Peridynamic Theory for Modeling Two-Dimensional Damage Growth in Quasi-Brittle Material

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KEYWORDS

Concrete
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ABSTRACT

The peridynamics theory is a continuum mechanics alternative theory that formulates problems using integral equations rather than partial differential equations. This theory, like molecular mechanics, proposes the idea of material points in a continuum interacting with one other over a finite distance. A numerical method for dealing with dynamic challenges is offered within peridynamics theory. In addition, the numerical method's performance is validated in this work by comparing it to the analytical solution. The results provide a complete understanding of the factors' effects on crack propagation caused by modifying particle spacing size and time step. Finally, this study allows for the investigation of the influence of the mechanical properties of concrete on the fracturing course.

1. INTRODUCTION

The behavior and failure of quasi-brittle materials, such as concrete and rock, are critical factors in assessing the durability and safety of structures. These materials exhibit complex damage patterns, including crack initiation, propagation, and eventual failure, which are influenced by local stress concentrations and microstructural features. Traditional modeling techniques, such as continuum mechanics, often fail to accurately represent these phenomena, especially when cracks spread dynamically and interact with the surrounding material. According to F. M. Mukhtar and Abdelrahman El-Tohfa [1], characteristics of concrete fracture growth are crucial for regulating the durability and lifespan of structures.

According to Giatec Scientific [2], concrete provides structural strength, stiffness, and deformation resistance. When subjected to external stresses, engineering instability can occur if new cracks form at the circular border, propagate along the route of the highest primary pressure, and join with existing circular holes. To optimize the design of engineering linked with circular holes, it is essential to investigate the pre-holed concrete's crack initiation, progression, and coalescence behavior and mechanism [3].

Previously, the finite element method (FEM) was used to quantitatively simulate concrete structures using phenomenological constitutive models. Based on C. Liu and R. G. Kelly [4], the FEM is a popular numerical technique for solving engineering and mathematical physics issues involving behaviors that may be stated through differential equations. It can accurately predict how a form will break and is still very important in structural design, especially for figuring out how big concrete structures will break. Even though the discrete element or particle methods are better at describing cracks and pieces, they need much more computing power than the continuous methods [5].

Thus, the Peridynamic (PD) theory was first proposed to resolve these concerns. PD is a numerical modeling technique that can be used to capture concrete cracks. PD is the mesh-free method used in this research effort on the numerical modeling of fracture patterns in concrete. Bond-based peridynamic (BB-PD), and state-based peridynamic (SB-PD) are the two well-known standards of PD. As reported by Tao Ni et al. [6], PD is particularly well-suited for modeling brittle materials like concrete, which crack easily. It can capture complex crack patterns, such as uneven crack pathways and branching, which are difficult to adequately describe using typical FEM approaches. Moreover, PD also can model fracture propagation without the use of a predetermined mesh. This makes it more adaptable and less susceptible to mesh distortion or element connectivity difficulties, which can wreak havoc on FEM simulations.

The main objective of this research is to optimize the method of studying concrete fracture and to model the propagation of cracks in concrete plates. To accomplish the stated purpose, the following study objectives have been planned. Firstly, to simulate the effect of different time steps of load steps on the crack propagation. Secondly, to examine the effect of particle spacing size within the Non-Ordinary Stated-Based Peridynamic (NOSB-PD) framework on hole fracture patterns and lastly to validate the PD equation by comparing it with an analytical solution.

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2. EXPERIMENTAL PROCEDURE

2.1 Modeling of Plate and Simulation of Model

This study investigates the progressive damage in a 1.0 m x 1.0 m square concrete plate with a central circular hole with a diameter of 0.25 m.

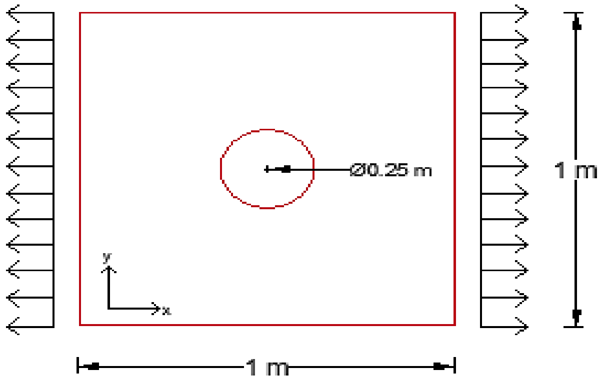

Figure 1. Plate with Central Circular Hole.

The simulations predict Mode-I fracture, characterized by an opening mode with forces acting perpendicular to the crack faces, using the Peridynamic (PD) modeling method. The focus is on analyzing crack initiation, location, and propagation over time at various time intervals.

The model's accuracy is evaluated by varying particle density, with three distinct particle spacings (0.005 m, 0.01 m, and 0.02 m). The plate thickness is fixed at 0.1 cm, and a time step size of 1.0 s is maintained for all simulations to ensure stable numerical resolution. All simulations and analyses will be coded and executed using MATLAB 2021a.

This approach allows for a comprehensive examination of how crack behavior evolves in response to different loading conditions and material properties [7].

2.2 Model Validation

This study validated the NOSB-PD mesh-free model using the FEM before the crack propagation was applied to the square plate. This is because there was no way to utilize the FEM to check for fractures without employing an additional treatment or function. FEM was rarely applied to discrete elements, as opposed to continuous elements. Hence, the FEM was only extracted in this work for validation during the 'stress' phase between material sites before cracking.

2.3 Damage Crack Modelling

The load is imparted to the plate in a configuration of a fixed bottom and an upward force, and it is anticipated that the plate fracture will manifest and propagate along the horizontal axis. In PD (bonds), the elimination of particle interaction represents material degradation. When broken bonds are eliminated, no force persists in the bond, and bond failure results in a fracture. According to Silling [8], the bond can no longer withstand force once it has failed, indicating that it has been irreparably severed. Consequently, the burden is redistributed to the remaining particles.

3. RESULTS AND DISCUSSION

3.1 Crack Type on the Particle Spacing

Figure 2 depict the propagation of a mode I fracture. As a result of the PD equations of motion, the crack appears to propagate naturally. At time step t = 500s, several bonds at the concrete hole are broken, resulting in local damage initiation. As more bonds are broken near the crack hole, crack propagation occurs. The crack will rapidly propagate to the plate's boundary, and the plate will be thoroughly broken. It can be observed that the displacement in the plate becomes discontinuous near the crack, posing challenges for numerical methods based on classical continuum mechanics theory. The crack size scales at different time intervals provide an intriguing perspective on the crack's behavior.

At time step 500, the size of the fissure is reported to be x=0.2675 and y=0.00751. The x-direction fracture size increases significantly as time steps progress, reaching x=0.4024 at time step 600 and increasing to x=0.4524 at both times steps 700 and 800. Despite the consistency in x-direction fracture size between time steps 700 and 800, the y-direction crack size remains constant at y=0.007508 for all time steps. This observation raises intriguing questions about the mechanisms underlying crack growth and suggests that the crack is predominantly expanding in the x-direction while maintaining a constant y-dimension.

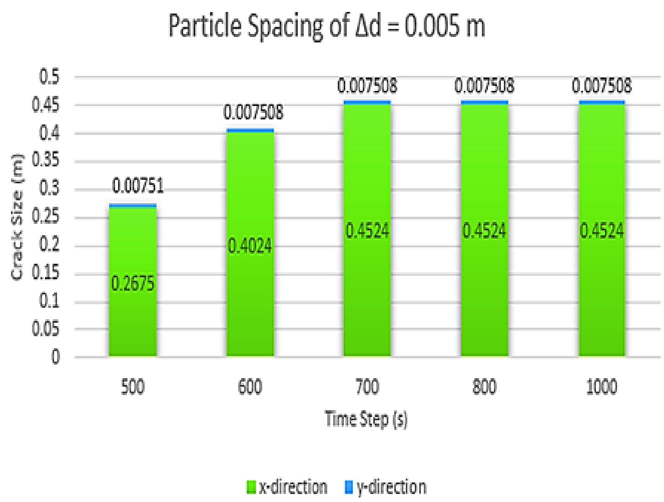

Figure 2. Peridynamic simulation of a fracture in a concrete plate with various time steps: (a) t = 500, (b) t = 600, (c) t = 700, (d) t = 800, and (e) t = 1000, respectively, with the particle spacing of Δd = 0.005 m.

The initial crack size is recorded at time step 500 as x=0.305 and y=0.02503 in Figure 3. The x-direction crack size is seen to be stable throughout time, with measurements of x=0.495 for time steps 600, 700, and 800. The y-direction crack size, however, is seen to gradually rise from y=0.02503 at time step 500 to y=0.02527 at time step 1000. The difference indicates that while the crack size in the x-direction is holding steady, it is growing in the y-direction. This suggests that forces occurring perpendicular to the crack's main axis may have a greater impact on its development. The impact failure simulation demonstrates the distinct advantage of peridynamic over conventional numerical methods when dealing with complicated discontinuity problems. Furthermore, the crack of particle spacing 0.01 m is superior to that of particle spacing 0.005 m. This is because the greater the particle separation, the better the crack propagation.

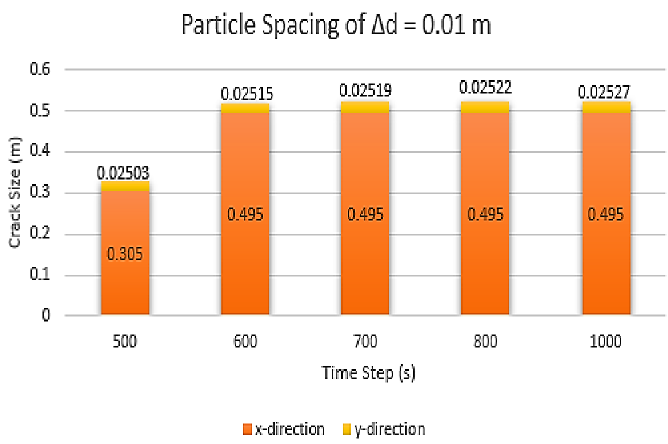

Figure 3. Peridynamic simulation of a fracture in a concrete plate with various time steps: (a) t = 500, (b) t = 600, (c) t = 700, (d) t = 800, and (e) t = 1000, respectively, with the particle spacing of Δd = 0.01 m.

Figure 4 demonstrates that the crack size is x=0.15 and y=0.04003 at time step 500. Significant changes occur in both the x and y directions as time passes. At time step 600, the crack size expands significantly in the x-direction, reaching x=0.4499, while remaining rather stable in the y-direction at y=0.04004. A significant change happens around time step 700, with a significant increase evident in both dimensions. The crack size grows to x=0.49 in the x direction and expands significantly to y=0.06019 in the y direction. Surprisingly, the crack size stays consistent at time step 800 compared to time step 700, with x=0.49 and y=0.06022.

Meanwhile, for the time step 1000, however, indicates a tiny rise in the y-direction crack size, measuring y=0.06027, while the x-direction remains unchanged at x=0.49. These findings illustrate the complicated nature of crack formation, in which alterations in both dimensions can occur concurrently or in isolation. The fracture pattern for these three-time steps is nearly the same as in Figure 4.3 and Figure 4.2 but with a wider width. This section's particulate spacing was 0.02 m; there are 50 particles in the x-direction and 25 particles in y-direction, for 1250 particles. This indicates that the particle spacing crack of 0.02 m is larger than the particle spacing cracks of 0.005 m and 0.01 m. The higher the particle separation, the greater the crack propagation.

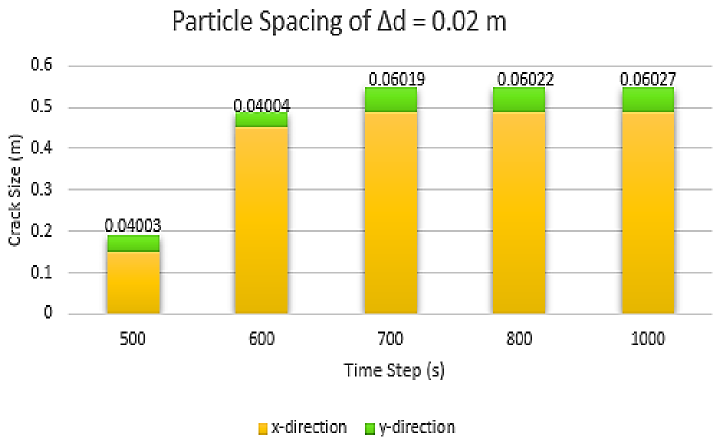

Figure 4. Peridynamic simulation of a fracture in a concrete plate with various time steps: (a) t = 500, (b) t = 600, (c) t = 700, (d) t = 800, and (e) t = 1000, respectively, with the particle spacing of Δd = 0.02 m.

4. CONCLUSION

This paper focuses on the application of PD, a revolutionary non-local modeling technique, to solve discontinuity problems in concrete structures. The research shows that PD can model damage evolution, fracture mechanisms, and dynamic failure in concrete structures, including crack propagation. It suggests that a stable time step of 700 steps be used for consistent fracture propagation prediction, as longer time steps may overestimate failure linkages [9]. Furthermore, the study looks at the effect of particle spacing on fracture propagation and discovers that smaller spacing, such as 0.005 m, results in better results. The usage of PD is validated by comparing it to analytical solutions, which show good agreement and demonstrate the method's capacity to effectively assess damage and fracture processes without the need for additional numerical methodologies. In studying fracture propagation, the results of PD simulations show remarkable computational precision.

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REFERENCE

[1] F. M. Mukhtar and Abdelrahman El-Tohfa, “A review on fracture propagation in concrete: Models, methods, and benchmark tests,” vol. 281, pp. 109100–109100, Feb. 2023.
[2] U. Giatec, “The leading wireless concrete sensor for measuring temperature and strength,” The leading wireless concrete sensor for measuring temperature and strength, p. undefined–undefined, 2019.
[3] W. Ma, Y. Chen, W. Yi, and S. Guo, “Investigation on crack evolution behaviors and mechanism on rock-like specimen with two circular-holes under compression,” Theoretical and Applied Fracture Mechanics, vol. 118, p. 103222, Apr. 2022.
[4] C. Liu and R. G. Kelly, “A Review of the Application of Finite Element Method (FEM) to Localized Corrosion Modeling,” CORROSION, vol. 75, no. 11, pp. 1285–1299, Sep. 2019.
[5] T. Saksala, “Numerical modelling of concrete fracture processes under dynamic loading: Meso-mechanical approach based on embedded discontinuity finite elements,” Engineering Fracture Mechanics, vol. 201, pp. 282– 297, Oct. 2018.
[6] T. Ni, Q. Zhu, L.-Y. Zhao, and P.-F. Li, “Peridynamic simulation of fracture in quasi brittle solids using irregular finite element mesh,” Engineering Fracture Mechanics, vol. 188, pp. 320–343, Feb. 2018.
[7] E. Oterkus and E. Madenci, “Peridynamic analysis of fiber-reinforced composite materials,” Journal of Mechanics of Materials and Structures, vol. 7, no. 1, pp. 45–84, Mar. 2012.
[8] S. A. Silling, M. Epton, O. Weckner, J. Xu, and E. Askari, “Peridynamic States and Constitutive Modeling,” Journal of Elasticity, vol. 88, no. 2, pp. 151–184, Jul. 2007.

[9] Ghareeb A. & Elbanna A. An Adaptive Quasi-Continuum Approach for Modeling Fracture in Networked Materials: Application to Modeling of Polymer Networks. Journal of the Mechanics and Physics of Solids, vol. 137(-) (2019).