Efficient modelling of fatigue crack propagation with a FEM-peridynamics coupled approach

M. Zaccariotto[1,2], T. Ni [1], U. Galvanetto [1,2]

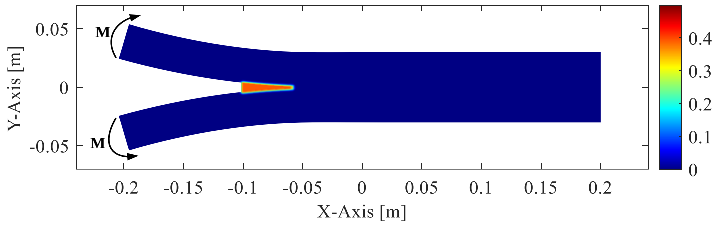
[1] Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131 Padova, Italy.

[2] Center of Studies and Activities for Space "Giuseppe Colombo". CISAS, Via Venezia 15,35131 Padova, Italy.

Abstract

Fatigue cracks propagation in structural materials is one of the most common problems in aeronautical applications. The proper analysis of the damage process evolution is of the highest importance to assess the life expectancy of structural components for a safe use and to define a scheduled maintenance program. The ideal condition would be to have computational methods that predict crack propagation and the ability to measure in real time the actual loading conditions applied to the components. This combination is a crucial ingredient for the development of effective digital twins [1]. Sensors dispersed in structural components will soon be capable of providing a detailed description of the loading conditions [2] while the simulation of the fracture and damage process is still on open issue. The numerical approaches used in structural mechanics have to face the problem of dealing with cracks since the underlying theory, the classical continuum mechanics, is formulated by using spatial derivatives that are not easily defined across discontinuities in the displacement field. On the contrary, Peridynamics (PD) [3,4] is a nonlocal continuum theory formulated with integral equations, therefore it is particularly suitable for dealing with crack propagation in solid materials. This theory is an ideal framework to study the crack propagation due to fatigue phenomena [5,6,7]. Unfortunately, due to its non-local nature, PD it is not computationally efficient; the coupling of FEM meshes with PD grids was proposed in [8] to produce a faster computational tool.

In this study, we suggest a strategy to simulate high cycle fatigue crack propagation combining the capability of Peridynamics in modelling crack propagation with a FEM-PD coupled method to optimize the computational effort. The fatigue damage formulation is inspired by [5]. The total load is composed by blocks of cycles, each block is characterized by a fixed load amplitude and a given number of cycles. Two components of damage increment are considered [5]: the static damage, and the fatigue damage, they both contribute to defining the damage status of the material. Fig. 1 shows the results of a cantilever beam test (in which a cyclic load is applied) simulated by using the proposed approach. Peridynamics is adopted in the area of the model where the crack is expected to propagate while the remaining part of the specimen is discretized by using FEM.



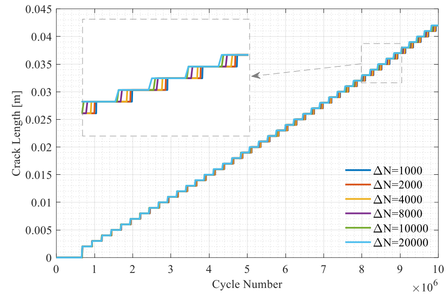


Fig.1 left: cantilever beam test simulated with a coupled FEM-PD model; right: a typical crack propagation diagram, lines show the results of a convergence study performed considering various numbers ΔN for each block of cycles.

We will demonstrate the capabilities of the proposed method by studying fatigue crack propagation phenomena in 2D systems. The effects of the presence of holes, heterogeneous materials and initial cracks will be analysed. Results will be evaluated taking into account different grid sizes, horizon dimension, initial crack lengths and crack orientations. The proposed method will pave the way to equip commercial FEM software with the capability to easily describe fatigue crack propagation in complex structures.

Acknowledgement

Authors would like to acknowledge the support they received from MIUR under the research project PRIN2017-DEVISU and from University of Padua under the research projects BIRD2018 NR.183703/18 and BIRD2020 NR.202824/20.

References

[1] L. Zhang , L. Zhou, B. K.P. Horn, Building a right digital twin with model engineering, J Manuf. Syst., 59, 151-164, (2021).
[2] G. Sarego, M. Zaccariotto, U. Galvanetto, Artificial neural networks for impact force reconstruction on composite plates and relevant uncertainty propagation, IEEE Aerosp. and Electr. Systems Magazine, 33(8) 38- 47, (2018)
[3] S.A. Silling. Reformulation of elasticity theory for discontinuities and long-range forces. J of the Mech. and Physics of Solids, 48(1):175–209, (2000).
[4] S.A. Silling, M. Epton, O. Weckner, J. Xu, E. Askari, Peridynamic states and constitutive modeling, J. Elasticity 88, 151–184, (2007).
[5] P. Robinson, U. Galvanetto,D. Tumino, G. Bellucci, D. Violeau, Numerical simulation of fatigue-driven delamination using interface elements, Int. J. Numer. Meth. Engng, 63,1824–1848, (2005).
[6] S. Bazazzadeh, M. Zaccariotto, U. Galvanetto, Fatigue degradation strategies to simulate crack propagation using peridynamic based computational methods, Latin Am. J Solids and Struct. 16(2), Article number e163, (2019).
[7] E. Madenci et alt., Combined peridynamics and kinetic theory of fracture for fatigue failure of composites under constant and variable amplitude loading, Theor. and Appl. Fract. Mech, 112, paper 102824, (2021).
[8] Ni, T., Zaccariotto, M., Zhu, Q.Z. and Galvanetto, U., Coupling of FEM and ordinary state-based peridynamics for brittle failure analysis in 3D. Mech. Adv. Mater. Struc., 28(9) 875-890, (2021).