Request of admission to the second year of the PhD Course

DAMAGE DETECTION IN AEROSPACE STRUCTURES

PhD Course in Space Sciences, Technologies and Measurements (STMS)

Curriculum: Sciences and Technologies for Aeronautics and Satellite Applications (STASA)
XXXIV Cycle

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RESEARCH BACKGROUND

MAIN PROBLEM

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Unavoidable presence of **cracks** in aeronautical and aerospace **structures**

MAJOR CHALLENGE

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Understanding of **fracture phenomenon** and **damage** initiation and evolution **mechanism** to **improve structural maintenance**

FINAL TARGET

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Creation of a reliable **structural health monitoring** (SHM) system

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Evaluation of damages and implementation of **continuous online monitoring** of aircraft **structures**

Example of a crack in an aircraft fuselage

HOW?

Implementation of innovative **coupled** computational **methods**

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Solution of **complex problems** involving **damage initiation** and **crack propagation** mechanisms

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Achievement of an **accurate description** of **large** and **complex structures**

PROJECT OBJECTIVES

I. Study of **CCM-PD coupling methods**: equipping of CCM based models with the capability to simulate crack formation and propagation

II. **Improvement** of the in-house **FEM-PD coupling software** for possible integration into an effective SHM system

III. Development of **reliable simulations** of **wave propagation** in the **presence of cracks**

IV. Identification of **suitable systems of sensors** for **damage detection** by means of **simulation tools**

V. **Validation** of numerical simulations through experimental activities

CCM = classical continuum mechanics

WORK METHODOLOGIES AND TOOLS (1/4)

Peridynamic Theory

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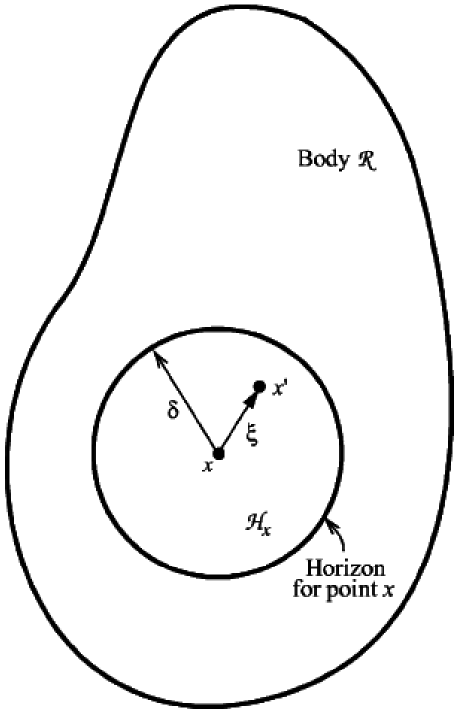
Nonlocal reformulation of classical continuum mechanics (**CCM**) based on **integro-differential equations**



Each point x in the body interacts with all the points located within its neighbourhood H_x through bonds

Fundamental equation of motion for any material point of the structure:

$$\rho(\boldsymbol{x})\ddot{\boldsymbol{u}}(\boldsymbol{x},t) = \int_{\boldsymbol{H_x}} \{\underline{\boldsymbol{T}}[\boldsymbol{x},t]\langle \boldsymbol{x}' - \boldsymbol{x}\rangle - \underline{\boldsymbol{T}}[\boldsymbol{x}',t]\langle \boldsymbol{x} - \boldsymbol{x}'\rangle\} dV_{\boldsymbol{x}'} + \boldsymbol{b}(\boldsymbol{x},t),$$

$$\boldsymbol{x}' \in \boldsymbol{H_x}$$

where:

- ρ is the mass density
- **x** is a material point of the domain R
- $\mathbf{H_x}$ is the finite neighbourhood centred at point **x**
- δ is the horizon radius
- **u** is the displacement vector field
- **b** is a prescribed body force density field
- $\underline{\boldsymbol{T}}[\boldsymbol{x},t]\langle \boldsymbol{x}' - \boldsymbol{x}\rangle$ is the force density vector that point **x′** exerts on point **x**

WORK METHODOLOGIES AND TOOLS (2/4)

FEM-PD coupling

Weak points of peridynamics numerical methods

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1. PD methods are **computationally very expensive**
2. **Bandwidth** of the stiffness matrix in PD software is **bigger** than that in CCM software
3. Defining **boundary conditions** in a non-local theory introduces some difficulties

SOLUTION →

Coupling of FEM meshes with PD grids is very convenient

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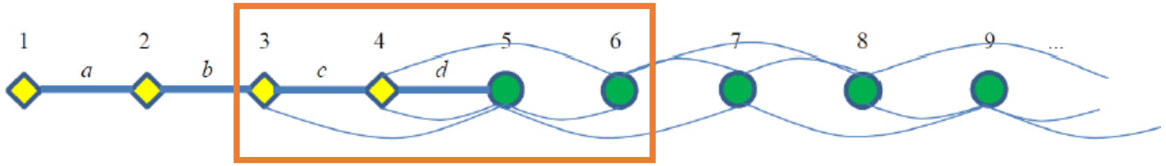
1. **Simple coupling method** that can be **easily introduced** in **commercial FE codes**
2. **PD grids** applied only to **portions** of the model where **cracks** are **likely to develop**
3. **No** need to **interpolate displacements** or **forces** between PD and FEM portions
4. **All PD nodes** have a **fully internal family**
5. **No arbitrary** choice or **blending functions** required

Proposed FEM-PD coupling strategy

The coupling method can be easily introduced with the help of a 1D model



Internal forces acting on a **node** are of the **same nature** as the **node itself**

A coupling zone is defined where **forces** are **exchanged** between the **FEM** and **PD parts** of the domain

Assembly of the **global stiffness matrix**: **equilibrium equations** of **FEM** (**PD**) **nodes** contain only **terms** coming from the FEM (PD) **formulation**

This 1D coupled model produces the following system of equations:

$$\begin{bmatrix} a & -a & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \vdots \\ -a & 2a & -a & 0 & 0 & 0 & 0 & 0 & 0 & \vdots \\ 0 & -a & 2a & -a & 0 & 0 & 0 & 0 & 0 & \vdots \\ 0 & 0 & -a & 2a & -a & 0 & 0 & 0 & 0 & \vdots \\ 0 & 0 & -\frac{1}{4}b & -b & \frac{5}{2}b & -b & -\frac{1}{4}b & 0 & 0 & \vdots \\ 0 & 0 & 0 & -\frac{1}{4}b & -b & \frac{5}{2}b & -b & -\frac{1}{4}b & 0 & \vdots \\ 0 & 0 & 0 & 0 & -\frac{1}{4}b & -b & \frac{5}{2}b & -b & -\frac{1}{4}b & \vdots \\ 0 & 0 & 0 & 0 & \dots & \dots & \dots & \ddots & \vdots & \vdots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \ddots & \vdots \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ u_N \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ f_N \end{bmatrix}$$

- a := EA/Δx , b := cViVj/Δx
- $\{u_i\}_{i=1,\dots\dots,N}$ = nodal displacements, $\{f_i\}_{i=1,\dots\dots,N}$ = external nodal forces
- **EA** = product between Young's modulus and cross-sectional area
- **Vi** = A Δx is the volume associated with node i
- **Δx** = grid spacing of the discretized numerical model
- **c** = micromodulus constant

WORK METHODOLOGIES AND TOOLS (4/4)

Wave propagation modelling and nonlinear ultrasonic techniques

As **experimental testing** is very **expensive** and **time-consuming**

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It is **essential** to develop **novel computational methods** for **damage detection and evaluation**

⬇

Basis of damage detection

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Wave propagation **features** are **different** in **damaged** and **pristine** materials

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Defects can be detected **analysing** the **interactions** between **materials** and **propagating waves**

➡ **Very small damages** (when signal wavelength is greater than the size of each micro-cracks)

➡ Development of **reliable nonlinear ultrasonic computational tools** is essential

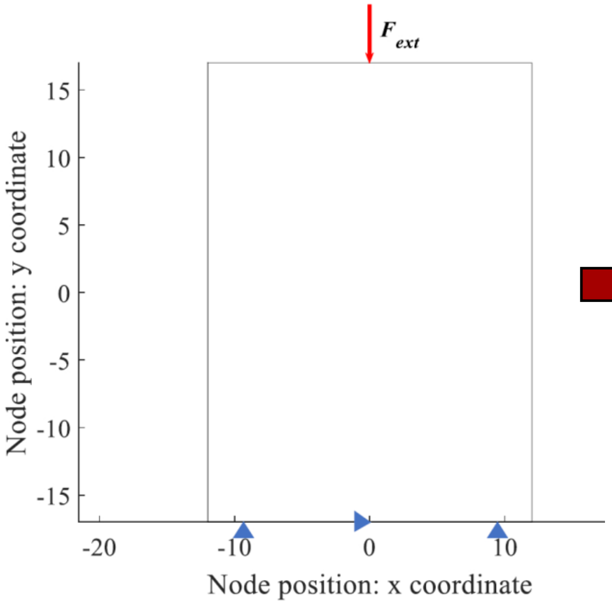
TASKS COMPLETED IN THE FIRST YEAR OF PhD COURSE

- **TASK 1: Bibliographic research on Peridynamics and wave propagation State of Art**
  - **Bond-based** and **state-based PD** theory
  - **CCM-PD coupling** strategies and coupled Multiphysics problems
  - **Wave propagation**: main features and numerical modelling techniques
- **TASK 2: Investigation of bond-based FEM-PD coupling software developed at the UniPD**
  - Study of **FEM software**, **MATLAB** environment and of **bond/state-based formulations**
  - Deep analysis of **FEM-PD coupling methods**: main features, strengths and weak points
  - Study of **nonlinear ultrasonic numerical tools** for damage detection and evaluation
- **TASK 3: Implementation of different structural elements**
  - Simulations on **beam** and **plate elements** and comparison with benchmark problems
- **TASK 4: Further development of the coupling method**
  - Analysis of **overall static equilibrium** and numerical **convergence** issues
  - Writing of **subroutines** to insert **PD codes** into **commercial software**
- **TASK 5: International collaborations**
  - Dr. **Pablo Seleson** (Oak Ridge National Laboratory, US): drafting of a **manuscript**

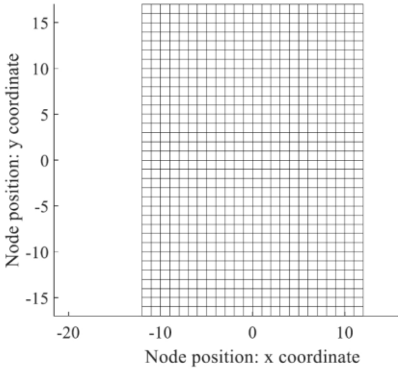
STUDY OF THE IN-HOUSE FEM-PD COUPLING SOFTWARE

Statement of the problem

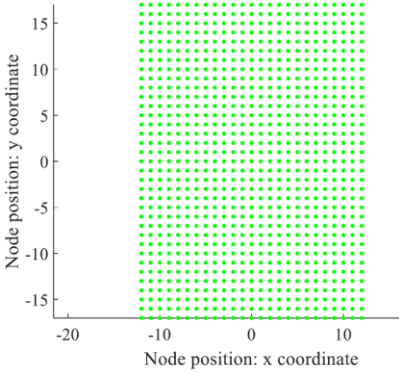
Often-overlooked issue in the use of **coupled computational methods** → **lack of overall static equilibrium**



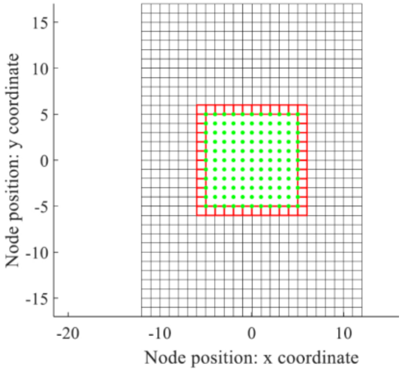
2D example used to numerically investigate the static equilibrium issue



FEM-only model



PD-only model



FEM-PD coupled model

Evaluation of the **sum** of the **vertical reactions**, $\sum \textbf{Reactions}$, and of the **relative out-of-balance errors**, e_{rel}, for the three models

$$e_{rel} := \frac{F_{ext} + \sum \text{Reactions}}{|F_{ext}|}$$

Computational technique	F_{ext}	$\sum$ Reactions	e_{rel}
FEM-only model	-10	9.9999	-2.51×10^{-13}
PD-only model	-10	10.0000	5.55×10^{-13}
Coupled FEM-PD model	-10	10.1425	1.42×10^{-02}

Out-of-balance forces: 'small' compared to external forces, but **not** as small as **round-off errors**

FINAL REMARKS

- For the **first time**: identification of a **coupling error** given by the **lack of overall equilibrium** in **static problems**
- It is easy to evaluate the relative out-of-balance error by computing the out-of-balance forces
- The relative out-of-balance **error** is a **fraction of a per cent** and **reduces as** $\boldsymbol{\delta \rightarrow 0}$
- The **tolerance** used in an **implicit solution** of a coupled numerical problem should be **carefully chosen**

FUTURE WORK

- **TASK 1: Further development and extension of the in-house FEM-PD coupling software**
  - Extension of the bond-based FEM-PD coupling software developed at the UniPD to 3D systems
- **TASK 2: Development of reliable nonlinear ultrasonic numerical techniques**
  - Damage evaluation and crack propagation modelling
- **TASK 3: Implementation of the adaptive refinement/coarsening approach**
  - Implementation of the adaptive refinement approach in an integrated code for multi-dimensional analyses
- **TASK 4: Study of Multiphysics phenomena and implementation in FEM commercial codes**
  - Simulations on Multiphysics problems
  - Comparison between obtained numerical results and results available in literature
- **TASK 5: Further collaborations with European and extra-European research centers**
  - Further investigation of the coupling method: **Dr. P. Seleson**, Oak Ridge National Laboratory, US
  - Validation of numerical simulation results: **Prof. P. Packo**, AGH UST, Krakow, Poland
  - Improvement of the knowledge on Peridynamics: **Prof. F. Bobaru**, University of Nebraska at Lincoln, US

LIST OF PUBLICATIONS

Journal paper:

G. Ongaro, U. Galvanetto, T. Ni, P. Seleson, M. Zaccariotto, Overall equilibrium in FEM-PD coupled models, submitted to Computer Methods in Applied Mechanics and Engineering (2019)

Conference contributions:

CFRAC2019 Germany
Overall structural equilibrium in Computational Methods Coupling Peridynamics with Classical Mechanics
M. Zaccariotto, T. Ni, G. Ongaro, P. Seleson, U. Galvanetto

USNCCM15 Austin
Global Equilibrium in Computational Methods Coupling Peridynamics with Classical Mechanics
U. Galvanetto, T. Ni, G. Ongaro, P. Seleson, M. Zaccariotto

ICCM2019 Singapore
The Problem of Static Equilibrium in Computational Methods Coupling Classical Mechanics and Peridynamics
U. Galvanetto, T. Ni, G. Ongaro, P. Seleson, M. Zaccariotto

AIDAA 2019
Computational methods coupling peridynamics with classical mechanics: out-of-balance forces in overall structural equilibrium
M. Zaccariotto, G. Ongaro, T. Ni, P. Seleson, U. Galvanetto

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THANK YOU FOR YOUR ATTENTION

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