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IMPLEMENTATION OF PERIDYNAMIC IN THE ANSYS LS-DYNA: VERIFICATION AND FRACTURE ANALYSIS

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Abstract. Problems solved by computational mechanics are becoming increasingly complex, involving diverse geometries, boundary conditions, and materials. Recent studies show that combining different numerical methodologies is one of the most effective approaches for advancing fracture simulation. In this context, this work presents the implementation of Peridynamics (PD) theory in the ANSYS LS-DYNA finite element software, enabling the creation of hybrid models called PD-DYNA. PD is a non-local theory in which particles are connected to one another, forming a continuum representation. Since the theory is not based on classical continuum mechanics, fracture simulation occurs naturally through bond breakage. To assess the results, comparisons with reference problems using the Finite Element Method are carried out to verify the implementation, while benchmark cases are employed to validate the fracture behavior of brittle materials. The results highlight the computational efficiency and applicability of the proposed implementation in structural analyses. This work emphasizes the potential of integrating PD and LS-DYNA as an advanced tool for fracture analysis in material engineering, pointing toward promising applications in new materials, varied loading conditions, and three-dimensional problems.

Keywords: Peridynamics, Fracture Mechanics, Crack Propagation, Finite Element Method, Hybrid Numerical Models, ANSYS LS-DYNA.

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1 INTRODUCTION

The study of fracture in structural materials is one of the great challenges of engineering, given the risks of catastrophic failures in critical components. Based on the renowned work of Griffith, Inglis, and Irwin, fracture mechanics has established itself as a fundamental field, providing more reliable design methods than traditional approaches based solely on material strength (Anderson 2017).

However, numerical prediction of crack nucleation and propagation still has limitations when using models derived from Classical Continuum Mechanics (CCM). This is because local differential equations are no longer valid in the presence of discontinuities, since spatial derivatives are not defined at the crack tip (Macek and Silling 2007). In the case of the Finite Element Method (FEM), widely applied in structural, thermal, and flow problems, such difficulties manifest themselves, for example, in the need to align the crack with the mesh and in excessive refinement in critical regions (Fang et al. 2019).

As an alternative, different numerical methods have been developed to directly address crack initiation and propagation. Among them, the Discrete Element Method (DEM) (Bićanić 2004) and the theory of (PD) (Silling and Askari 2005) stand out. PD, originally proposed by Silling (2000), reformulates solid mechanics by replacing local derivatives with non-local integrals, allowing a body to be represented as a set of interconnected material points. Fractures emerge naturally in this context through the breaking of bonds between particles, without the need for additional external criteria.

Although peridinamics provides a consistent and effective approach to dealing with discontinuities, it has a high computational cost compared to FEM. Thus, the integration of approaches, using PD in critical regions and FEM in the rest of the domain, has been considered a promising strategy, resulting in so-called hybrid models (Sun and Fish 2019). This type of coupling is particularly advantageous in analyses involving heterogeneous and anisotropic materials, as well as situations where fault propagation is complex (Belytschko et al. 2014).

In this scenario, the implementation of peridinamics theory in commercial software, such as ANSYS LS-DYNA, gains relevance, as it combines the efficiency of FEM and the ability of PD to deal with fracture. Thus, this research is dedicated to the implementation and verification of the PD-DYNA method, seeking to validate its application in reference problems and contribute to the advancement of numerical simulation techniques in fracture mechanics.

2 THEORETICAL BASIS

2.1 Peridynamic Theory

The peridynamic theory was originally proposed by Silling (2000), and it is based on the interactions that occur within a neighborhood H_x of a material point, limited by a radius δ, as illustrated in Figure (1). Within this approach, the formulation can be divided into two categories: bond-based peridynamics and state-based peridynamics. In this work, the bond-based model is adopted due to its conceptual simplicity and greater ease of implementation.

A formulação da peridinâmica pode ser interpretada como uma versão integral da equação de equilíbrio do momento linear utilizada na Mecânica Clássica do Contínuo (MCC). Assim, o movimento de um ponto material em um meio elástico pode ser descrito pela Equação (1)

$$\rho \ddot{u}(x,t) = \int_{H_x} f\left(u\left(x',t\right) - u(x,t), x' - x\right) dV_{x'} + b(x,t) \tag{1}$$

This equation, f represents the pairwise interaction function, indicating the force that point x'

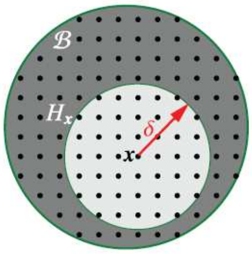


Figure 1: Main parameters of Peridynamics. [Adapted from Javili et al. (2019)]

exerts on point x, which is expressed in units of force per squared volume. The term u represents the displacement field, b refers to the applied body forces, and ρ is the material density. The integral is calculated over H_x, called the horizon or neighborhood, defined as the region around point x where all points are within a distance less than δ in the reference configuration, as shown in Figure (1). The set of points belonging to this neighborhood is referred to as the family of x (Javili et al. 2019).

In peridynamics, the interaction between two material points occurs through a bond, whose behavior is described by a linear relationship between force and stretch. This formulation is known as the Prototype Microelastic Brittle (PMB) model, illustrated in Figure (2), and it is widely used in simulations of brittle materials.

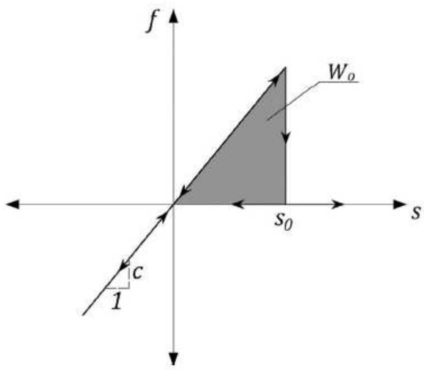


Figure 2: PMB peridynamic model. [Adapted from **?**]

In the PMB model, the bond strain is given by Equation (2):

$$s = \frac{|\xi + \eta| - |\xi|}{|\xi|} = \frac{|\xi + \eta| - \xi}{\xi} \tag{2}$$

Where:
- ξ is the relative position vector between two points;
- η is the relative displacement vector. Both are defined in the reference configuration.

According to Cabral et al. (2019), the elasticity modulus is associated with the link, where this parameter varies depending on the model's dimensions. For the plane stress condition, $E' = E$ and $\nu' = \nu$ are assumed. Nevertheless, for the plane strain condition, these values are adjusted to $E' = E/(1-\nu^2)$ and $\nu' = \nu/(1-\nu)$.

It is also worth noting that, in bond-based peridynamics, the Poisson's ratio has restricted values: $1/3$ for plane stress and $1/4$ for both plane strain and three-dimensional problems. In the peridynamic model, damage is considered from the breaking of bonds, which occurs when the critical stretch s_0 is reached, as illustrated in Figure (1).

As rupture links are irreversible, the model depends on the applied loading history. Furthermore, if a point does not have rupture links, the local damage will be $\varphi = 0$, if the point is completely disconnected from the body, the value will be $\varphi = 1$.

3 METHODOLOGY

This section will describes the methodology for implementing peridynamics in ANSYS LS-DYNA. The application cases used to validate the implementation are presented in sequence.

3.1 PD-DYNA Implementation

ANSYS LS-DYNA integrates the program's explicit finite element analysis capabilities with the ANSYS APDL pre- and post-processing environments. This tool is widely used in transient simulations involving nonlinearities, such as related to geometry, contact, large strain, and complex material constitutive laws. The implementation of Peridynamics in ANSYS LS-DYNA, called PD-DYNA, was accomplished through the following steps: - Declare the material properties;
- Calculate connection stiffness;
- Generate the geometry (nodes and connections): PD connections are represented by spring elements;
- Calculate the volume correction factor;
- Calculate the surface correction factor;
- TAssign the constitutive law to each connection;
- Masses are distributed among the nodes and implemented using the explicit 3-D Structural Mass (MASS166) element. This generates the PD-DYNA model.
- Boundary conditions are applied;
- Problem solution.

Further details of the adopted methodology can be found at Maciel (2022).

3.2 Case Studies

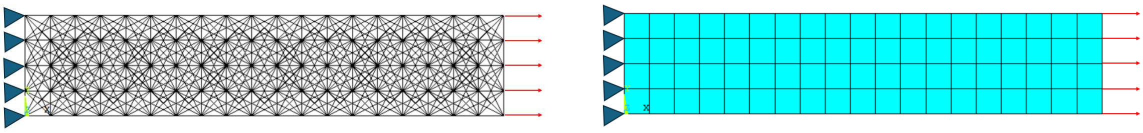
The results of the PD-DYNA and FEM models are shown using three different case studies. In all cases, the same material properties listed in Table (1) are adopted. The model parameters are determined according to the methodologies established in the previous section, with δ defined as $\delta = 3.015\Delta$.

E (GPa)	ν	$\rho\ (kg/m^3)$
192	1/3	8000

Table 1: Proprieties

3.2.1 Case Study 1

This study aims to evaluate the performance of the PD-DYNA model in a two-dimensional problem. To this end, a comparison with the Finite Element Method (FEM) is performed using a 2D plate. The plate is constrained on the left side, while a prescribed displacement is imposed on the right side. The dimensions adopted for the model are: length $L = 950,$ mm and height $W = 200,$ mm. Figure (3a) depicted the PD-DYNA model of the two-dimensional plate, in which a material point spacing of $\Delta = 50$mm was adopted.



(a) (b)

Figure 3: Comparison between models: (a) PD-DYNA and (b) MEF.

The same problem was also modeled using FEM, employing the SHELL163 element, while maintaining the same discretization level and boundary conditions adopted in PD-DYNA. Figure (3b) depicts the two-dimensional plate generated in ANSYS LS-DYNA.

The comparison between the two models is carried out by analyzing the displacements in the x-direction of the nodes located along the plate's centerline. Furthermore, the correlation between the applied force and the imposed displacement is also evaluated.

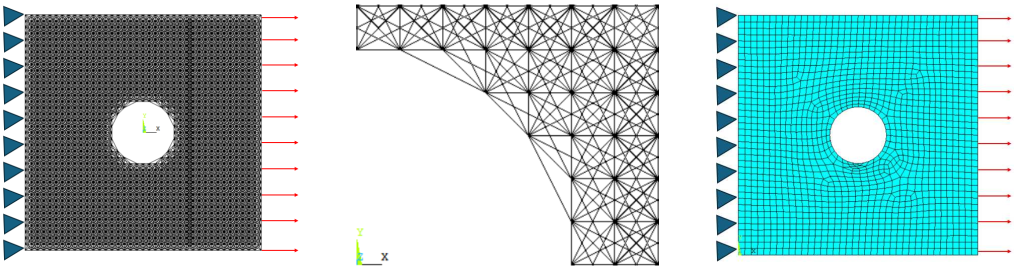
3.2.2 Case Study 2

In this study, a two-dimensional plate with a central hole is considered. The structure is constrained on the left side, constrained in both the x and y directions. A prescribed displacement is applied to the right side. The dimensions adopted for the model are: a length $L = 190$ mm, a height $W = 190$ mm, and a central hole diameter $D = 45$ mm.

Figure (4a) shown the PD-DYNA model developed for the two-dimensional plate with a central hole, using a spacing between material points of $\Delta = 5mm$. Figure (4b) provides a detailed view of the upper-right region of the hole.

The same case was modeled in ANSYS LS-DYNA using the SHELL163 element, maintaining the same level of discretization and the same boundary conditions applied to the PD-DYNA model. Figure (4c) shows the two-dimensional plate with a central hole generated in LS-DYNA.

The comparison between the two models is performed by analyzing the displacements of the nodes located along the X and Y lines. In addition, the force-displacement curve obtained in each case is also evaluated.

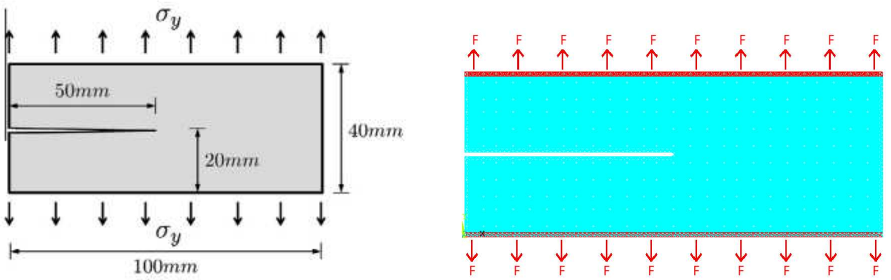


(a) (b) (c)

Figure 4: (a) PD-DYNA model for the plate with center hole, (b) Zoomed-in section of the hole corner. (c) Plate with center hole in ANSYS LS-DYNA.

3.2.3 Case Study 3

The first model, whose geometry is illustrated in Figure (5a), was adapted from the work of Braun and Fernández-Sáez (2014). The problem consists of a rectangular PMMA plate containing a central notch starting from the left edge. The mechanical properties adopted for the material correspond to the following: elastic modulus $E = 32GPa$, density $\rho = 2450kg/m^3$, Poisson's ratio $\nu = 0.33$, and fracture toughness $G_f = 3Nm$. The model was subjected a constant tensile stress of $1MPa$ along its upper and lower edges.



(a) (b)

Figure 5: (a) Pre-notched PMMA plate under tensile loading. [Braun and Fernández-Sáez (2014)]. (b) PD-DYNA model of application 3.

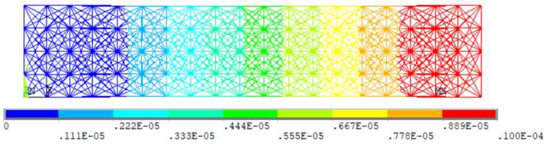
The 2D peridynamic model (PD-DYNA), whose configuration is shown in Figure (5b), comprises a mesh of 100×40 nodes, equidistant in the x and y directions, respectively. The initial interparticle spacing, Δx, adopted in the model is 1.0 mm. The interaction horizon, δ, was set according to the relation $\delta = 3.015\Delta x$.

4 RESULTS

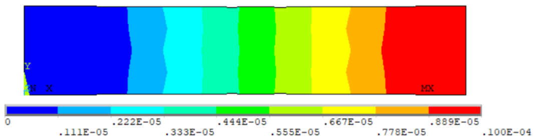
4.1 Case Study 1

The displacement fields in the x-direction for the flat plate, obtained using PD-DYNA and FEM, are shown in Figure (6). Visual analysis reveals a good agreement between the two models.

For a more detailed analysis, the displacements in the x-direction of the nodes located along the central region of the plate were compared, as shown in Figure (7). The results demonstrate good agreement among the both models.



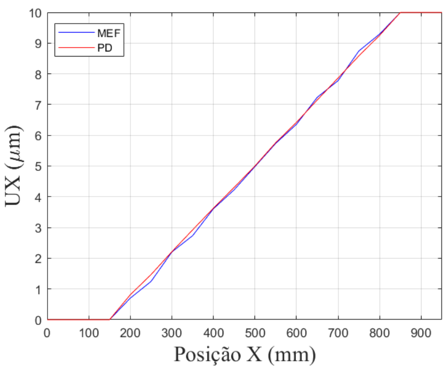
(a)



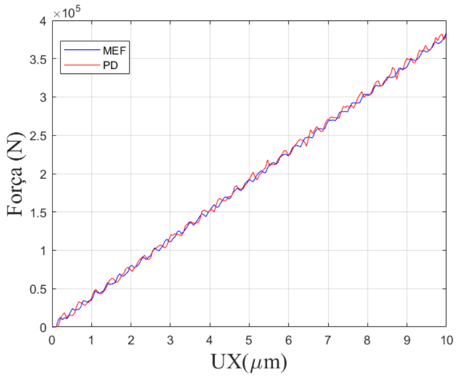
(b)

Figure 6: Comparison between x-displacement fields using: (a) PD-DYNA and (b) FEM.

Figure (7b) presents the force-displacement curve in the x-direction (U_x) for the PD-DYNA and FEM models. Good agreement between the results is observed, with the relative error in the maximum tensile at the end of the applied displacement not exceeding 3.75%.



(a)

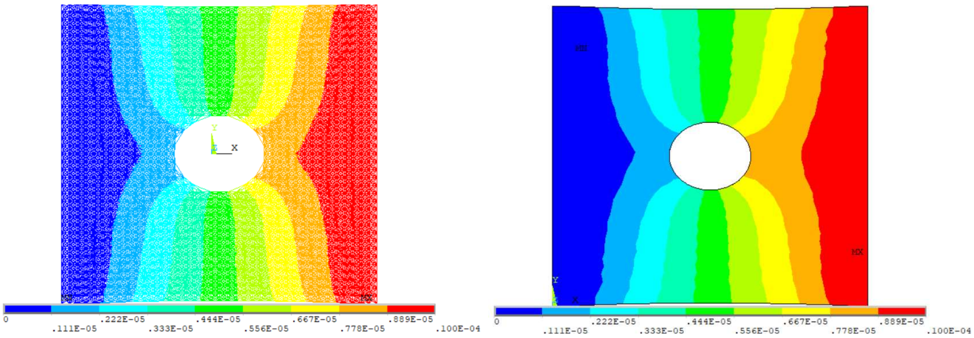


(b)

Figure 7: (a) Displacement field at x for each node along the bar with the FEM and PD-DYNA. (b) Force-displacement relation (Ux) for the flat plate.

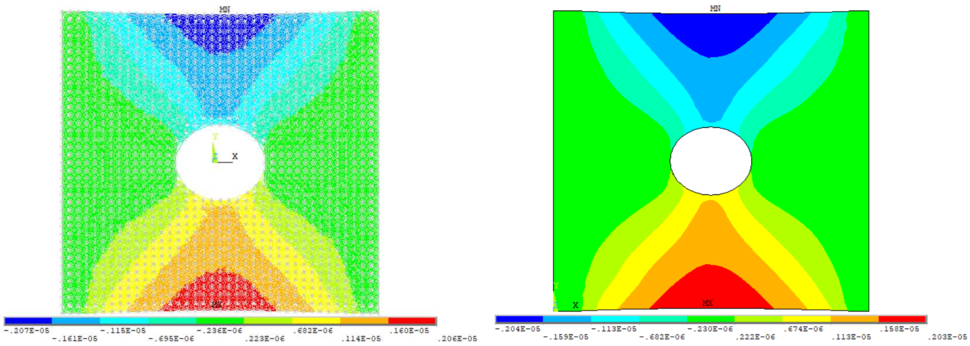
4.2 Case Study 2

Figure (8) compares the displacement fields in the x-direction for the plate with a central hole, as modeled by the PD-DYNA and FEM methods. Figure (9) shows the corresponding displacement fields in the y-direction for the same problem.



(a) (b)

Figure 8: Displacement fields in x for the plate with a central hole using: (a) PD-DYNA and (b) FEM.



(a) (b)

Figure 9: Displacement fields in y for the plate with a central hole using: (a) PD-DYNA and (b) FEM.

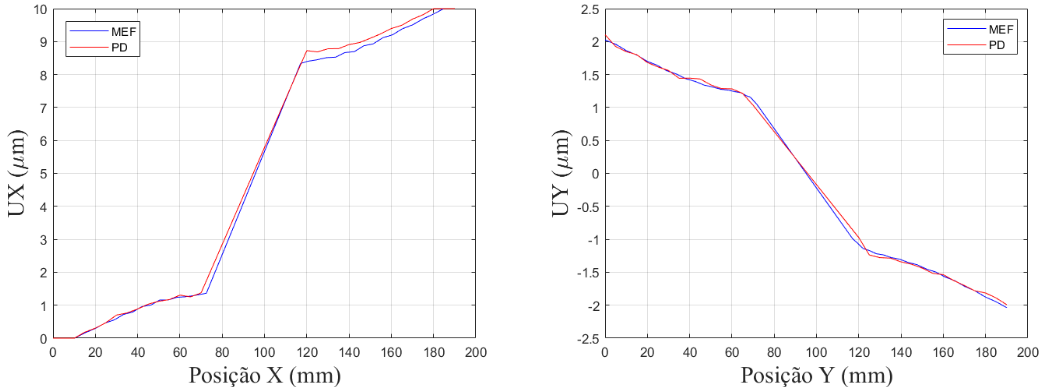
The comparison is illustrated in Figures (10a) and (10b), which show the displacements in the x- and y-directions along the reference lines. A slightly more pronounced difference is observed only for the displacements in the x-direction, (Figure 10a), yet the relative error remains limited to 3.71%.

4.3 Case Study 3

The PMMA plate simulation (Figures 11a–11c), crack propagation is observed at different instants, with branching resulting from the high stress concentration, as predicted by classical fracture theories. Figures (11d–11f) show comparative results from Song et al. (2008) (XFEM), Braun and Fernández-Sáez (2014) (2D Discrete Models), and Islam and Shaw (2020) (SPH with pseudo-springs).

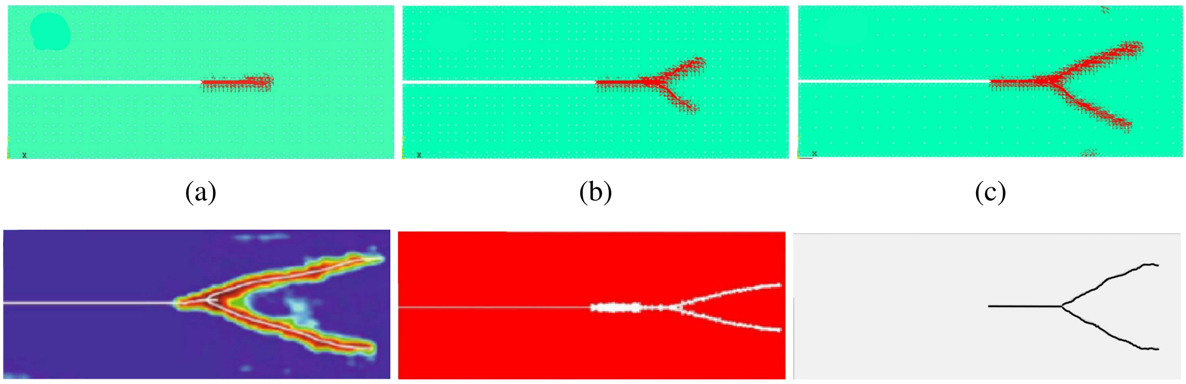
Furthermore, analyses at different stress levels were performed in Case Study 3. The results, presented in Figure (12), demonstrate that the method maintains its accuracy even under varying loads.

At 0.5 MPa, the crack propagated linearly and uniformly, without significant branching. At 1.5 MPa and 2 MPa, more complex branching emerged, demonstrating the influence of load magnitude on fracture progression. These results are in agreement with those reported by Islam and Shaw (2020) for PMMA plates under similar conditions.



(a) (b)

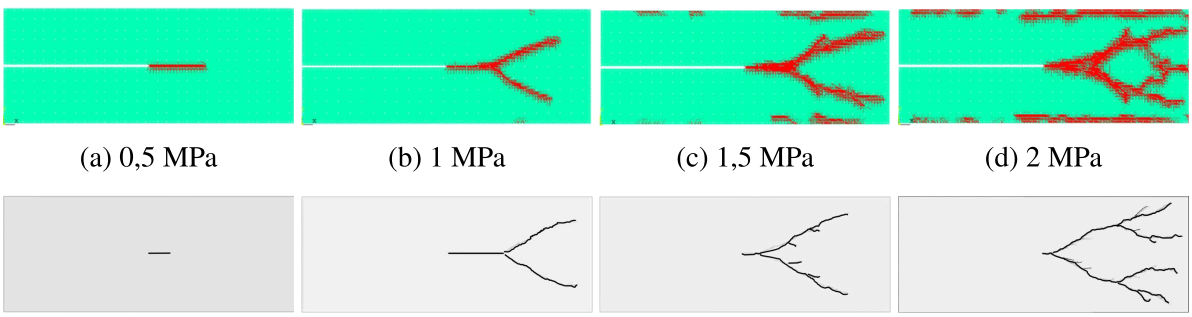
Figure 10: (a) Horizontal displacements along the model's X line. (b) Vertical displacements along the model's Y line.



(a) (b) (c)

(d) (e) (f)

Figure 11: Result of application I in the PD-DYNA model with times of (a) 30 μs, (b) 40 μs and (c) 50 μs; fracture patterns found by (d) Song et al. (2008), (e) Braun and Fernández-Sáez (2014) and (f) Islam and Shaw (2020)



(a) 0,5 MPa (b) 1 MPa (c) 1,5 MPa (d) 2 MPa

(e) 0,3 MPa (f) 1 MPa (g) 1,2 MPa (h) 2 MPa

Figure 12: (a), (b), (c) and (d) Result of application 3 with variation of the loads applied in PD-DYNA; (e), (f), (g) and (h) patterns found by Islam and Shaw (2020).

5 CONCLUSIONS

The implementation of the peridynamic model in ANSYS LS-DYNA yielded results consistent with the Finite Element Method (FEM) and other numerical methods documented in the literature, confirming its effectiveness and reliability for fracture analysis in brittle materials. PD-DYNA accurately captured crack propagation and branching patterns, even under varying load levels, demonstrating its potential for addressing complex fracture problems. Consequently, the method establishes itself as a promising alternative for future investigations involving heterogeneous materials and diverse loading scenarios.

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