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UNIVERSITÀ DEGLI STUDI DI PADOVA

An improved peridynamic framework for the accurate solution of multi-physics problems involving fracture

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

Table of contents

1. Introduction

Problem
Multi-physics phenomena causing damage in aerospace structures

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Current solution
Design with high safety margins, with consequent increase of costs

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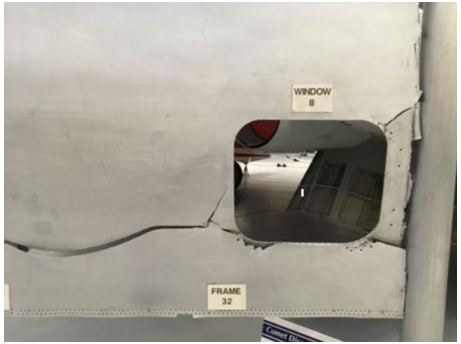
Proposed solution
Development of a reliable numerical tool to improve safety and limit financial losses



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

$$\rho(\mathbf{x})\,\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathcal{H}_{\mathbf{x}}} \mathbf{f}(\mathbf{x},\mathbf{x}',t)\,\mathrm{d}V_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

ρ : density

$\mathbf{u}$: displacement vector field

δ : horizon

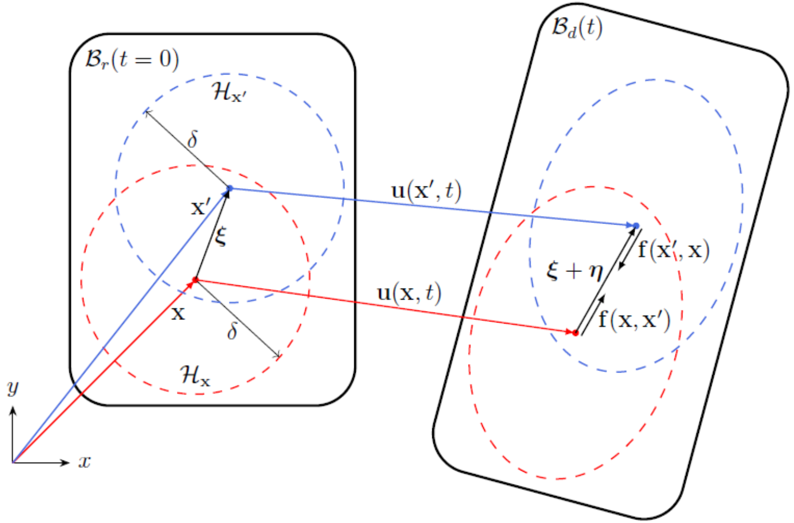
$\mathbf{b}$: body force vector

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

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

$\mathbf{f}(\mathbf{x},\mathbf{x}',t)$: pairwise force density

$\mathcal{H}_{\mathbf{x}}$: neighborhood



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.

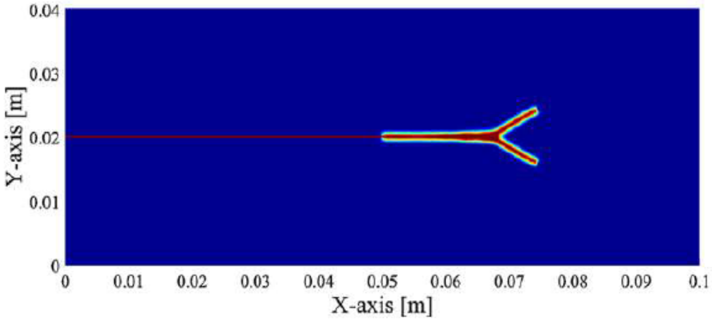
Peridynamics

Main advantages

1. Introduction of the concept of structural damage for a material point
2. No ad-hoc criteria to model crack initiation and propagation

Disadvantages

1. Higher computational cost than classical continuum models
2. Accurate quadrature is required
3. Issues on mechanical properties near the boundary (surface effect) and on the imposition of boundary conditions

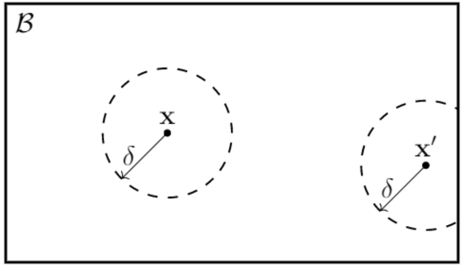


Simulation of a crack propagation in a pre-notched specimen modeled with Peridynamics.

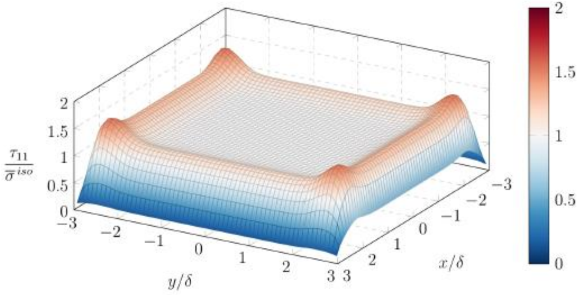
3. Project objectives

1. Development of an innovative method to mitigate boundary problems due to peridynamic non-locality
2. Improvement of currently used algorithms to compute quadrature weights
3. Coupling of Peridynamics with local models to reduce the overall computational cost
4. Solution to complex multi-physics problems with the improved peridynamic framework

Mitigation of boundary problems

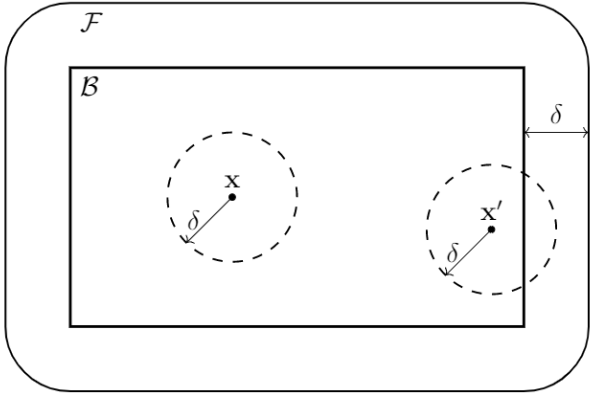


Peridynamic body without boundary corrections.

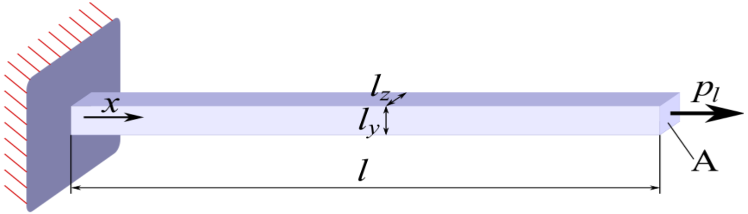


Stiffness fluctuation (surface effect) near the boundary due to the incomplete neighborhoods.

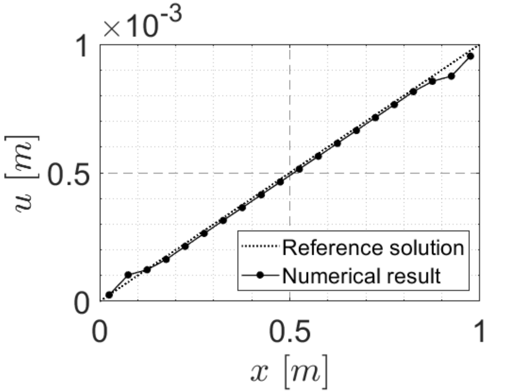
A novel method is proposed in order to mitigate the surface effect and properly impose the non-local boundary conditions in Peridynamics.



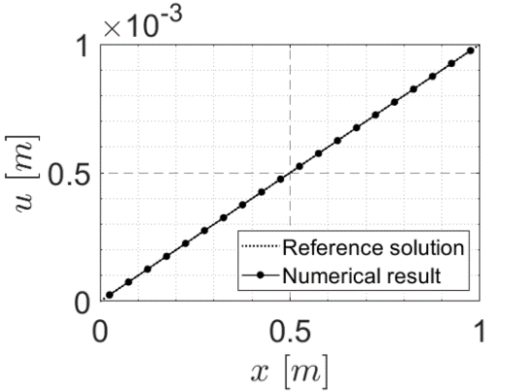
Mitigation of boundary problems



1-dimensional example.



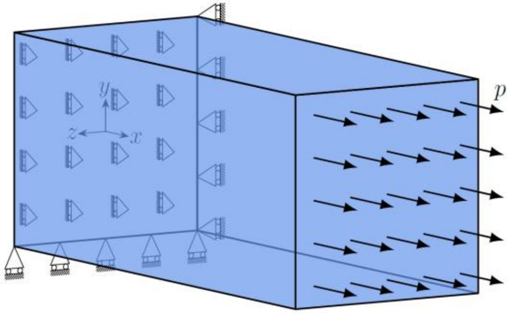
Solution without correction.



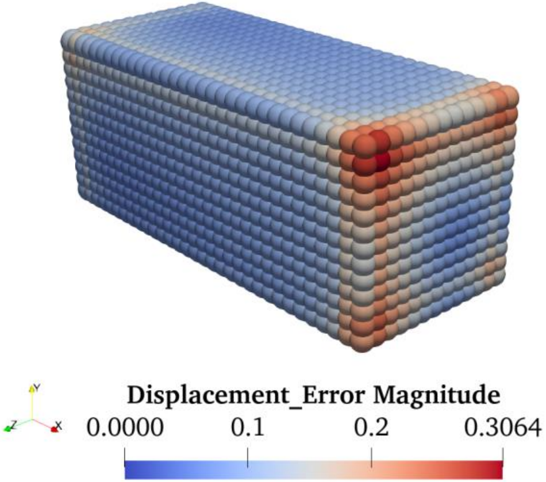
Solution with the proposed method.

4. Current results of the work

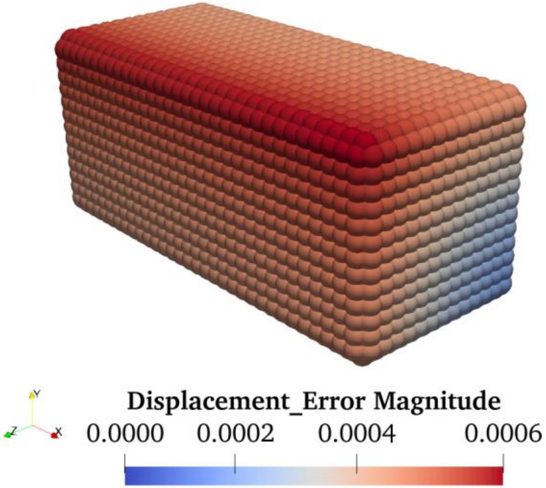
Mitigation of boundary problems



3-dimensional example.



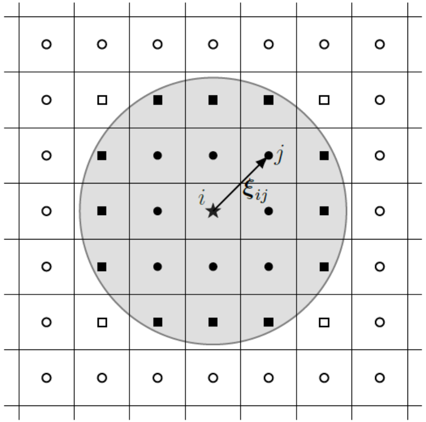
Errors of the solution without correction.



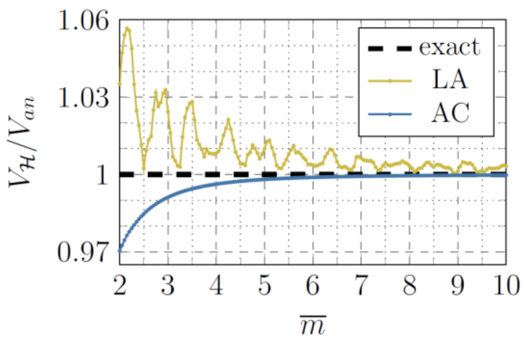
Errors of the solution with the proposed method.

New algorithm for peridynamic quadrature

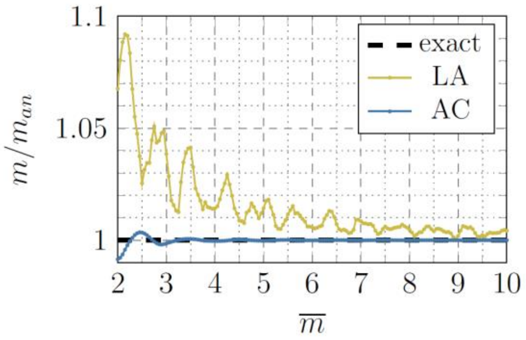
An algorithm to compute accurately quadrature weights in 3D peridynamic models is developed.



Discretization of the neighborhood (2D model for image clarity).



Normalized volume of the neighborhood.

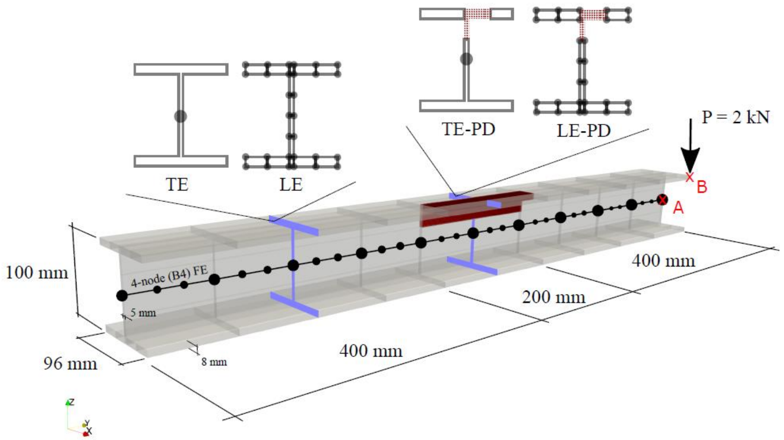


Normalized weighted volume.

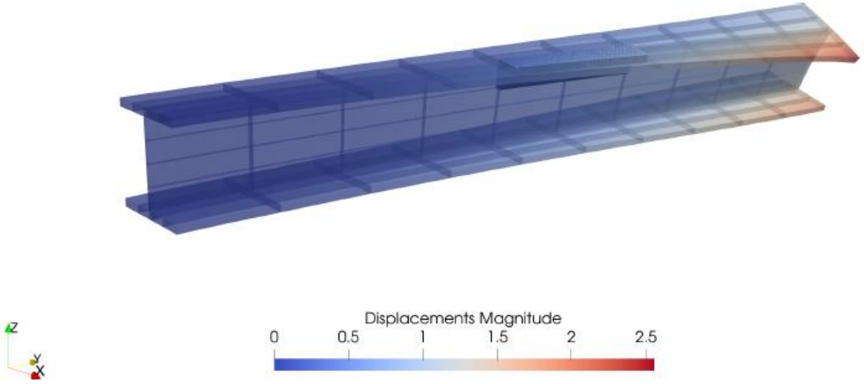
4. Current results of the work

Coupling of Peridynamics with local models

Peridynamics is coupled with Carrera Unified Formulation (CUF), a local theory able to reproduce arbitrary kinematic models, to reduce the overall computational cost.



Coupled model.

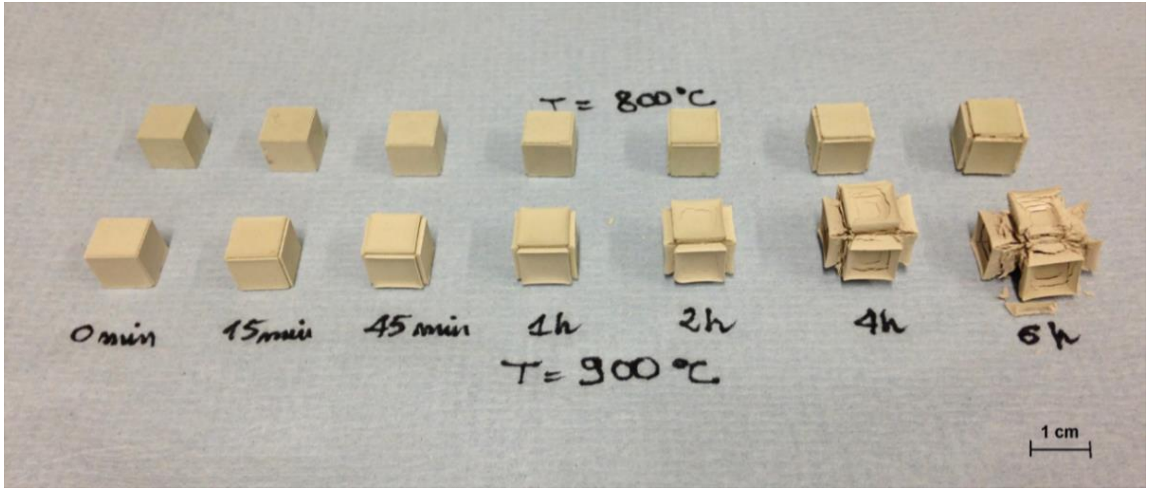


Numerical results, in good agreement with the results of a refined 3D FEM model.

5. Future developments

Solution to multi-physics problems with Peridynamics

The causes of structural damaging can be very different due to the wide variety of materials, environmental conditions and loading modes. Therefore, a numerical tool to model multi-physics problems is useful to improve safety, design, performance, and financial return of aerospace vehicles.



Oxidation of a cube made of zirconium carbide.

5. Research schedule

Gantt chart

WBS NUMBER	TASK TITLE	% OF TASK COMPLETE
1	Mitigation of boundary problems in Peridynamics	
1.1	Bibliographic research	100%
1.2	Formulation of the Taylor-based extrapolation method in 1D	100%
1.2.1	Analytical analysis of the surface effect in 1D	100%
1.2.2	Correction of the surface effect in 1D	100%
1.2.3	Proper imposition of the peridynamic boundary conditions in 1D	100%
1.3	Extension of the Taylor-based extrapolation method to 2D and 3D	100%
1.3.1	Numerical analysis of the surface effect in 2D	100%
1.3.2	Numerical computation of the force flux in 2D and 3D	100%
1.3.3	Numerical examples of the Taylor-based extrapolation method in 2D and 3D	100%
2	New algorithm for numerical quadrature in Peridynamics	
2.1	Bibliographic research	100%
2.2	Development of the new algorithm for peridynamic numerical quadrature	100%
2.2.1	Development of the new algorithm in 2D	100%
2.2.2	Extension of the new algorithm to 3D	100%
3	Coupling of Peridynamics with Carrera Unified Formulation	
3.1	Bibliographic research	100%
3.2	Coupling between Peridynamics and Carrera Unified Formulation	83%
3.2.1	Implementation of state-based Peridynamics in Mul2 software	100%
3.2.2	Novel method to couple Peridynamics and Carrera Unified Formulation	75%
4	Solution of complex multi-physics problems involving fracture with Peridynamics	
4.1	Bibliographic research	100%
4.2	Analysis of the oxigen diffusion in zirconium carbide/oxide with Peridynamics	50%
4.2.1	Analysis of the oxygen diffusion in zirconium oxide in 1D	100%
4.2.2	Analysis of the oxygen diffusion in zirconium carbide/oxide in 1D	50%
4.2.3	Analysis of the oxygen diffusion in zirconium carbide/oxide in 2D and 3D	0%
4.3	Solution of oxidation of zirconium carbide with Peridynamics	0%
4.3.1	Solution of the multi-physics problem with Peridynamics in 2D and 3D	0%
4.3.2	Investigation of new fields of application	0%
5	Educational activities	
5.1	Exams	100%
5.2	Conference and seminars	100%
6	Writing of papers/conference proceedings and PhD thesis	
6.1	Writing of papers/conference proceedings	64%
6.2	Writing of PhD thesis	0%

FIRST YEAR (T1 T2 T3 T4: O N D J F M A M J J A S) — SECOND YEAR (T1 T2 T3 T4: O N D J F M A M J J A S) — THIRD YEAR (T1 T2 T3 T4: O N D J F M A M J J A S)

6. Final remarks

1. An innovative method to mitigate boundary issues in peridynamic models has been implemented for 1D, 2D and 3D problems.
2. A new algorithm to compute quadrature weights in 2D and 3D peridynamic models has been developed and its results have been thoroughly assessed.
3. Peridynamics has been coupled with CUF to reduce the overall computational cost. The spurious forces arising at the interfaces have been decreased by improving the coupling technique.
4. The multi-physics problem of the oxidation of the zirconium carbide has been addressed and will be modelled in the improved peridynamic framework.

Publications

Papers

- F. Scabbia, M. Zaccariotto and U. Galvanetto. “A novel and effective way to impose boundary conditions and to mitigate the surface effect in state-based Peridynamics”. Int J Numer Methods Eng, 2021, DOI: 10.1002/nme.6773.
- F. Scabbia, M. Zaccariotto and U. Galvanetto. “A new method based on taylor expansion and nearest-node strategy to impose Dirichlet and Neumann boundary conditions in ordinary state-based Peridynamics”. Comput Mech, 2022, DOI: 10.1007/s00466-022-02153-2.
- F. Scabbia, M. Zaccariotto and U. Galvanetto. “Accurate computation of partial volumes in 3D Peridynamics”. Eng Comput, 2022, accepted.

Abstracts and conference proceedings

- U. Galvanetto, T. Ni, F. Pesavento, M. Zaccariotto, F. Scabbia and B.A. Schrefler. “Hybrid FEM and peridynamic simulation of hydraulic fracture propagation in saturated porous media”. Workshop on Experimental and Computational Fracture Mechanics (WFM), February 26-28, 2020, Baton Rouge, LA, USA.
- F. Scabbia, M. Zaccariotto and U. Galvanetto. “A note on the surface effect in OSB-PD models”. 3rd annual meeting of the SIAM Texas-Louisiana Section, October 16-18, 2020, College Station, TX, USA.
- M. Zaccariotto, A. Shojaei, T. Ni, D. Dipasquale, G. Sarego, D. Mudric, S. Bazazzadeh, G. Ongaro, R. Alebrahim, F. Scabbia and U. Galvanetto. “Discontinuous mechanical problems studied with a peridynamics-based approach: simulation of fracture and damage propagation”. Innovative structures for lightweight vehicles, November 23-25, 2020, CISM-UNIUD Advanced Webinar.
- U. Galvanetto, F. Scabbia and M. Zaccariotto. “How to reduce the surface effect and to apply the boundary conditions in 1D peridynamic models”. 16th U.S. National Congress on Computational Mechanics, July 25-29, 2021, A virtual event.
- F. Scabbia, M. Zaccariotto and U. Galvanetto. “An effective method for imposing peridynamic boundary conditions and mitigating the surface effect”. AIDAA XVII International Congress, August 31 and September 1-3, 2021, Pisa, Italy.

Publications

Abstracts and conference proceedings (continued)

- M. Enea, F. Scabbia, A. Pagani, M. Zaccariotto, E. Carrera and U. Galvanetto. “One-dimensional high order finite elements embedding 3D state-based peridynamic subdomains”. AIDAA XVII International Congress, August 31 and September 1-3, 2021, Pisa, Italy.
- F. Scabbia, M. Zaccariotto and U. Galvanetto. “An innovative method to manage non-local boundaries in ordinary state-based Peridynamics”. XVI International Conference on Computational Plasticity, Fundamentals and Applications (COMPLAS), September 7-9, 2021, Barcelona, Spain.
- U. Galvanetto, F. Scabbia and M. Zaccariotto. “Accurate numerical integration in 3D meshless peridynamic models”. The Eighth International Conference on Structural Engineering, Mechanics and Computation (SEMC), September 5-7, 2022, Cape Town, South Africa.
- F. Scabbia, M. Zaccariotto and U. Galvanetto. “Exact computation of the cube-sphere intersection volume to improve peridynamic numerical integration”. 10th International Conference on Design, Modelling and Experiments of Advanced Structures and Systems (DeMEASS2020), May 1-4, 2022, Scopello, Italy.
- M. Enea, F. Scabbia, A. Pagani, M. Zaccariotto, E. Carrera and U. Galvanetto. “Analysis of beam structures by combined 3D peridynamics and refined 1D finite elements”. 10th International Conference on Design, Modelling and Experiments of Advanced Structures and Systems (DeMEASS2020), May 1-4, 2022, Scopello, Italy.
- F. Scabbia, M. Zaccariotto and U. Galvanetto. “An innovative method to correct the boundary issues in Peridynamics”. 11th European Solid Mechanics Conference (ESMC2022), July 4-8, 2022, Galway, Ireland.

Thanks for the attention