UNIVERSITÀ
DEGLI STUDI
DI PADOVA

A FEM-Peridynamics coupling approach for the simulation of dynamic non-linear multi-physics problems involving crack propagation

Francesco Scabbia - 36th Cycle

Proposal of research activity - 06/11/2020

PhD course in **Sciences, Technologies and Measurements for Space (STSM)**

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

Table of contents

1. Introduction

Problem
Dielectric breakdown phenomena causing damage in aerospace structures

Current solution
Thickening of metallic external layers and inspections after every event,
with consequent increase of costs

Proposed solution
Development of a reliable numerical tool to improve safety and limit financial losses

Aircraft struck by a lightning.

Dielectric breakdown in a solid insulator.

Damage caused by a lightning strike on an aircraft rudder.

2. Research background

Peridynamics

Non-local continuum theory with an integral formulation capable of modeling discontinuities in the displacement field, such as crack initiation and evolution of any type.

Equation of motion of point x

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathrm{H}_{\mathbf{x}}} \left(\underline{\mathbf{T}}[\mathbf{x},t]\langle\boldsymbol{\xi}\rangle - \underline{\mathbf{T}}[\mathbf{x}',t]\langle\text{-}\boldsymbol{\xi}\rangle\right) \mathrm{d}V_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

ρ : density

$\mathbf{u}$: displacement vector field

δ : horizon

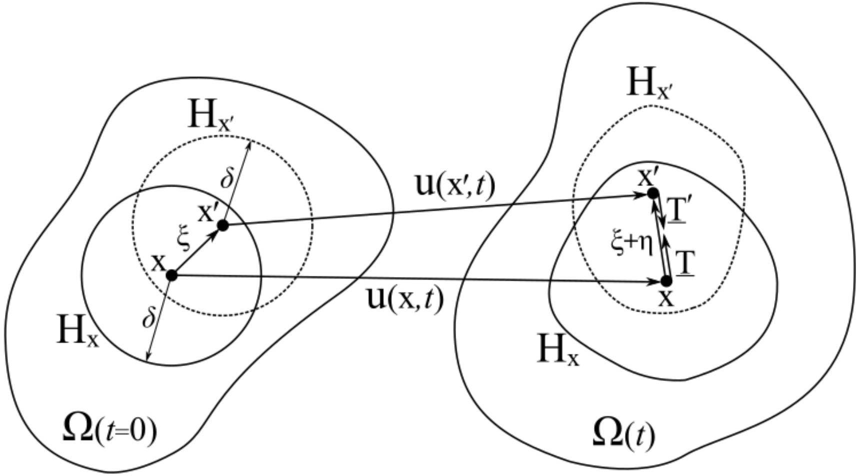
$\mathbf{b}$: body force vector

$\boldsymbol{\xi} = \mathbf{x}' - \mathbf{x}$: relative position vector (bond)

$\boldsymbol{\eta} = \mathbf{u}(\mathbf{x}',t) - \mathbf{u}(\mathbf{x},t)$: relative displacement vector

$\underline{\mathbf{T}}[\mathbf{x},t]\langle\boldsymbol{\xi}\rangle = \underline{\mathbf{T}}$: force density vector state of point x

$\underline{\mathbf{T}}[\mathbf{x}',t]\langle\text{-}\boldsymbol{\xi}\rangle = \underline{\mathbf{T}}'$: force density vector state of point x’



Reference and deformed configuration of a peridynamic body Ω: each point x interacts with the points x’ in its neighborhood H_x through the bonds.

2. Research background

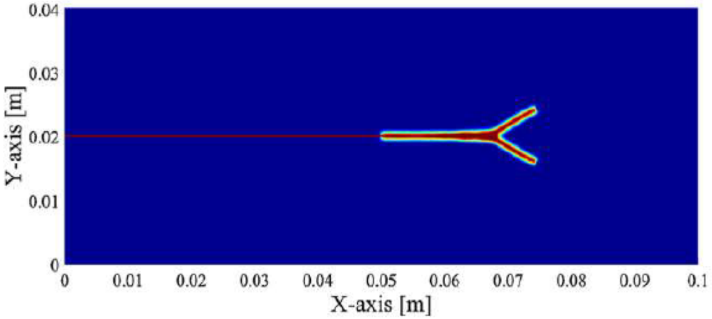
Peridynamics

Main advantages

1. Introduction of the concept of structural damage for a material point
2. No a-priori knowledge about crack initiation and propagation is required

Disadvantages

1. Higher computational cost than classical continuum models (such as FEM)
2. Issues on mechanical properties near the boundary (surface effect) and on the imposition of boundary conditions



Simulation of a crack propagation in a pre-notched specimen modeled with Peridynamics.

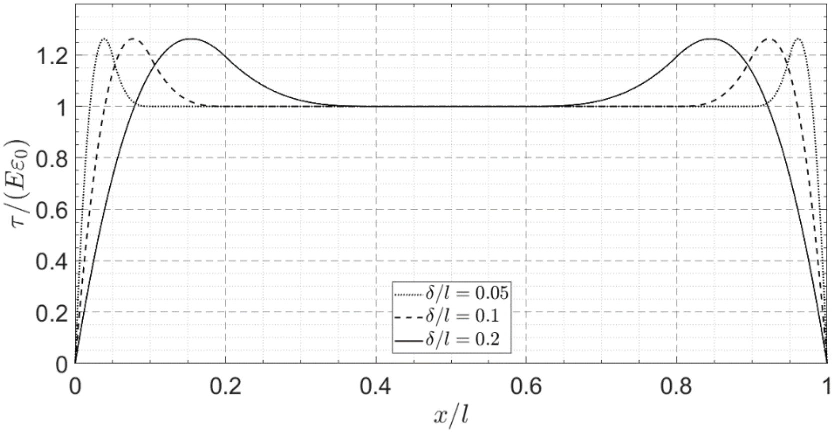
3. Project objectives

1. Development of an innovative method to mitigate boundary problems due to peridynamic non-locality
2. Incorporation of data-driven computing paradigm in Peridynamics
3. Implementation of the FEM-Peridynamics multi-physics coupling for electro-thermo-mechanical problems
4. Development of the multi-physics FEM-Peridynamics coupling approach for composite materials
5. Model validation against literature data and through experimental activities

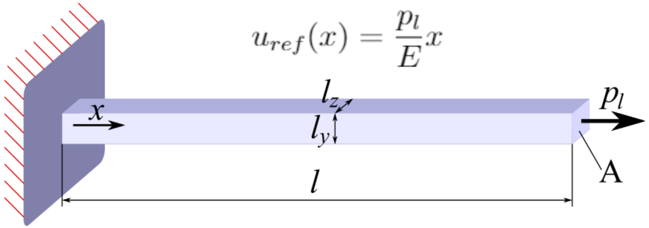
4. Work methodology and tools

Mitigation of boundary problems

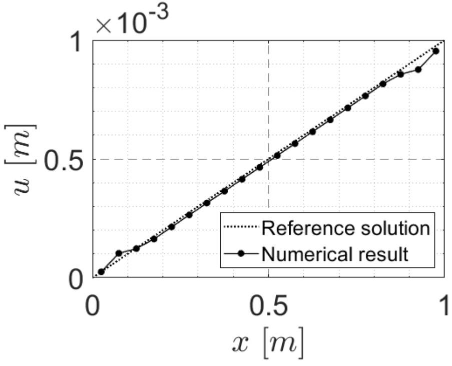
A novel method, involving a layer of fictitious nodes above the exterior surface of the body, is proposed in order to mitigate the surface effect and properly impose the non-local boundary conditions in Peridynamics.



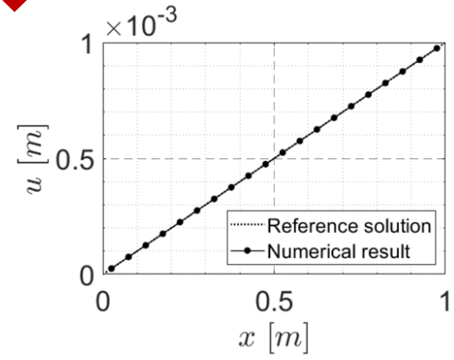
Stiffness fluctuation near the boundary due to the surface effect



1-dimensional constant strain example.

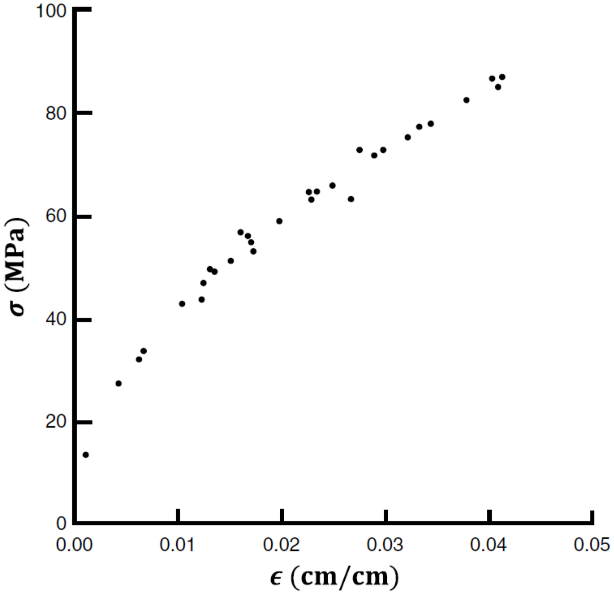


Solution without correction.



Solution with the proposed method.

4. Work methodology and tools



Typical data set of the experimental stress-strain diagram.

Data-driven computing paradigm

Calculations are carried out directly from experimental material data, bypassing the empirical conventional step of formulation of a constitutive model.

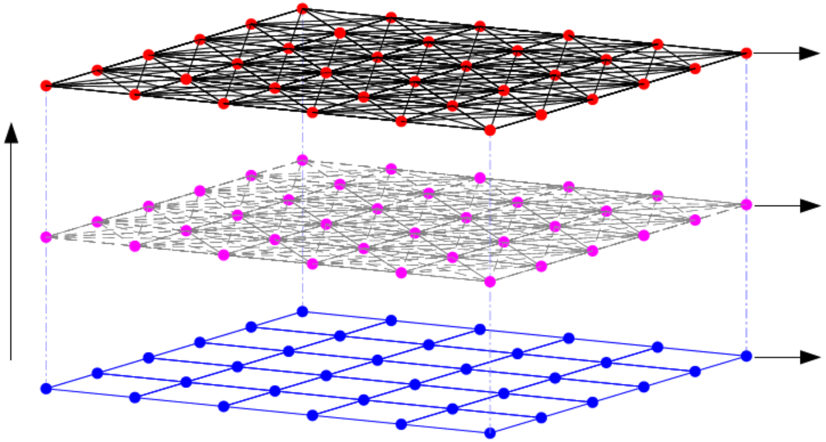
Incorporation in Peridynamics

The data-driven computing paradigm can be included in the peridynamic definition of material property.

4. Work methodology and tools

FEM-Peridynamics multi-physics coupling

Peridynamic theory is employed to model the mechanical field since it is suitable to accurately simulate the initiation and propagation of cracks.



Mechanical field
(governed by Peridynamics)

Coupling layer
(peridynamic formulation for the thermal and electrical variables)

Thermal and electrical fields
(governed by FEM)

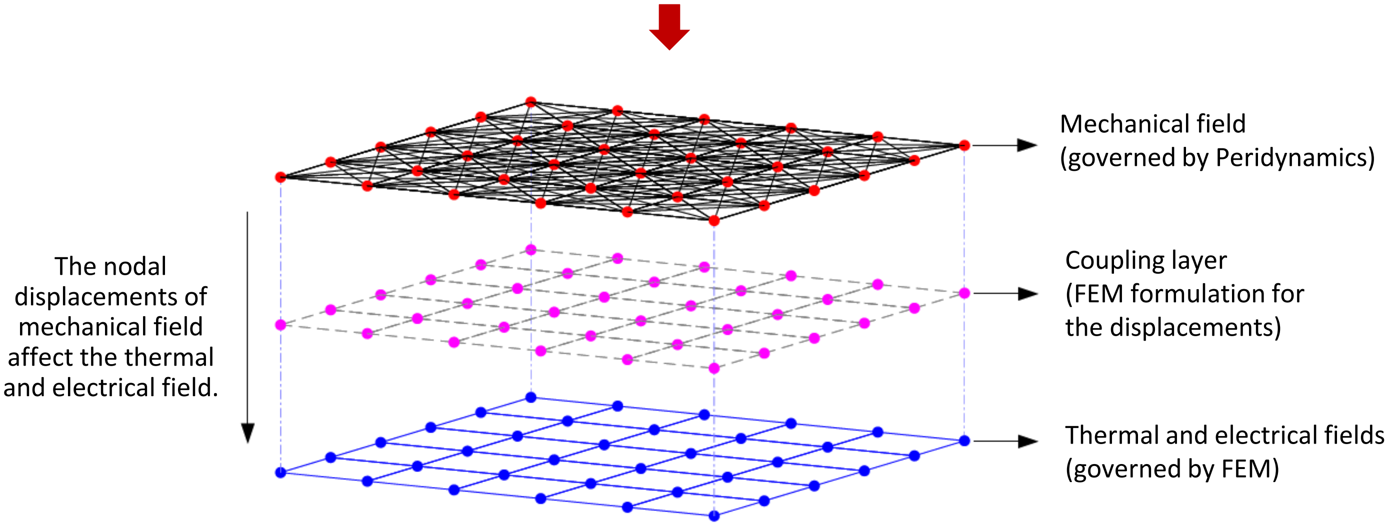
The nodal variables of thermal and electrical fields affect the deformation of the mechanical field.

Peridynamic formulation of the mechanical problem.

4. Work methodology and tools

FEM-Peridynamics multi-physics coupling

FEM is employed to model the thermal and electrical fields since it reduces the computational time of the simulation.



The nodal displacements of mechanical field affect the thermal and electrical field.

Mechanical field (governed by Peridynamics)

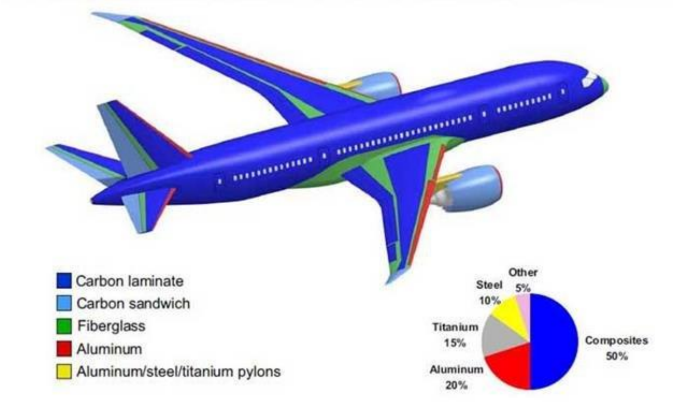
Coupling layer (FEM formulation for the displacements)

Thermal and electrical fields (governed by FEM)

FEM formulation of the thermal and electrical problem.

4. Work methodology and tools

Development of the proposed method for composites



Materials in Boeing 787.

The quantity of composite materials in aircraft and spacecraft structures is rapidly increasing.

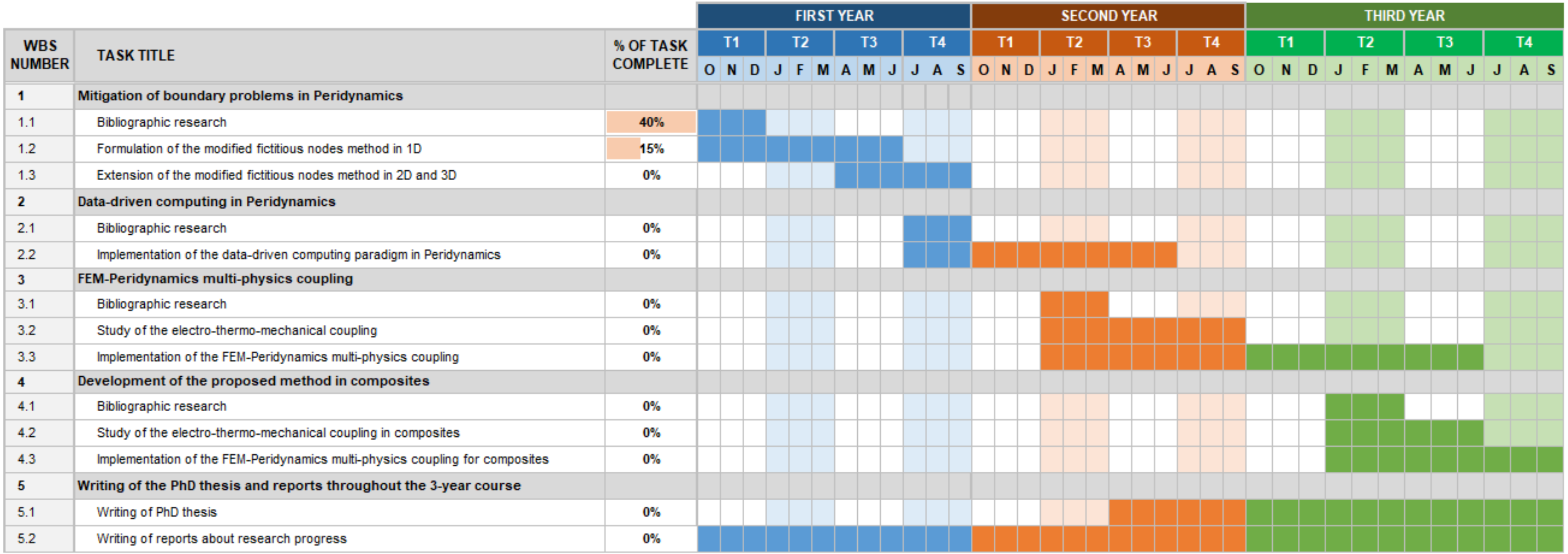
The polymeric matrix of the composites can be severely damaged by a lightning strike.

The extension of the proposed multi-physics model to composite materials will be useful to improve aircraft design methods.

5. Research methodology and schedule

Gantt chart

PHD STUDENT	Francesco Scabbia	DATE	06/11/2020
PHD THESIS	A FEM-Peridynamics coupling approach for the simulation of dynamic non-linear multi-physics problems involving crack propagation	ADMISSION TO	First year



WBS NUMBER	TASK TITLE	% OF TASK COMPLETE	FIRST YEAR												SECOND YEAR												THIRD YEAR											
			T1			T2			T3			T4			T1			T2			T3			T4			T1			T2			T3			T4		
			O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
1	**Mitigation of boundary problems in Peridynamics**																																					
1.1	Bibliographic research	40%	■	■	■																																	
1.2	Formulation of the modified fictitious nodes method in 1D	15%	■	■	■	■	■	■	■	■	■																											
1.3	Extension of the modified fictitious nodes method in 2D and 3D	0%							■	■	■	■	■	■																								
2	**Data-driven computing in Peridynamics**																																					
2.1	Bibliographic research	0%										■	■	■																								
2.2	Implementation of the data-driven computing paradigm in Peridynamics	0%										■	■	■	■	■	■	■	■	■	■	■	■															
3	**FEM-Peridynamics multi-physics coupling**																																					
3.1	Bibliographic research	0%																■	■	■																		
3.2	Study of the electro-thermo-mechanical coupling	0%																■	■	■	■	■	■	■	■	■												
3.3	Implementation of the FEM-Peridynamics multi-physics coupling	0%																■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
4	**Development of the proposed method in composites**																																					
4.1	Bibliographic research	0%																											■	■	■						
4.2	Study of the electro-thermo-mechanical coupling in composites	0%																											■	■	■	■	■	■			
4.3	Implementation of the FEM-Peridynamics multi-physics coupling for composites	0%																											■	■	■	■	■	■	■	■	■
5	**Writing of the PhD thesis and reports throughout the 3-year course**																																					
5.1	Writing of PhD thesis	0%																			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
5.2	Writing of reports about research progress	0%	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

6. Final remarks

Main proposed research activities

1. Formulation of an innovative fictitious nodes method to mitigate the surface effect and properly impose the boundary conditions in Peridynamics
2. Adoption of the data-driven computing paradigm to define the material properties in Peridynamics
3. Implementation of a FEM-Peridynamics coupling approach to model electro-thermo-mechanical phenomena involving fracture, both in homogeneous and composite materials

Thanks for the attention

1222 · 2022
800
ANNI

UNIVERSITÀ
DEGLI STUDI
DI PADOVA