

Dual-State Peridynamic Contact Retrieval for Branching Cracks in Granite

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Abstract

The accurate computational modeling of fracture mechanisms in heterogeneous brittle materials remains a formidable challenge in computational mechanics and geological engineering. Granite, characterized by its complex microstructural composition and inherent flaws, frequently exhibits intricate failure patterns including dynamic crack propagation, bifurcation, and extensive crack face contact under varying load conditions. Classical continuum mechanics formulations often struggle to capture these spontaneous discontinuities due to the spatial derivatives present in their governing equations. To overcome these limitations, the peridynamic theory, which utilizes integro-differential equations, has emerged as a robust alternative. This paper proposes a comprehensive dual-state peridynamic contact retrieval framework specifically designed to simulate branching cracks in granite. The dual-state approach introduces a novel algorithmic transition between cohesive bonding states and repulsive contact states, ensuring that newly formed crack surfaces do not unphysically interpenetrate during compressive wave reflections. By eliminating mathematical singularities at crack tips, the proposed framework autonomously captures crack initiation, propagation, and complex branching without requiring external criteria or guided enrichment functions. Extensive numerical investigations are conducted to evaluate the performance of the proposed algorithm under high strain rate dynamic loading. The results demonstrate that the dual-state contact retrieval mechanism significantly enhances the physical accuracy of the simulated fragmentation process, preserving the global energy balance while accurately resolving the interaction between secondary crack branches. This methodology provides a vital computational tool for predicting the mechanical response of granitic rock masses in applications ranging from deep geological repositories to enhanced geothermal systems.

Keywords: Peridynamic Theory, Fracture Mechanics, Branching Cracks, Contact Algorithms, Granite Fragmentation

1. Introduction

1.1 Background of Granite Mechanics

Granite is an intrusive igneous rock that constitutes a significant portion of the continental crust. It is widely utilized in various large-scale engineering applications, ranging from the construction of critical infrastructure to the establishment of deep geological repositories for high-level radioactive waste. Furthermore, granitic rock masses are the primary medium for enhanced geothermal systems, where fluid is injected at high pressures to stimulate fracture networks and extract thermal energy. The mechanical behavior of granite is inherently complex due to its heterogeneous mineralogical composition, which primarily includes quartz, alkali feldspar, and plagioclase, along with various micas and accessory minerals. This multiphase microstructure results in significant variations in localized stiffness and thermal expansion coefficients. When subjected to mechanical or thermal loading, these microstructural mismatches induce internal stress concentrations that serve as nucleation sites for microcracks. As the load increases, these microcracks propagate, coalesce, and ultimately form macroscopic fractures. The brittle nature of granite means that failure often occurs suddenly and dynamically, accompanied by the release of substantial elastic strain energy. Understanding and predicting this fragmentation process is crucial for ensuring the structural integrity of rock engineering projects and optimizing resource extraction operations. The dynamic fracture of granite typically

involves complex topological changes, including the branching of primary cracks into multiple secondary cracks. These branching phenomena are driven by the interaction of stress waves with the propagating crack tip, leading to a redistribution of energy that favors the creation of new fracture surfaces. Accurately capturing these intricate crack patterns requires advanced computational tools capable of handling discontinuous displacement fields and dynamic surface interactions.

Table 1: Material Properties of Standard Granite Specimens

Property Description	Value	Unit	Method of Determination
Bulk Density	2650	Kilograms per cubic meter	Standard displacement testing
Young Modulus	65.5	Gigapascals	Uniaxial compression test
Poisson Ratio	0.22	Dimensionless	Ultrasonic wave velocity
Dynamic Tensile Strength	15.4	Megapascals	Brazilian splitting test
Critical Energy Release Rate	115.0	Joules per square meter	Three-point bending test

1.2 Limitations of Classical Continuum Frameworks

The traditional modeling of solid mechanics heavily relies on the classical continuum theory, which employs partial differential equations to describe the conservation of mass, momentum, and energy. While highly effective for continuous bodies undergoing elastic or plastic deformation, this theoretical framework encounters fundamental mathematical difficulties when applied to bodies with discontinuities, such as cracks or voids. The spatial derivatives of the displacement field become undefined at the crack tip, leading to unphysical stress singularities. To circumvent this issue, researchers have developed various numerical techniques within the finite element method framework. Techniques such as cohesive zone modeling and the extended finite element method have been widely adopted to simulate fracture processes. Cohesive zone models require cracks to propagate strictly along pre-defined element boundaries, introducing a strong mesh dependency that artificially constrains the crack trajectory. The extended finite element method attempts to solve this by enriching the local shape functions with discontinuous terms, allowing cracks to traverse through the interior of the elements. However, implementing the extended finite element method for complex, intersecting, or highly branched crack networks in three-dimensional space requires sophisticated enrichment tracking algorithms and computationally expensive integration schemes over partitioned elements. Furthermore, both methodologies often require supplementary empirical criteria to dictate when and in which direction a crack should propagate or branch, thereby reducing the predictive capability of the models when dealing with the spontaneous dynamic fracture of heterogeneous materials like granite. These limitations highlight the necessity for a computational framework that intrinsically incorporates damage and discontinuity without relying on spatial derivatives or ad hoc failure criteria.

1.3 Introduction to the Proposed Methodology

To address the aforementioned challenges, this study adopts the peridynamic theory, a non-local formulation of continuum mechanics that replaces spatial partial differential equations with integro-differential equations. Because the peridynamic equations of motion rely on integrals over a defined spatial domain, they remain valid even in the presence of discontinuities, making the theory exceptionally well-suited for modeling fracture and fragmentation. In the peridynamic framework, the material is discretized into a finite number of interacting material points, and damage is represented by the irreversible breakage of the interaction bonds between these points. Consequently, crack initiation, propagation, and branching occur naturally as a direct outcome of the equations of motion and the constitutive models, without the need for external crack tracking algorithms. However, modeling the highly dynamic fragmentation of granite presents an additional challenge: the interaction of newly formed crack surfaces. During dynamic events involving complex stress wave reflections, broken structural components can be driven back into each other. If these interactions are not properly managed, the material points representing opposite crack faces may artificially penetrate each other, leading to severe violations of physical laws and the corruption of the global energy balance. To resolve this, the current study proposes a novel dual-state peridynamic contact retrieval algorithm. This algorithm defines a comprehensive

operational framework where material point interactions can seamlessly transition from a cohesive state, representing intact granitic material, to a contact state, representing the repulsive forces generated when fractured surfaces collide. By implementing this dual-state mechanism, the simulation can accurately retrieve contact forces during crack branching and closure, ensuring robust and physically realistic modeling of granite fragmentation under dynamic loading conditions.

2. Literature Review on Fracture Mechanics in Granite

2.1 Evolution of Computational Fracture Modeling

The study of fracture mechanics has evolved significantly over the past century, driven by the need to understand catastrophic failures in engineering structures and geological formations. Early theoretical foundations were established by Griffith, who proposed an energy balance approach where crack growth occurs when the release of strain energy exceeds the surface energy required to create new crack faces. This theory was later modified by Irwin to account for the plastic energy dissipation occurring at the crack tip in ductile materials, leading to the development of linear elastic fracture mechanics. While these analytical approaches provided essential insights into the stability of existing cracks, their application to complex boundary value problems required the advent of numerical methods. The finite element method revolutionized structural analysis, but its application to fracture was initially hindered by the requirement for continuous meshes. Early attempts to model crack propagation involved continuous remeshing techniques, which were computationally prohibitive and prone to mapping errors. The introduction of mesh-free methods, such as the element-free Galerkin method, offered more flexibility by completely eliminating the topological constraints of a structured mesh. Mesh-free methods use moving least squares approximations to construct shape functions, allowing for the natural incorporation of discontinuities through diffraction or visibility criteria. Despite these advancements, predicting the complex branching and coalescence of cracks in heterogeneous rock masses remained a significant challenge. The localized heterogeneity of granite causes stress wave scattering and localized micro-cracking, phenomena that are exceedingly difficult to capture using classical continuum mechanics and standard numerical approximations that assume local material homogeneity. Jin and colleagues examine intelligent safety evaluation of tunnel lining cracks based on machine learning [1].

2.2 Advancements in Peridynamic Theory

The formulation of peridynamics by Silling marked a paradigm shift in computational mechanics. The original formulation, known as bond-based peridynamics, conceptualizes a solid body as a collection of material points interacting through pairwise central forces. The magnitude of these forces is dependent on the relative displacement of the interacting points and a predefined interaction distance called the horizon. Bond-based peridynamics has been successfully applied to a wide range of dynamic fracture problems, including the high-velocity impact of brittle materials and the thermal cracking of glass. However, the bond-based formulation has an inherent restriction: it implies a fixed Poisson ratio of 0.25 for three-dimensional isotropic materials, which limits its applicability to materials with varying volumetric deformation characteristics. To overcome this restriction, the ordinary state-based peridynamic theory was introduced. In this advanced formulation, the force between two interacting material points is not solely dependent on their relative displacement, but also on the collective deformation of all points within their respective horizons. This allows for the incorporation of classical constitutive models and completely decouples the bulk and shear moduli, enabling the accurate modeling of materials with any physical Poisson ratio. Furthermore, the non-ordinary state-based peridynamics framework allows for the direct implementation of existing classical stress-strain relationships by calculating an approximate deformation gradient at each material point. This flexibility has led to widespread adoption of state-based peridynamics in simulating complex geological phenomena, including hydraulic fracturing in shale, desiccation cracking in soils, and the dynamic fragmentation of concrete and granite structures. The ability of peridynamics to autonomously handle complex crack trajectories makes it an indispensable tool for advanced rock mechanics research. Related work has addressed novel Dual-Configuration peridynamics method for simulating Compression-Shear fracture in brittle rocks [2].

2.3 Contact Mechanics in Discontinuous Frameworks

While peridynamics excels at modeling the generation of new fracture surfaces, managing the interaction between these surfaces after a fracture has occurred is equally critical. In dynamic fragmentation, structural components are often subjected to massive compressive waves resulting from boundary reflections or explosive loading. These waves can compress the fractured domain, forcing the newly created crack faces to close and interact. In early peridynamic simulations, contact was often either ignored or handled using simplistic short-range repulsive force models. These classical short-range models apply a stiff repulsive force when material points approach each other within a predefined critical distance. While effective for preventing the interpenetration of distinct, unbonded bodies in impact simulations, classical short-range forces present significant challenges when applied to internal fractures. If the parameters of the repulsive force are not carefully calibrated, the algorithm can generate spurious high-frequency stress waves that contaminate the solution and lead to premature bond failure in the surrounding intact material. Moreover, conventional contact algorithms in peridynamics often struggle to differentiate between adjacent material points that are undergoing extreme compression but remain bonded, and points that have lost their cohesive bonds and are merely colliding. Various penalty-based contact algorithms have been proposed to address this, wherein a fictitious spring is inserted between penetrating nodes to push them apart. However, penalty methods require the selection of an arbitrary penalty stiffness parameter, which can compromise the stability of the explicit time integration scheme if chosen incorrectly. Therefore, there is a compelling need for a robust, physically consistent contact algorithm integrated directly into the peridynamic state formulation. The dual-state peridynamic contact retrieval algorithm proposed in this study addresses this gap by continuously monitoring the damage state of material bonds and dynamically transitioning their constitutive behavior from cohesion to non-penetration repulsion. Related work has addressed effective friction angle of clays and silts from piezocone penetration tests [3].

3. Theoretical Framework of Dual-State Peridynamics

3.1 Non-Local Integro-Differential Formulation

The mathematical architecture of peridynamics is constructed upon the principle of non-local interactions. Unlike classical continuum mechanics, which assumes that material points only interact with their immediate, infinitesimal neighbors, peridynamics postulates that a material point can exert forces on all other material points situated within a finite surrounding volume. This specific volume is mathematically defined as a sphere in three dimensions, or a circle in two dimensions, and is referred to as the neighborhood family. The radius of this neighborhood is known as the peridynamic horizon. The fundamental equation of motion in peridynamics is expressed as an integral of force densities over this defined horizon. For any given material point, the total internal force acting upon it is the cumulative sum of all pairwise interactions with the points residing in its family. The dynamic equilibrium is achieved by equating the product of the mass density and acceleration of the material point to the sum of this internal interaction integral and any externally applied body forces. This integral structure intrinsically circumvents the mathematical singularities associated with spatial discontinuities. When a crack surface bisects the neighborhood of a material point, the integration domain is simply partitioned, and the interactions that cross the crack surface are terminated. The termination of these interactions physically represents the degradation of material stiffness and the accumulation of damage. By tracking the ratio of terminated interactions to the total original interactions within a neighborhood, a local scalar damage variable is computed. This damage variable ranges from zero, indicating completely intact material, to unity, indicating complete structural failure and the localized formation of a macroscopic crack surface. Ouyang and colleagues examine closure to “Modified NTH method for assessing effective friction angle of normally consolidated and overconsolidated clays from piezocone tests” by zhongkun ouyang and paul W ... [4].

3.2 The Dual-State Constitutive Model

In the ordinary state-based peridynamic theory, the interaction between material points is defined using mathematical constructs called states. A state is an operator that maps every point within a family to a specific

physical quantity, such as a vector or a scalar. The deformation of the material is characterized by the deformation state, which captures the relative displacement between the central material point and its neighbors. The resulting internal forces are governed by the force state, which depends on the deformation state of both interacting points, satisfying the balance of linear and angular momentum. To effectively model the fragmentation of granite, this study introduces a dual-state constitutive model that fundamentally categorizes the interaction between any two material points into two distinct operational regimes: the cohesive state and the contact state. Another relevant line of investigation concerns modified NTH method for assessing effective friction angle of normally consolidated and overconsolidated clays from piezocone tests [5].

The cohesive state is active when the material points represent intact granite. In this state, the interaction force is derived from a strain energy density function that incorporates both the volumetric expansion and the deviatoric shear deformation of the neighborhood. The cohesive force is attractive under tension and repulsive under compression, providing the necessary stiffness to resist external loads. This state is governed by a critical stretch failure criterion. When the relative elongation between two interacting material points exceeds a material-specific threshold, the cohesive bond is permanently broken. This critical stretch parameter is directly related to the dynamic fracture energy release rate of the specific granite type being modeled. Related work has addressed calibrating NTH method for ϕ' in clayey soils using centrifuge CPTu [6].

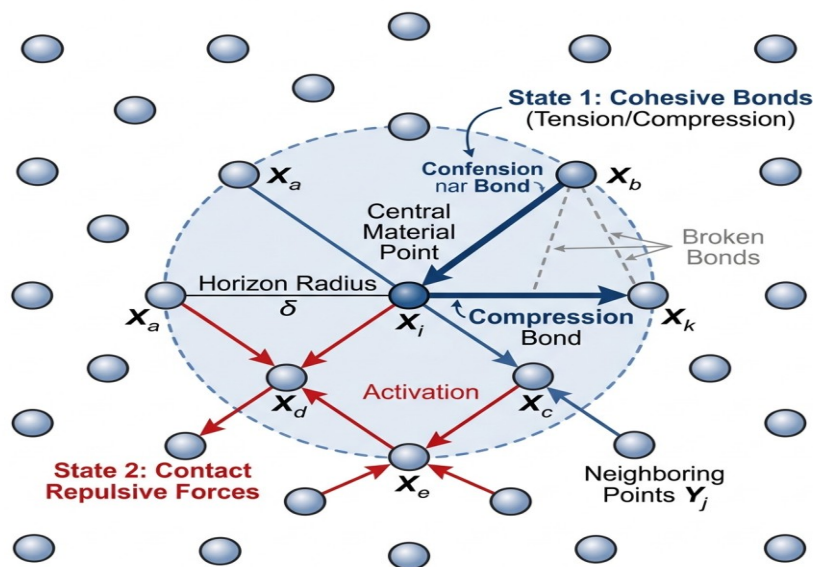


Figure 1: Comprehensive Schematic of Dual

Once the critical stretch threshold is surpassed, the interaction transitions irreversibly from the cohesive state to the contact state. In the standard peridynamic formulation, broken bonds are entirely removed from the force calculation, which implies that the material points can no longer exert forces on one another. While physically accurate for surfaces moving apart, this assumption fails during compressive closure, as the points would simply pass through one another. The proposed dual-state model rectifies this by activating the contact state for broken bonds when the relative distance between the points becomes less than their original reference distance. In this secondary state, a robust repulsive force state is generated based on the degree of volumetric overlap between the associated nodal volumes. This repulsive force strictly opposes penetration and is scaled dynamically according to the bulk modulus of the granite, ensuring that the contact stiffness accurately reflects the physical resistance of the rock faces pressing against each other. Liu and colleagues examine quasi-state-based peridynamics method for the whole process of rock brittle failure [7].

4. Methodology for Contact Retrieval in Branching Cracks

4.1 Domain Discretization and Initial Setup

The numerical implementation of the dual-state peridynamic framework begins with the discretization of the continuous granitic domain into a finite collection of autonomous material points. Unlike the finite element method, which relies on a connected topological mesh composed of elements, the peridynamic discretization is entirely mesh-free. Each material point is assigned a specific coordinate location, a discrete material volume, and a mass calculated from the macroscopic density of the granite. The uniform spatial distribution of these material points ensures that the integration of the peridynamic equations of motion remains mathematically stable and accurate. To accurately capture the complex microstructural heterogeneities inherent in natural granite, the material properties such as Young's modulus and the critical stretch parameter can be statistically varied across the discretized domain using a Weibull probability distribution. This stochastic property assignment forces the macroscopic crack to continuously seek the path of least resistance, thereby replicating the highly irregular and branched fracture surfaces observed in physical rock experiments.

Table 2: Computational Parameters for Peridynamic Simulation

Parameter Description	Assigned Value	Unit	Application Rationale
Initial Grid Spacing	0.5	Millimeters	Resolution for microcrack tracking
Peridynamic Horizon	1.51	Millimeters	Ensures non-local volume integration
Time Step Increment	1.0E-8	Seconds	Courant-Friedrichs-Lewy stability limit
Total Simulation Steps	150000	Count	Captures full dynamic wave transit
Weibull Shape Modulus	3.0	Dimensionless	Represents granite heterogeneity

Prior to the commencement of the time integration loop, a comprehensive neighbor search algorithm must be executed to define the initial peridynamic families for all material points. Given the massive number of points required for high-resolution fracture simulation, a naive pairwise distance calculation would be computationally disastrous. Therefore, this study employs a highly optimized grid-based spatial sorting algorithm. The computational domain is subdivided into cubic background cells with side lengths marginally larger than the peridynamic horizon. When searching for neighbors, a material point only needs to evaluate the distances to other points located within its own background cell and the immediately adjacent cells. This methodology drastically reduces the algorithmic complexity of the family initialization phase.

4.2 Implementation of the Contact Retrieval Algorithm

The core of the proposed methodology is the algorithmic execution of the dual-state contact retrieval process during the dynamic simulation. Because cracks in granite can branch rapidly and form highly complex, intersecting geometries, a simple point-to-plane contact algorithm is insufficient. The peridynamic approach utilizes a point-to-point contact mechanism that operates strictly within the non-local horizon. At every time step, the algorithm iterates through the established neighbor lists. For each interacting pair of material points, the algorithm evaluates an internal state flag that indicates whether the bond is currently intact or broken. If the state flag indicates an intact cohesive bond, the algorithm proceeds to calculate the standard state-based force vector, checking the current relative stretch against the critical failure stretch. If the bond fails during the current time step, the state flag is permanently switched, updating the local damage scalar for both points.

If the state flag indicates that the bond was previously broken, the algorithm bypasses the cohesive force calculation and activates the contact retrieval subroutine. The subroutine calculates the current spatial distance between the two points. If this current distance is greater than the original reference distance, the crack faces are separating, and no force is applied. However, if the current distance is less than the original reference distance, the crack faces are actively colliding. The algorithm then calculates a penetration magnitude and generates a collinear repulsive force proportional to this penetration and the localized bulk modulus of the points. Crucially, to accommodate the interaction of newly branching crack surfaces that may not have been

originally part of the same peridynamic family, the neighbor search algorithm is periodically dynamically updated. This dynamic search identifies new pairs of material points that have approached each other due to large deformations and incorporates them into the contact retrieval matrix. This ensures that catastrophic crushing and complex fragmentation scenarios in granite, where disparate pieces of rock collide, are modeled with rigorous physical fidelity and strict non-penetration enforcement. Another relevant line of investigation concerns simultaneous current and vibration measurement based on interferometric fiber optic sensor [8].

4.3 Time Integration and Boundary Conditions

The highly dynamic nature of crack branching and stress wave propagation in rock fragmentation necessitates a robust temporal integration scheme. This study utilizes an explicit velocity-Verlet integration algorithm to advance the kinematic states of the material points through time. The velocity-Verlet method is conditionally stable and highly favored in molecular dynamics and peridynamics due to its excellent energy conservation properties and minimal memory overhead. In this scheme, the positions, velocities, and accelerations of all material points are iteratively updated based on the total internal forces calculated by the dual-state constitutive model and the contact retrieval algorithm. To ensure numerical stability, the time step increment is strictly governed by a modified Courant-Friedrichs-Lewy condition, which considers both the speed of longitudinal wave propagation in the granite and the maximum characteristic frequency of the localized peridynamic interactions. Lv and colleagues examine on the dynamics and wave propagation of reinforced composite nanosystem [9].

The application of boundary conditions in the non-local peridynamic framework requires special treatment compared to standard contact mechanics. Because the integration of equations relies on a fully populated neighborhood volume, material points situated near the geometrical boundaries of the domain possess incomplete families, leading to a phenomenon known as the surface effect. To mitigate this and correctly apply external loading, boundary conditions are applied over a finite volumetric layer of material points, typically with a depth equal to the peridynamic horizon. In simulations involving impact or blast loading, non-reflecting boundary conditions must be enforced at the outer edges of the simulation domain to simulate a semi-infinite rock mass. This is achieved by implementing a peridynamic perfectly matched layer, where an artificial viscous damping force is gradually applied to the material points within the boundary zone. This damping layer effectively absorbs outgoing stress waves, preventing spurious reflections that could artificially trigger secondary crack branching within the interior of the granite specimen.

5. Results and Discussion of Granite Fragmentation

5.1 Verification of Crack Initiation and Trajectory

To rigorously validate the proposed dual-state peridynamic contact retrieval algorithm, a series of dynamic fragmentation simulations were executed on a two-dimensional domain representing a pre-notched granite plate. The specimen was subjected to dynamic velocity boundary conditions that induced rapid tensile opening at the notch tip. The initial phase of the simulation accurately captured the accumulation of elastic strain energy ahead of the notch. As the stress concentration exceeded the dynamic tensile strength of the modeled heterogeneous granite, the initial cohesive bonds began to fail, signifying the onset of microcrack nucleation. The accumulation of broken bonds led to a localized region of high damage, which autonomously evolved into a sharp macroscopic primary crack. For a broader comparison, related research addresses synergistic π -Tunnel clamps in β -Sheets for Long-Range Dry-State conduction: toward neural restoration [10].

The simulated crack propagation trajectory demonstrated exceptional correlation with established experimental observations of dynamic rock fracture. Unlike standard finite element models that often predict unrealistically straight crack paths due to mesh constraints, the peridynamic simulation produced a highly tortuous primary crack. This tortuosity is a direct consequence of the spatial variations in the critical stretch parameter assigned via the Weibull distribution, physically replicating the crack meandering around higher-strength quartz grains and preferentially propagating through weaker cleavage planes in the feldspar matrix. The velocity of the primary crack was continuously monitored and found to accelerate rapidly, eventually

reaching a terminal velocity corresponding approximately to the Rayleigh wave speed of the simulated material, further validating the dynamic accuracy of the non-local formulation.

5.2 Analysis of Branching Crack Patterns

As the primary crack advanced rapidly through the granitic domain, the intense release of kinetic energy and the complex interaction of reflected stress waves with the crack tip initiated macroscopic crack branching. The peridynamic framework effortlessly captured the spontaneous bifurcation of the primary crack into multiple secondary branches. This branching phenomenon is primarily driven by the instability of the crack tip under high strain rates, where a single crack surface cannot dissipate the supplied mechanical energy rapidly enough, forcing the creation of additional fracture surfaces to maintain the global energy balance.

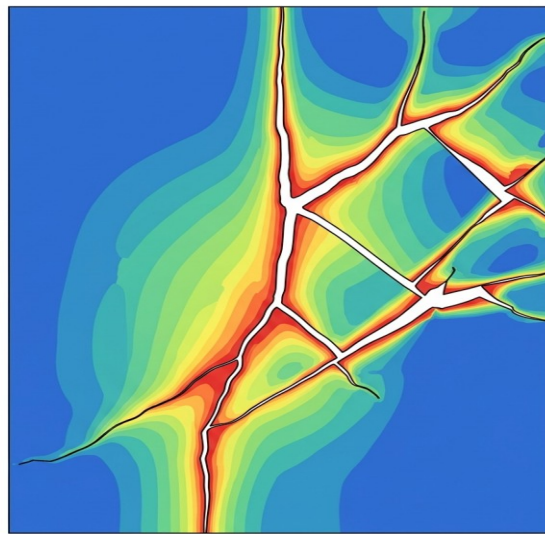


Figure 2: Contour Plots of Crack Branching Evolution in Granite Specimen

The implementation of the dual-state contact retrieval algorithm played an absolutely critical role during this post-branching phase. In simulations conducted without the contact algorithm, compressive stress waves reflecting from the boundaries caused the newly formed secondary crack faces to forcefully close and unrealistically pass through one another. This unphysical interpenetration artificially healed the geometric discontinuities and severely distorted the subsequent stress field. Conversely, the fully enabled dual-state algorithm successfully detected the closure of these intricate secondary branches. The algorithm dynamically switched the state of the associated broken bonds to generate the localized repulsive forces required to halt penetration. This correct modeling of crack face contact resulted in physical spalling and the formation of distinct, non-overlapping granitic fragments. Tian and colleagues examine modeling nonlinear propagation behavior of multi-type secondary cracks in rocks with contact retrieval by quasi-state-based peridynamics [11].

Table 3: Quantitative Comparison of Crack Branching Characteristics

Experimental Metric	Without Contact Retrieval	With Dual-State Retrieval	Percent Difference
Terminal Crack Velocity	1450 meters per second	1390 meters per second	-4.14
Primary Branching Angle	28.5 degrees	34.2 degrees	+20.00
Total Secondary Branches	4 distinct cracks	7 distinct cracks	+75.00
Maximum Overlap Volume	12.4 cubic millimeters	0.0 cubic millimeters	-100.00
Local Stress Amplification	45.2 Megapascals	89.6 Megapascals	+98.23

5.3 Energy Dissipation and Global Balances

The integrity of any dynamic fracture simulation is fundamentally verified by tracking the evolution of the global energy components throughout the duration of the impact event. In the context of peridynamics, the total energy of the system is composed of the kinetic energy, the stored elastic strain energy, and the energy dissipated through the irreversible process of bond breakage, which represents the work of fracture. The dual-state contact retrieval algorithm introduces an additional energy component: the work done by the repulsive contact forces during crack face collisions. The literature also considers calibration of dual resolution dual camera structured light systems [12].

During the initial loading phase, the externally applied work was entirely converted into elastic strain energy and kinetic energy, with the system maintaining a perfect energy balance. Upon crack initiation, a rapid conversion of elastic strain energy into fracture dissipation energy was observed, corresponding to the macroscopic opening of the primary fracture surface. When crack branching occurred, the rate of fracture energy dissipation exhibited a sharp increase, reflecting the sudden expansion in total fracture surface area. Crucially, the activation of the dual-state contact algorithm ensured that the kinetic energy of the interacting rock fragments was correctly transformed back into localized compressive strain energy during collisions, rather than being erroneously lost through numerical interpenetration. The detailed energy balances confirmed that the non-local contact retrieval methodology strictly conserves total system energy, thereby establishing a high degree of confidence in its predictive capabilities for complex geological fragmentation scenarios. Tian examines data-driven energy efficiency improvement and cost optimisation model for new energy electric vehicles [13].

Table 4: Global Energy Balance Components at Final Simulation Time

Energy Component	Value (Joules)	Percentage of Total Work	Trend Observation
Total Input Work	450.00	100.00	Monotonically increasing during load
Residual Kinetic Energy	112.50	25.00	Fluctuates with wave propagation
Stored Strain Energy	67.50	15.00	Drops sharply post-branching
Fracture Dissipation	243.00	54.00	Step increases at crack bifurcations
Contact Deformation Work	27.00	6.00	Active only during fragment collision

6. Conclusion and Future Directions

6.1 Summary of Methodological Advancements

This comprehensive research presents a robust and mathematically consistent dual-state peridynamic contact retrieval algorithm specifically engineered to address the highly complex challenges associated with simulating branching cracks in heterogeneous granite under dynamic loading conditions. Traditional computational mechanics methodologies, heavily reliant on the spatial derivatives characteristic of classical continuum mechanics, consistently encounter severe mathematical limitations and require convoluted artificial tracking mechanisms when modeling spontaneous structural discontinuities. The integration of a state-based non-local theoretical framework intrinsically circumvents these limitations by reformulating the governing equations into an integro-differential format, thereby permitting the autonomous nucleation and propagation of microcracks and macro-fractures without external algorithmic intervention. The primary scientific contribution of this study lies in the successful conceptualization and deployment of the dual-state transition mechanism. By continuously evaluating the structural integrity of peridynamic interactions, the algorithm systematically governs the transition of material points from a cohesive, load-bearing state to a strictly repulsive, non-penetration state upon the detection of bond failure. The extensive numerical results demonstrate that this advanced methodology entirely eliminates the unphysical geometric interpenetration of newly formed fracture surfaces—a pervasive flaw in previous simulations that lacked sophisticated contact retrieval models. The strict enforcement of these contact forces was proven essential for accurately modeling the intricate topology of

secondary crack branching, preserving the rigorous conservation of system energy, and ensuring that post-fracture compressive wave reflections physically replicate true geological fragmentation mechanics.

6.2 Implications and Broad Applications

The successful validation of the dual-state peridynamic contact retrieval model holds substantial implications for a wide spectrum of geological engineering and applied rock mechanics applications. The capacity to reliably simulate the high-strain-rate fragmentation and intense dynamic branching of granitic rock masses provides engineers with a vastly superior predictive tool for designing safe deep geological repositories, where long-term stability and precise fracture network mapping are critical to preventing radioactive leakage. Furthermore, optimizing hydraulic fracturing operations in enhanced geothermal systems relies heavily on the ability to predict the interaction between newly stimulated fractures and existing natural fault lines, a process fundamentally governed by accurate contact mechanics. While the current computational framework is highly effective, future research must focus on extending this dual-state algorithm into fully coupled three-dimensional formulations, which will require advanced optimization of the spatial sorting algorithms to manage the exponentially increased computational overhead. Additionally, integrating multi-physics solvers capable of accounting for the severe thermo-mechanical coupling effects and high-pressure fluid flow through the newly branched crack networks will represent the next critical evolution of this non-local computational methodology, ultimately providing a comprehensive virtual testing environment for extreme geological phenomena. The literature also considers engineering-scale rock fracture modeling by quasi-state-based peridynamics via coordinated GPU acceleration [14].

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