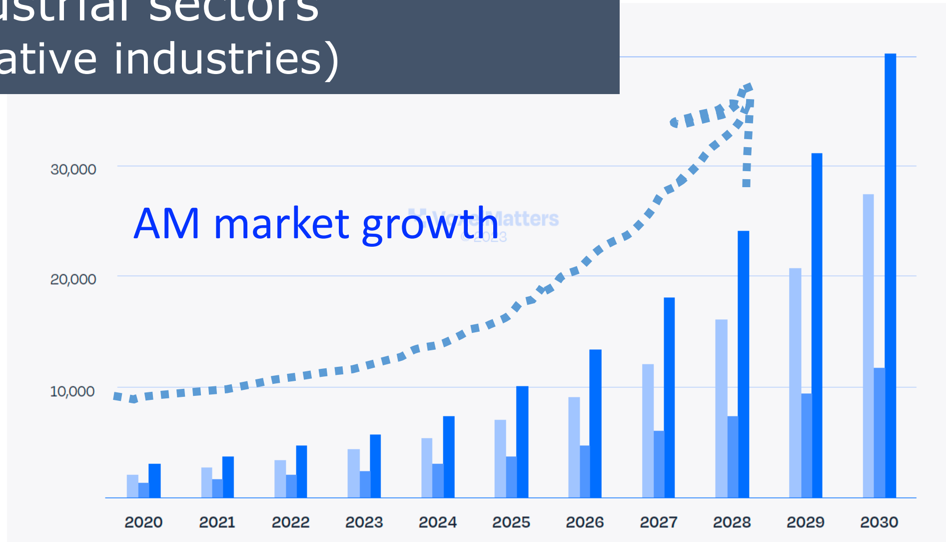
2nd Year – 1st Semester

AM is acting as technological enabler to design and manufacture a **new generation** of **lightweight**, **highly-efficient** products in many industrial sectors (aerospace, automotive, biomedical, machinery, defense, creative industries)

AM for satellites: Reaction Wheel Bracket (ESA)





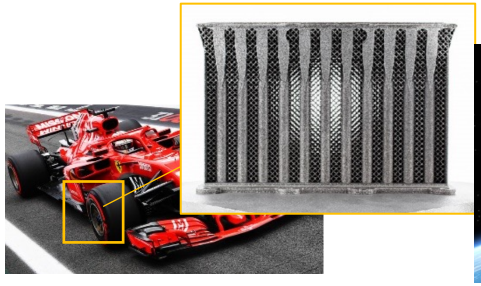


	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hardware	2,042	2,522	3,298	4,393	5,416	7,008	9,034	11,892	15,972	20,938	27,782
Materials	1,151	1,426	1,752	2,167	2,740	3,497	4,512	5,784	7,388	9,353	11,730
Services	2,813	3,649	4,513	5,703	7,455	10,137	13,323	18,108	24,155	31,538	40,688

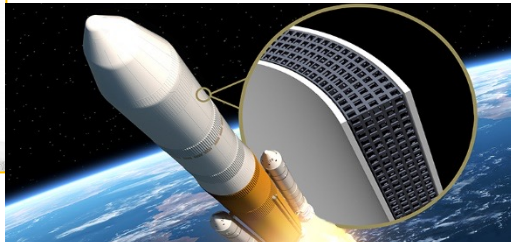
Hardware Materials Services

Source: VoxelMatters (only producers and services)

Helicopter exhaust gas nozzle with integral cooling. (https://altairenlighten.com)



Lattice-filled turbo intercooler for racing car (https://altairenlighten.com)



Vibration absorbers - sandwich panels filled with a lattice core. https://powerandmotionworld.it/

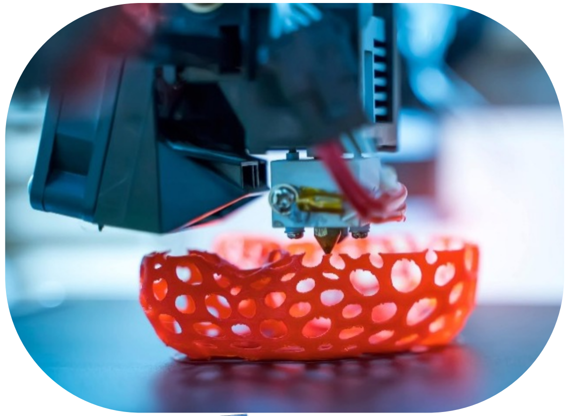
The course provides a description of AM technologies, fosucing on their applications, constraints, technical and business-oriented implications for the digital and green transitions.

Computational Mechanical Design

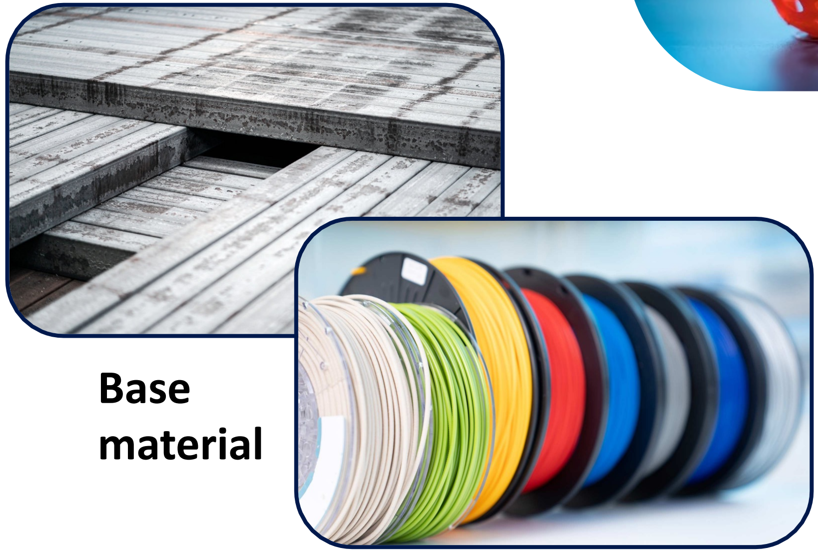
Lab Courses: 2nd Year – 2nd Semester

LAB: Metamaterials and Metastructures

- Held by Dr. Matteo Gavazzoni and Dr. Emanuele Riva



3D printing

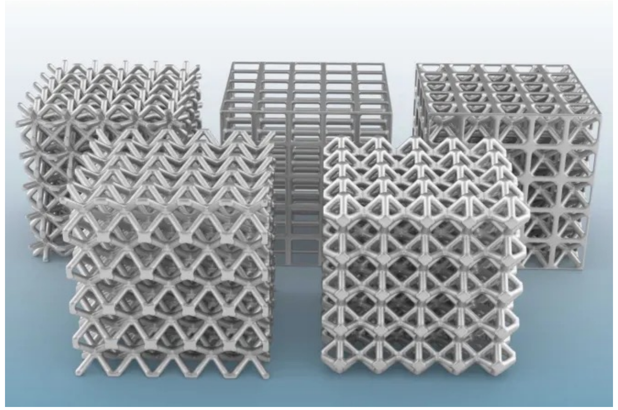


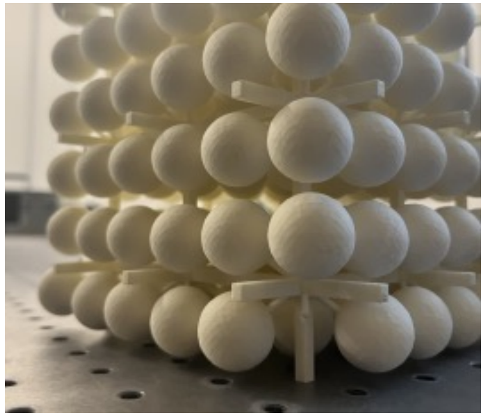
Base material

Metamaterials and metastructures

Double scale materials:

heterogenous meso-scale ⬄ homogenoues macro-properties





Macroscopic properties that go beyond the limits of natural conventional materials

LAB: Metamaterials and Metastructures

Numerical modeling competences
(Structural, dynamic and thermo-fluid dynamic)

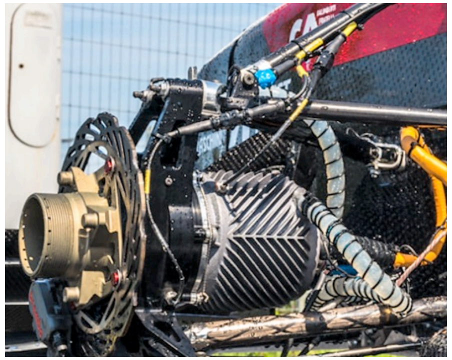
Experimental competences
(Mechanical and dynamic characterization of structures and materials)

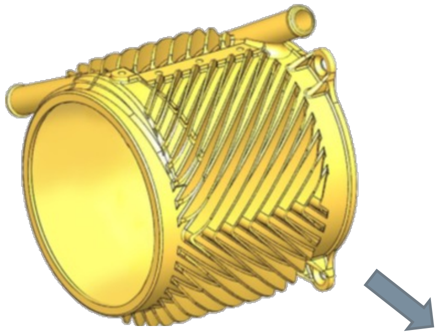
Theoretical competences

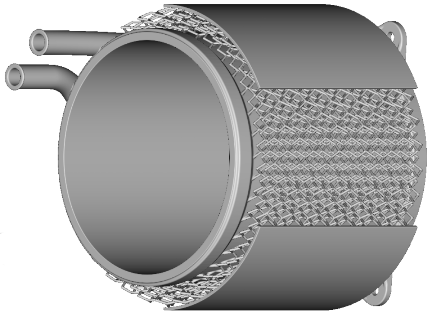
Development of real-case projects

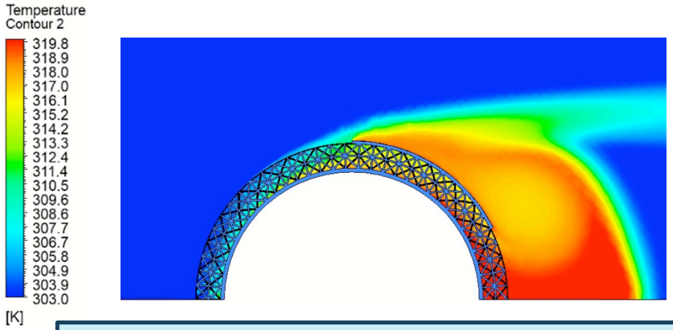
Students will develop a **multi-disciplinary project** that will constitute the exam evaluation

Possible project example: improvement of a race-car electric motor cooling jacket









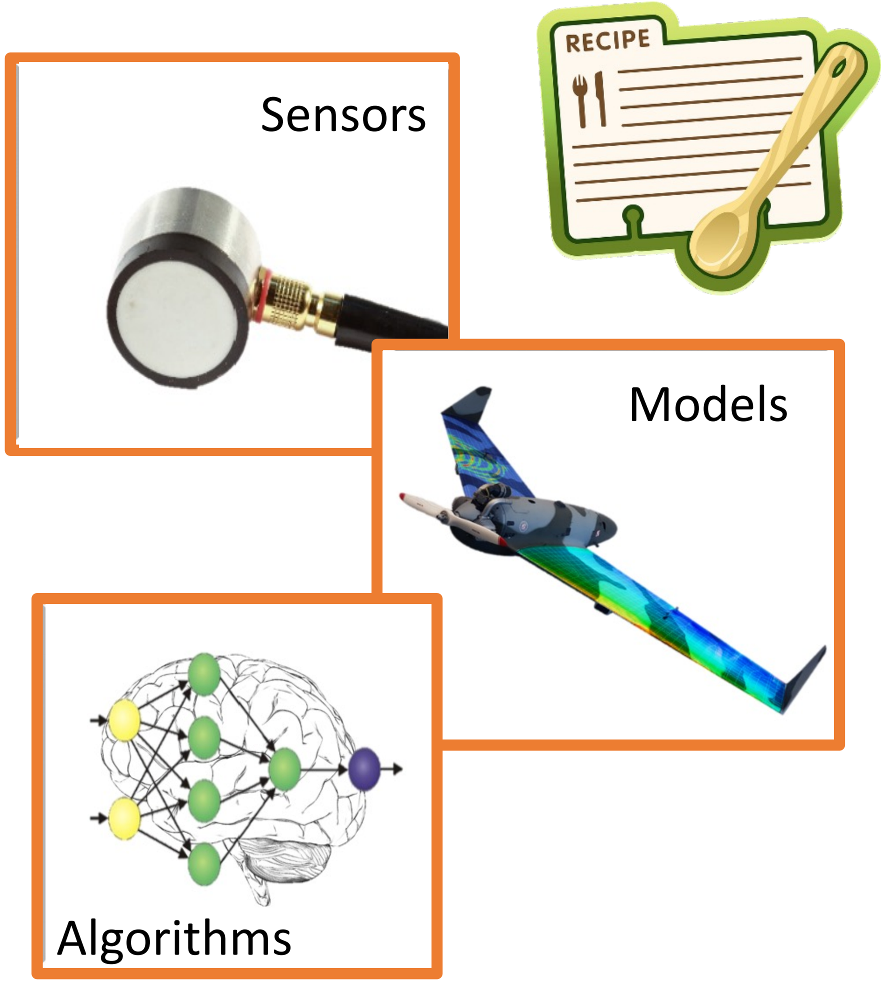
- Thermal exchange improvement
- Structural integrity must be assessed under vibrations and thermal loads

LAB: Structural Health and Usage Monitoring in Action

Description

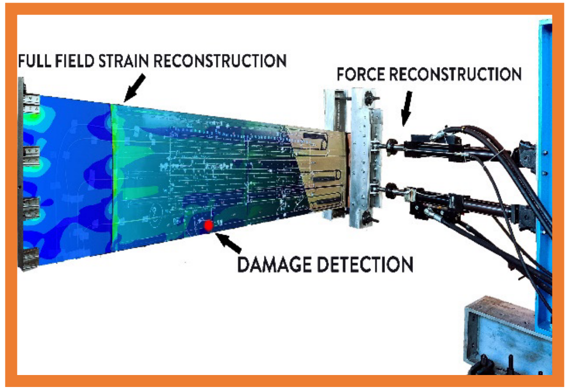
Students will face first-hand a series of experimental structural monitoring case studies, based on research topics addressed in international projects. Students will be able to experience different multidisciplinary aspects typical of monitoring systems, including:

- **sensor installation and signal acquisition**, post-processing and data interpretation
- **Implementation of algorithms** for load identification and health condition monitoring
- Implementation of methods for coupling models with sensors based on **artificial intelligence** and **statistics**
- **Test through demonstrators**

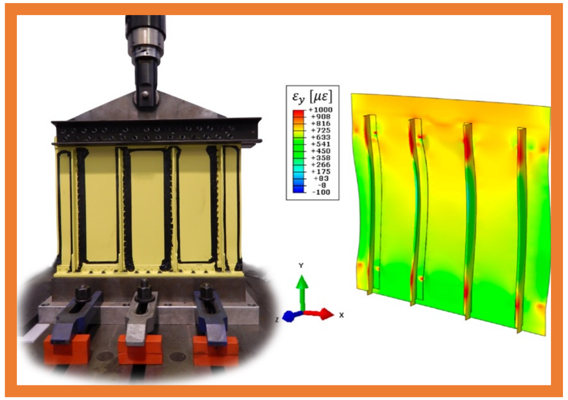


LAB: Structural Health and Usage Monitoring in Action

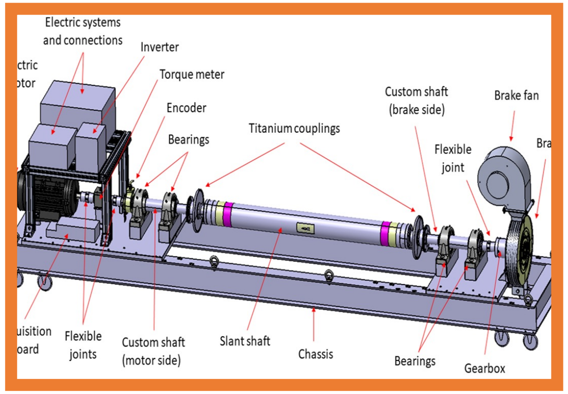
Experiences and challenges



Application of force reconstruction and damage identification algorithms on a composite full-scale component



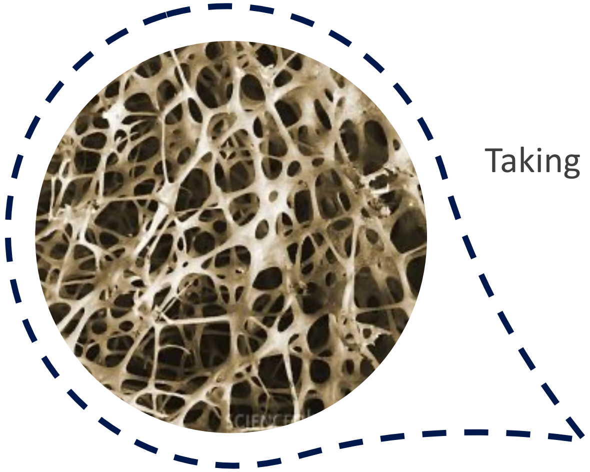
Damage diagnosis and prognosis on a metallic stiffened panel subject to fatigue damage



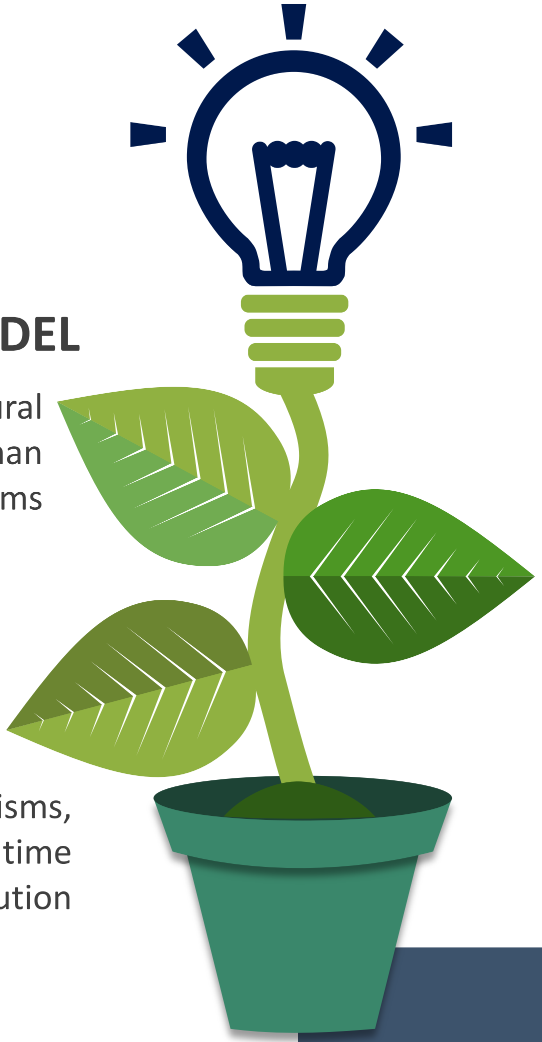
Damage and impact identification on a transmission shaft subject to impacts and bearing degradation

Application of methods and data analysis for corrosion monitoring of metallic structures

LAB: Prototyping of Bio-inspired Solutions - 3M Principle



... NATURE AS...



MODEL

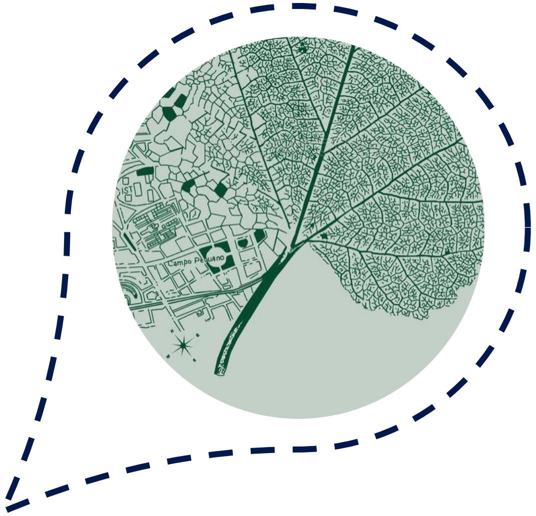
Taking inspiration from natural design to solve human problems

MENTOR

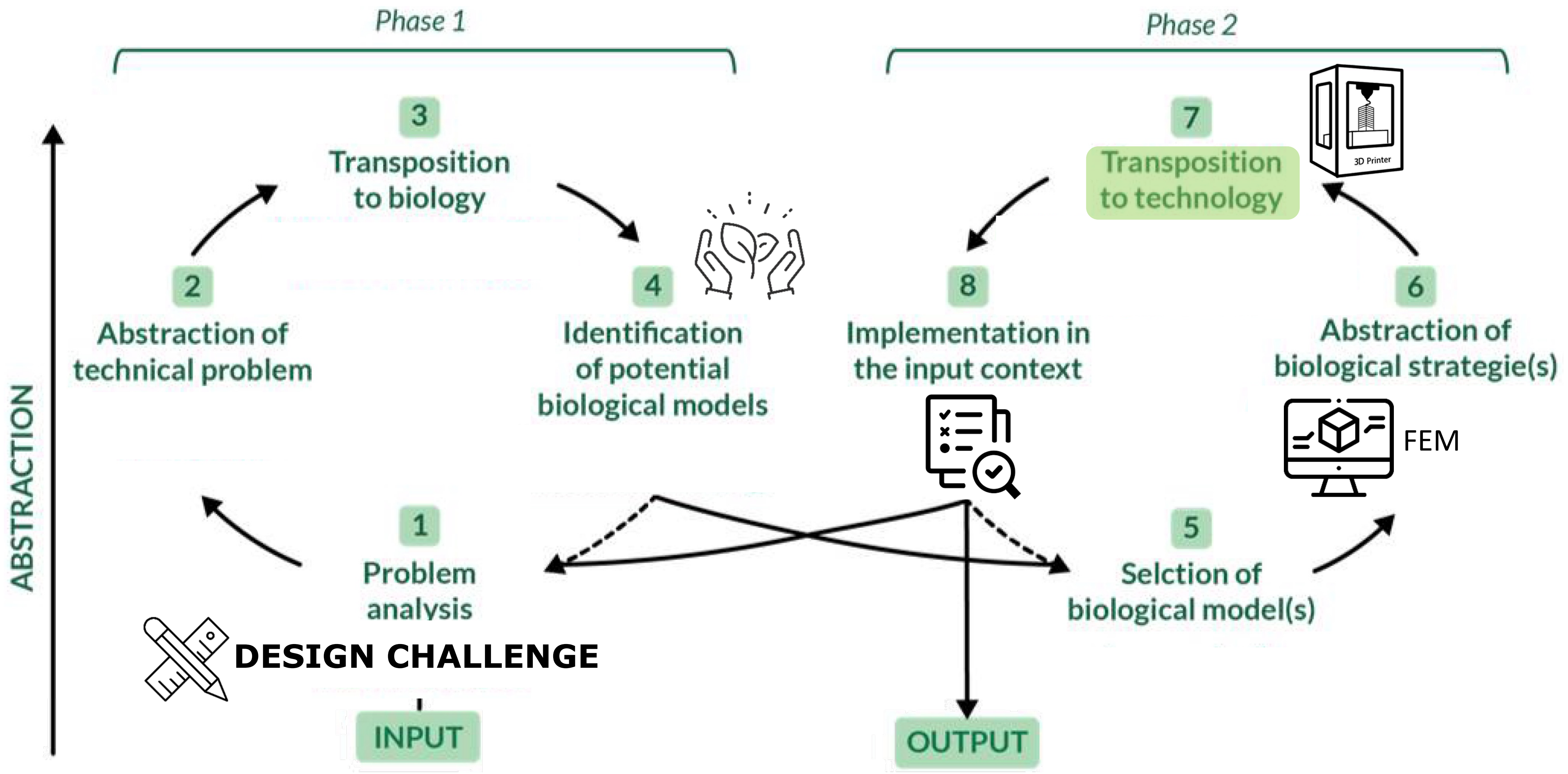
Learn from natural mechanisms, hierarchy, multi-scale response, time evolution

MEASURE

Ecological standard to judge the appropriateness of innovations



LAB: Prototyping of Bio-inspired Solutions – Hands-on approach

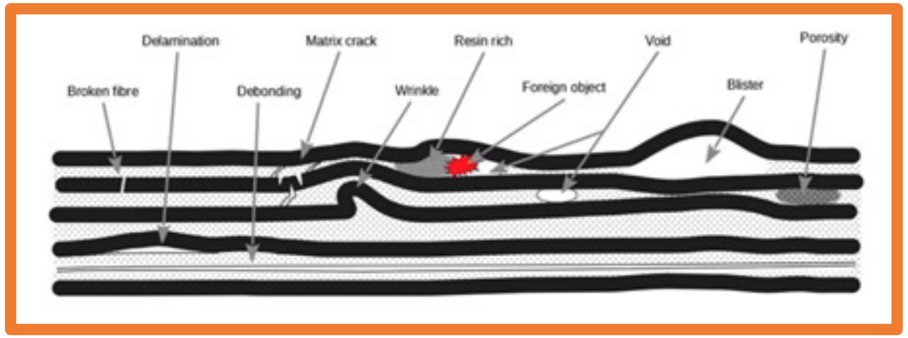


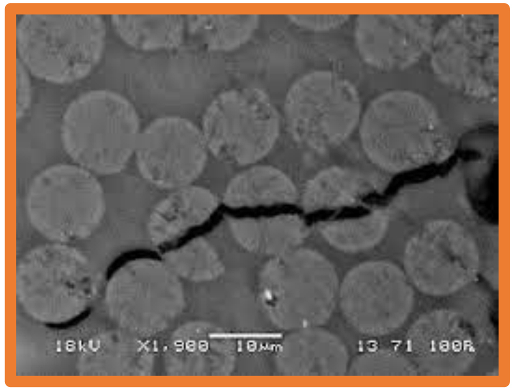
LAB: Destructive and non-destructive testing of composite materials and structures

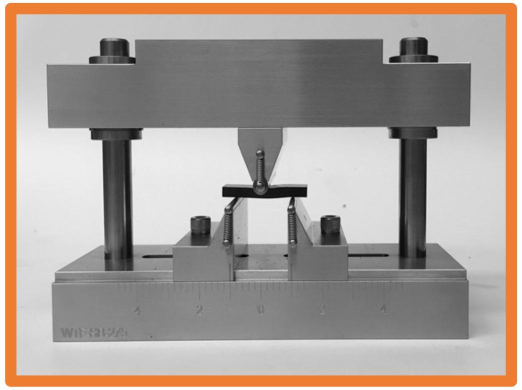
The experimental Lab aims to show and give practical insight on mechanical testing and on non-destructive testing for characterizing mechanical properties of and damage mechanisms in composite materials and structures

The main topics are:

- quasi static and fatigue mechanical tests on composite materials supported by advanced experimental stress/strain analysis techniques, e.g., digital image correlation and others
- delamination tests on laminates and adhesive bonded joints along with the application of non-destructive inspection techniques for damage evaluation (micro computed tomography, ultrasonic testing, thermography, visual testing, …)
- fatigue tests on laminates and adhesive bonded joints, supported by non-destructive inspection techniques, for identification and characterization of damage mechanisms by advanced data analysis







LAB: Destructive and non-destructive testing of composite materials and structures

Who:

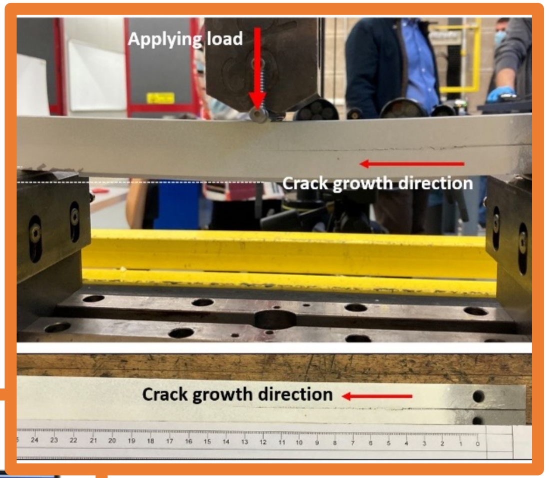
Prof. Andrea Bernasconi

Prof. Michele Carboni

Where:

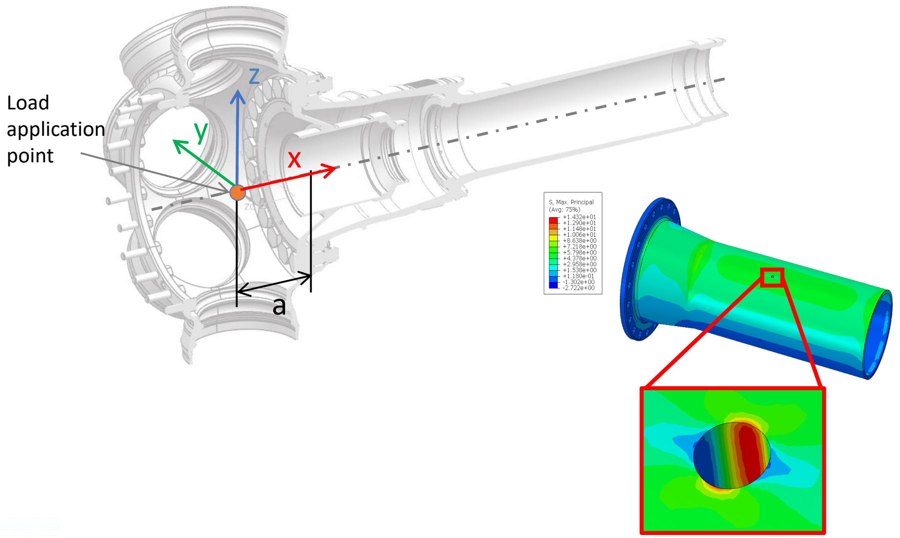
The course will mainly consist of practical exercises to be held in the experimental labs of DMEC (B13, B16, B23)

Traditional and computerized classrooms will be used for elaboration and discussion of the experimental outcomes, as well



LAB: Structural Integrity of Aerospace and Mechanical Components

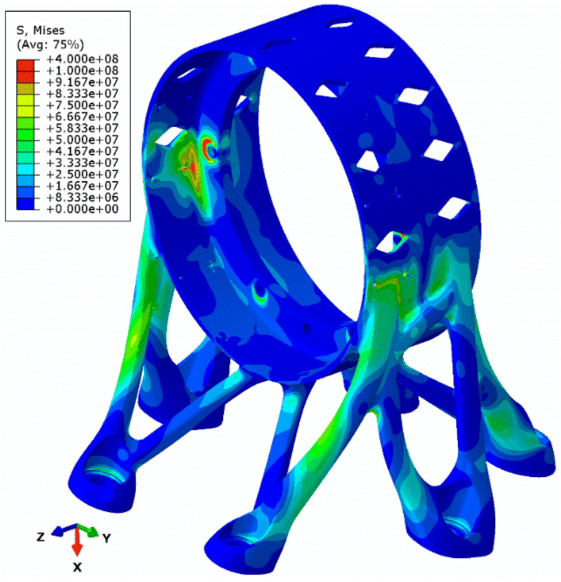
Airbus A400M
Four-engine turboprop

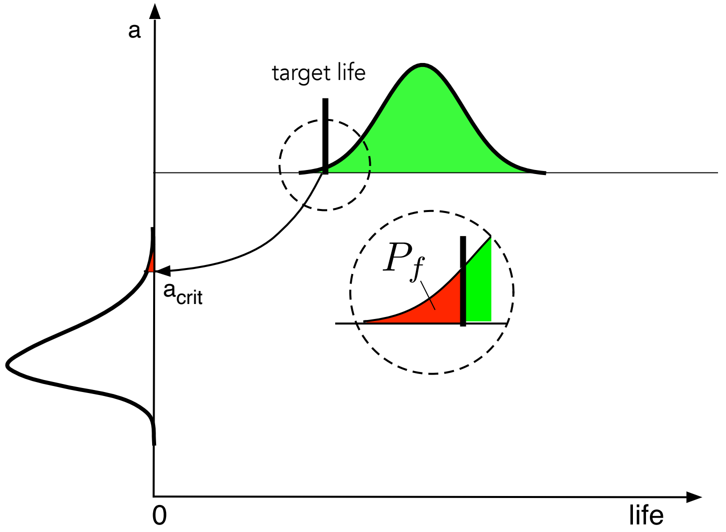


How can critical aerospace components be safe ?

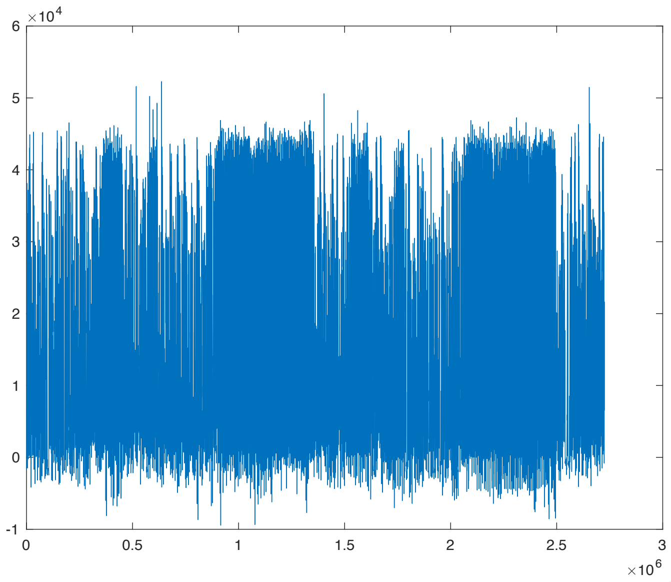
Students will apply hands-on the concepts already applied in Core Courses for:

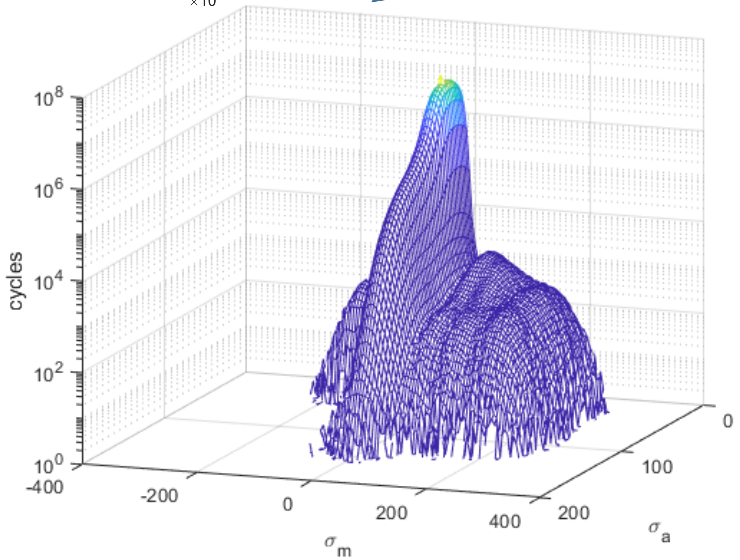
- learn the safe-life and damage tolerance requirements of the standards;
- apply them using state-of-the art software;
- how to simply analyze anomaly data to support the structural integrity assessment;
- how to deal with AM components and the qualification of new processes.





LAB: Structural Integrity of Aerospace and Mechanical Components





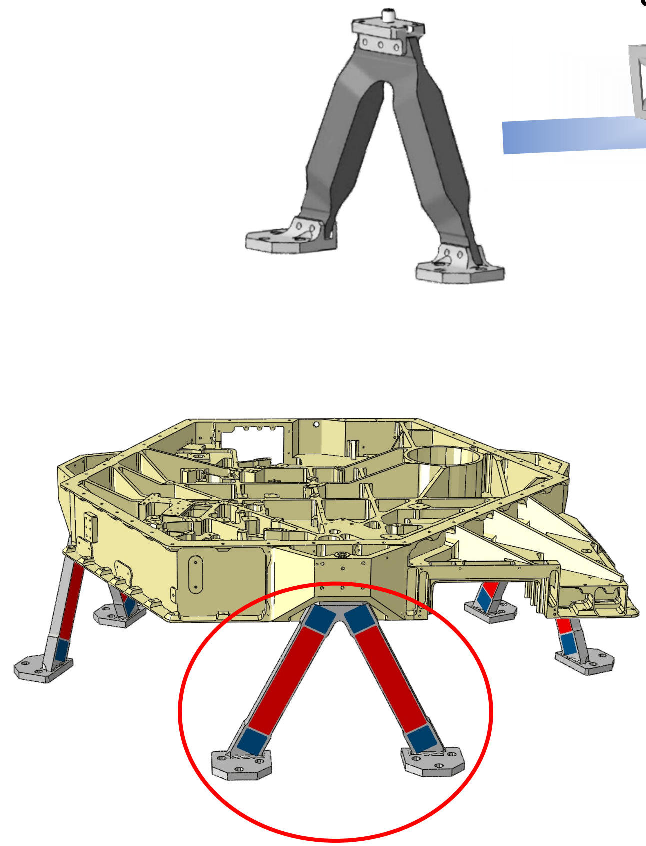
Students will work 'hands-on' on realistic race signals on different components to learn statistical tools and apply them for:

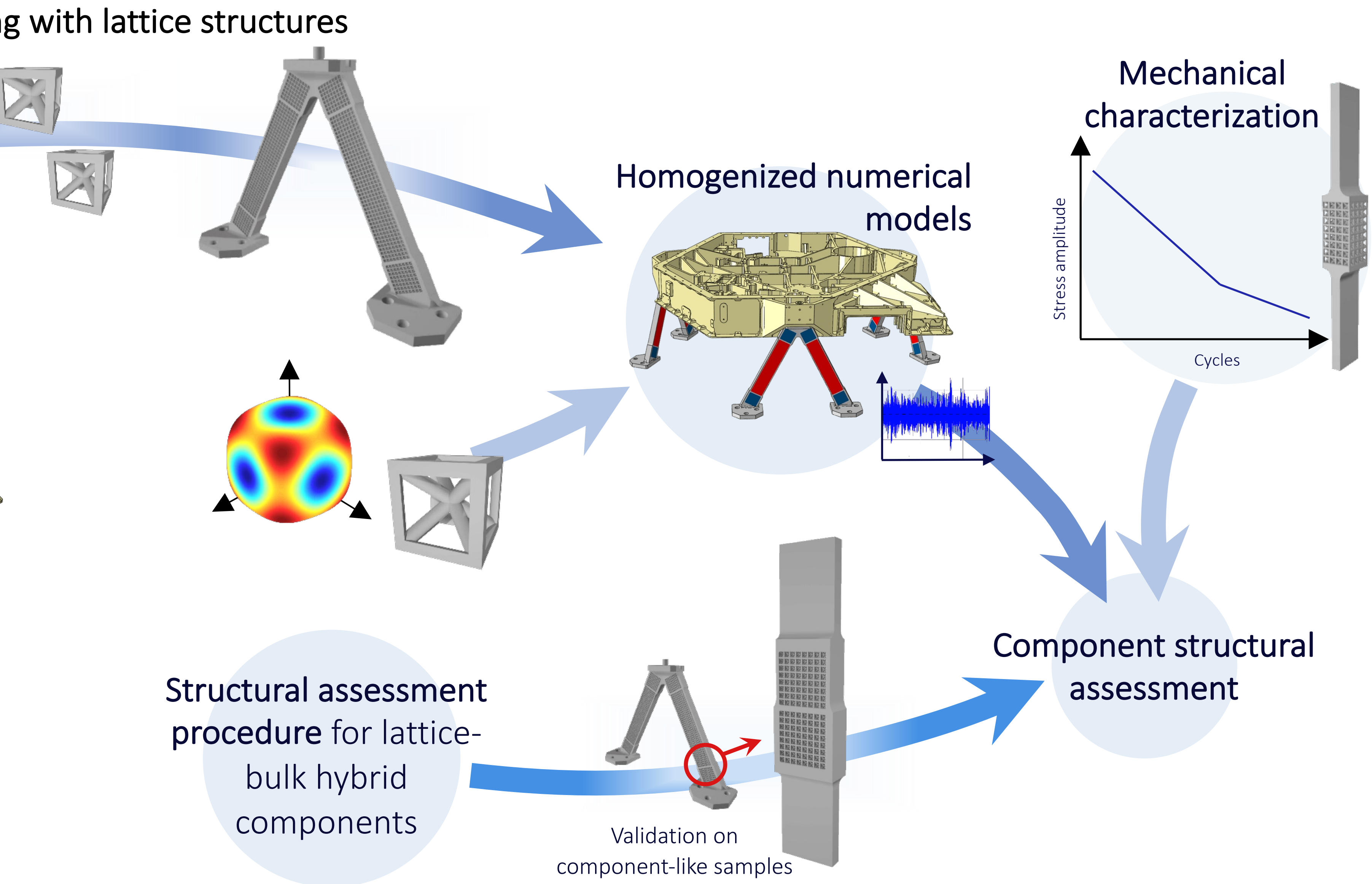
- analyzing stress- histories for fatigue analyses;
- extrapolating the measurements to determine the '1% driver' spectrum;
- elaborating significant time signals for accelerated testing of the components.

Computational Mechanical Design

Examples of MSc Theses developed by the students

Example of thesis: Isostatic mounting device for space applications



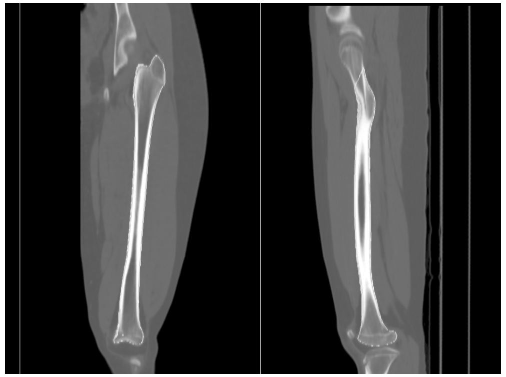


- Isostatic mounting device (IMD)
  - → Lattice-Bulk hybrid component
    - → To isostatically substain and thermally insulate the instrumentation

LEONARDO

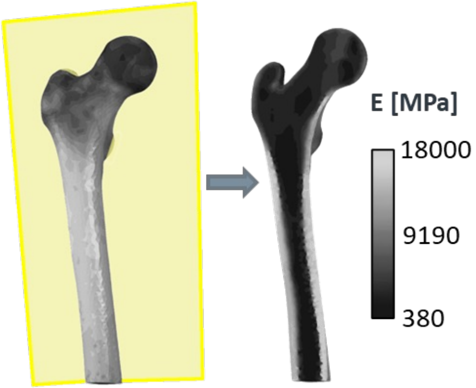
Example of thesis: porous patient-specific hip implant

Patient clinical data



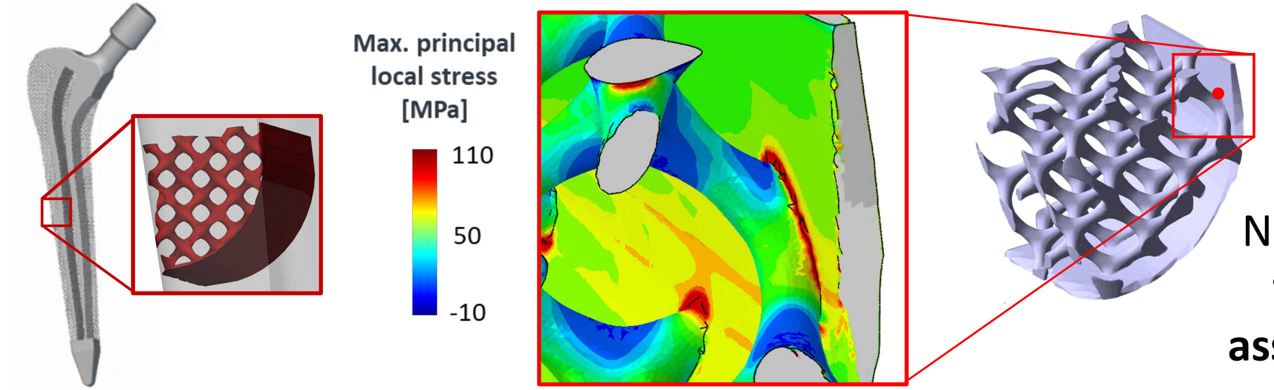
Patient CT scan are used to set **design targets** in terms of implant stiffness **to minimize stress-shielding**

PATIENT-SPECIFIC

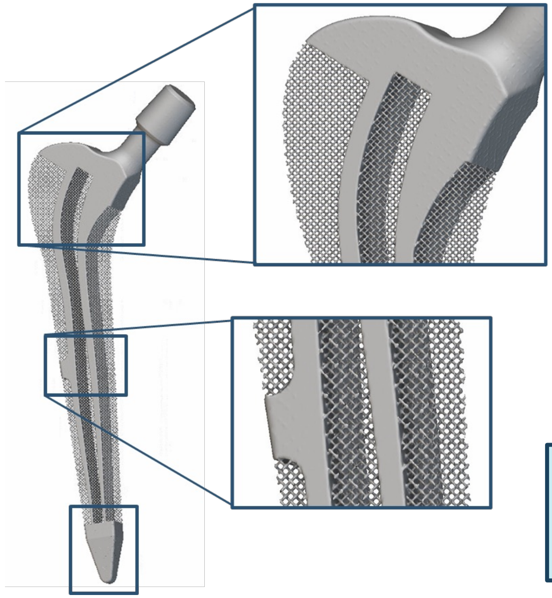


Numerical model of the patient bone

FATIGUE-RESISTANT



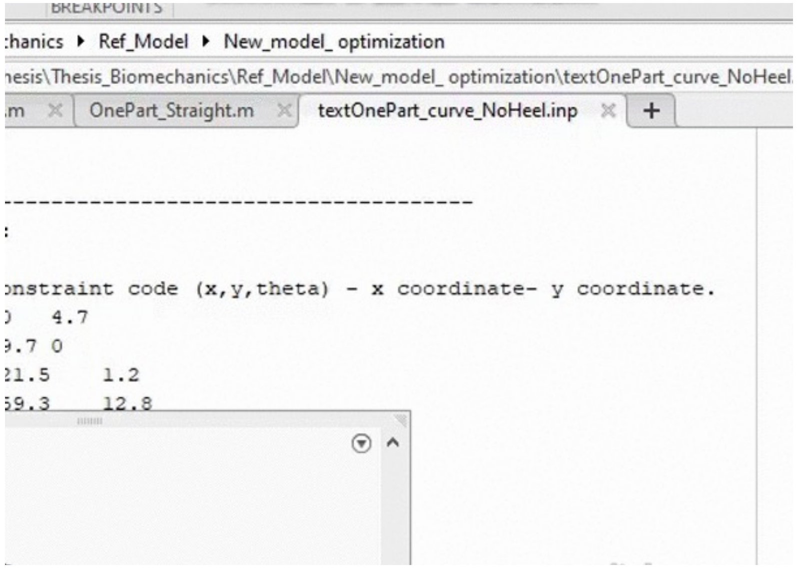
Numerical **fatigue assessment**



POROUS HIP IMPLANT DESIGN

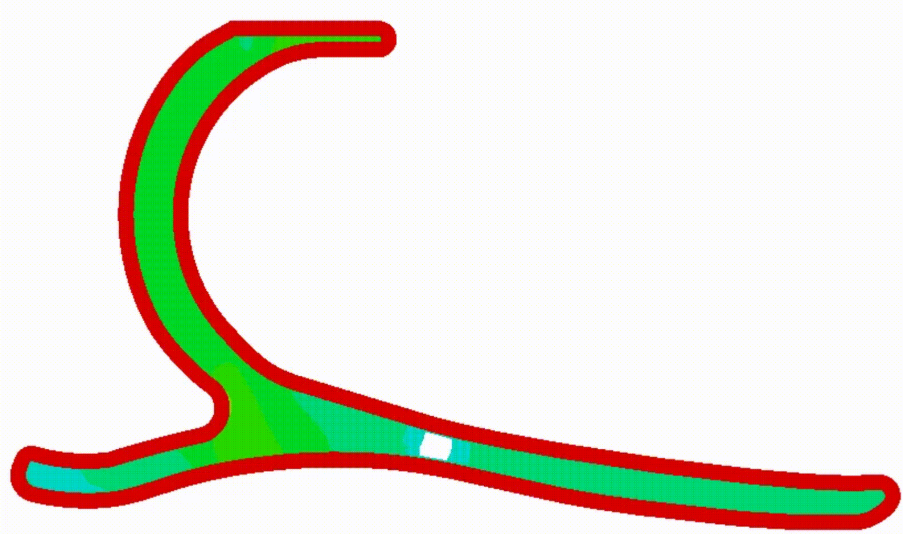
Numerical design and optimisation of a carbon fibre reinforced 3D printed foot prosthesis

Objective: design a 3D printed composite prosthetic foot with given mechanical and bio-mechanical performance and optimal shape and topology



Initial steps:

- Geometrical optimisation of a 3D printed foot prosthesis
- Development of a simulation approach for the full gait analysis considering mechanical and bio-mechanical parameters
- FE validation of the optimised solution



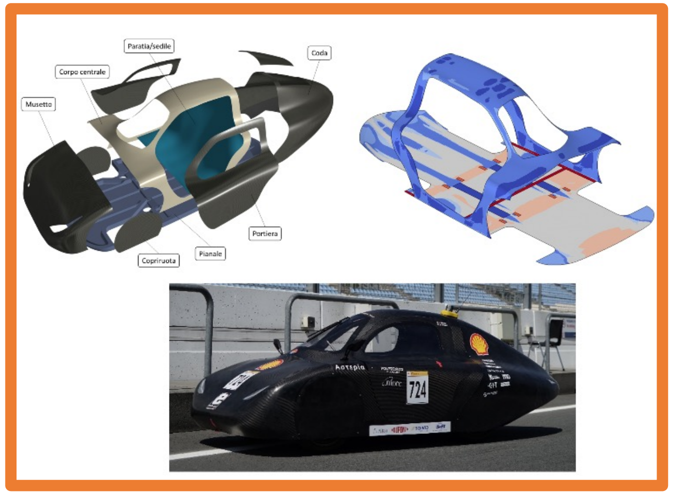
Advanced activities:

- Perform a topology optimisation analysis on the prosthesis core
- Adopt a core-less solution to optimise weight and performance of the prosthetic foot

Example of thesis: Topology Optimization

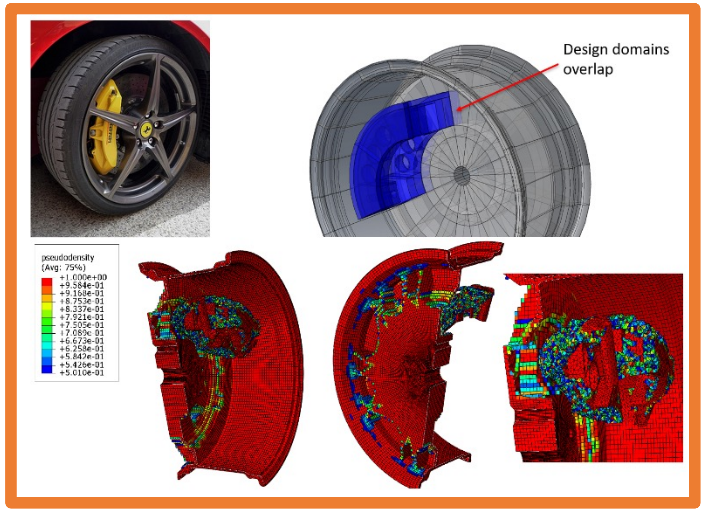
Lightweight design of an ultra-efficient electric vehicle

- Design and structural optimization of the main body of a lightweight electric vehicle for mileage competitions.



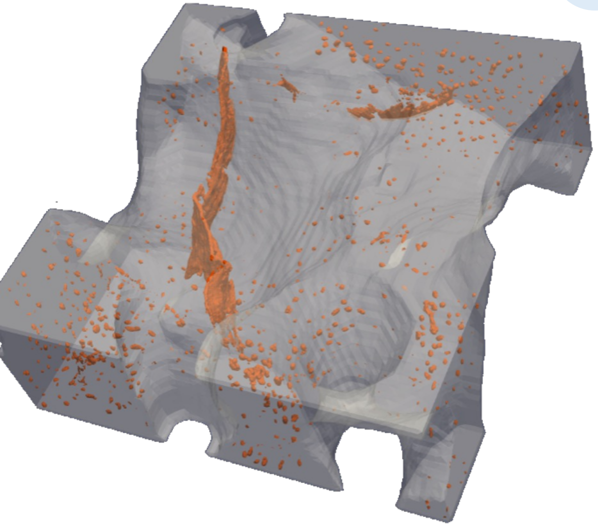
A numerical approach for topology optimization of two bodies sharing the design domain

- Innovative numerical method for TO of multiple bodies sharing a portion of the design domain
- Material distribution and space allocation are optimized simultaneously



Example of thesis: A Biomechanical Case Study

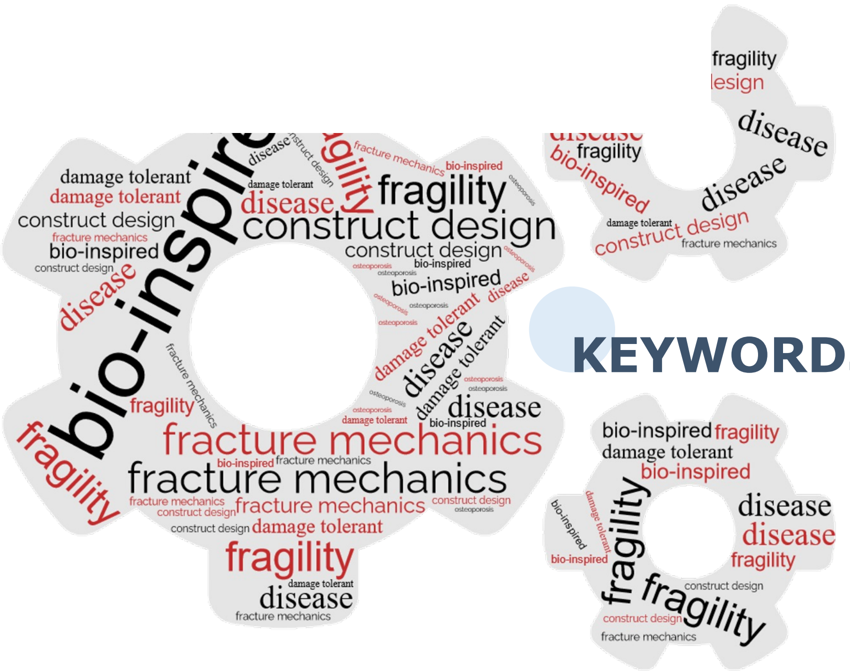
The development of new materials with enhanced performance has always presented a challenge for scientists and engineers.



CONTEXT

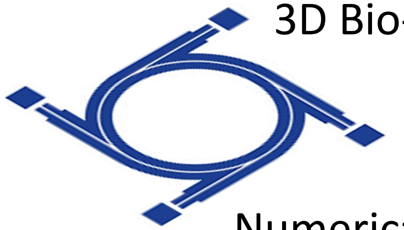
A promising approach is to study natural materials that possess unique properties and attempt to replicate their characteristics using new artificial solutions. This approach, known as **bio-inspired design**, has been utilized to develop materials that mimic the **adaptable internal structure of bone tissue**, which can specifically adjust to environmental demands.

While recent efforts have been made to apply bio-inspired design in the **healthcare** system, there is still a long way to go to overcome the burden of fragility fractures.



KEYWORDS

METHODS



3D Bio-printing

Synchrotron imaging

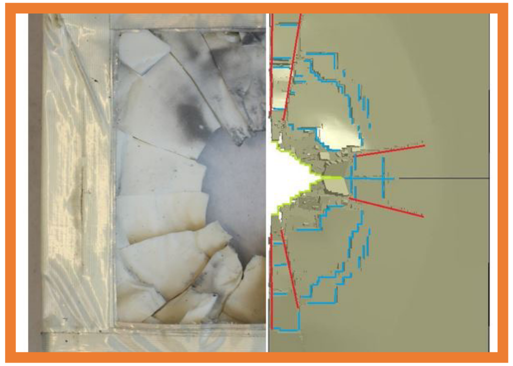
Numerical multi-scale modeling

AIM

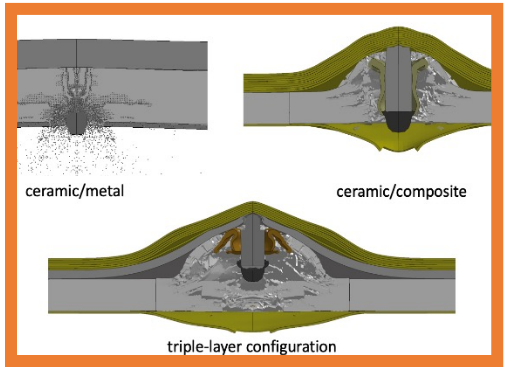
We aim at adopting a cutting-edge **multidisciplinary approach** oriented at translating bio-inspired strategies to the **design**, **realization** and **testing** of optimal **constructs for bone repair**.

Example of thesis: Impact Engineering

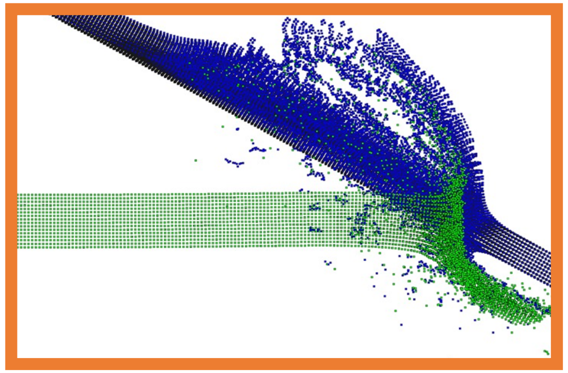
Material modelling up to the limit: plasticity, failure modes, etc



Experimental testing

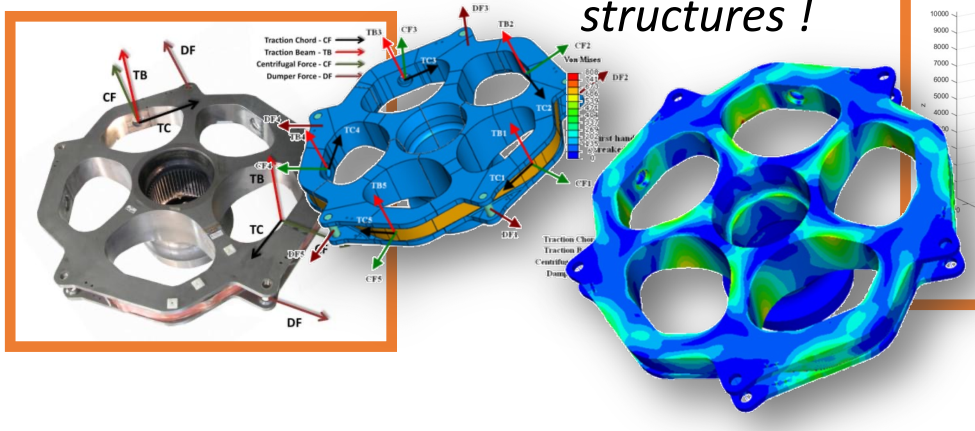


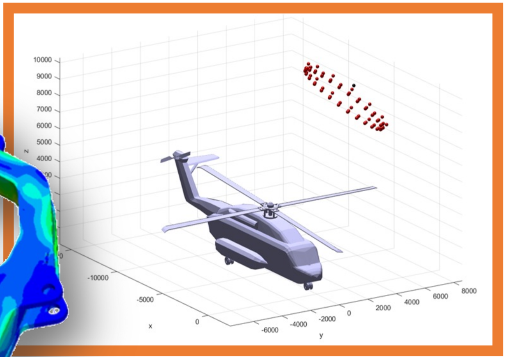
Impact (LVI, high velocity, ballistic, etc)



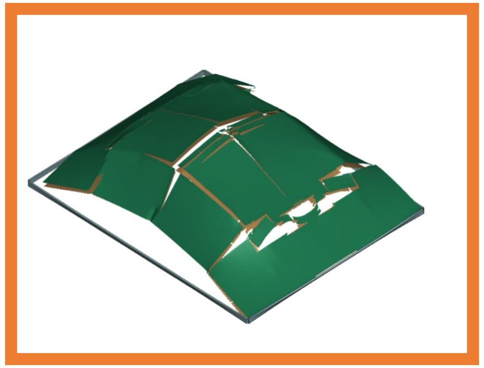
Meshless approaches

We work on actual structures !





Vulnerability

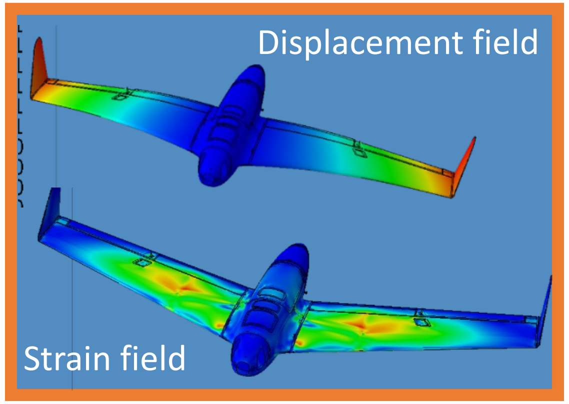


Blast, including FSI

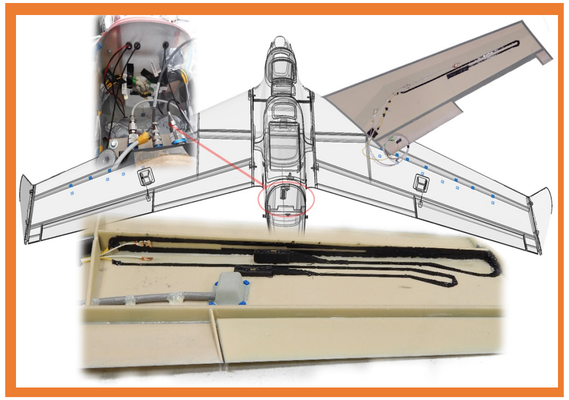
Example of thesis: Digital Twin for HUMS

Multidisciplinary thesis involving different aspects of computation mechanics, from **model** development, to **algorithm** development (artificial intelligence and statistics), **sensor** installation, and **system testing and validation**.

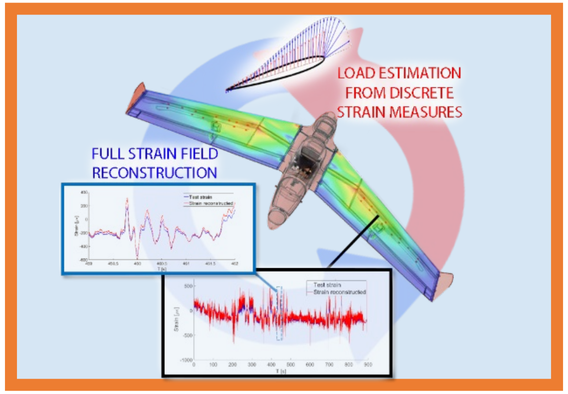
Example TITLE: real-time load identification and full-field displacement and strain reconstruction on a composite wingbox for usage monitoring



Construction of models (numerical or multiphysical)



Sensor network optimization, installation and preliminary model validation



Algorithm development for real-time fusion of models with sensor data

DT-HUMS validation with real tests and data analysis for usage monitoring

(DEMONSTRATOR)

Example of thesis: Digital Twin for HUMS

mecc

DIPARTIMENTO DI ECCELLENZA
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