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Review of Advances in Numerical Simulation of Concrete under Low-Temperature Conditions

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Abstract: In recent years, concrete has continued to be widely used as a core material in construction and infrastructure projects globally. With the continuous advancement of construction technology and materials science, there are increasing demands on the mechanical properties of concrete structures, including their performance under low-temperature conditions. However, traditional experimental methods are limited by time and cost constraints, making it difficult to fully reveal the behavior of concrete under low-temperature conditions. Moreover, early numerical simulations can provide critical insights to ensure the safety of concrete structures in such environments. As a result, research on the mechanical behavior of concrete under low-temperature conditions, based on digital simulation technologies, has become a forefront topic in this field. With the enhancement of computational capabilities and the refinement of numerical methods, significant progress has been made in digital simulation techniques for concrete mechanics. Advanced simulation methods, such as the finite element method, discrete element method, finite difference method, and boundary element method, have become central to improving the reliability of simulation results through more precise models and efficient computational approaches. Against this backdrop, the review "Review of Advances in Numerical Simulation of Concrete under Low-Temperature Conditions" has emerged, summarizing the latest advancements in digital simulation techniques for studying the mechanical behavior of concrete under low temperatures, analyzing current challenges, and exploring future directions. This review aims to provide researchers with a comprehensive reference framework, fostering further development in the field of concrete mechanics.

Keywords: Numerical simulation, Concrete, Overview, Low-Temperature.

1. Introduction

The construction of concrete under low temperature conditions is one of the technical issues that is generally valued at home and abroad. When the daily average temperature during concrete construction is below 5°C or the minimum temperature is below -3°C, it is called low-temperature concrete construction, that is, "concrete winter construction". According to the anti-freeze theory of concrete, when the early strength of concrete is lower than 5 MPa (critical strength) and is frozen, the physical-mechanical properties and construction-technical properties of concrete will be deteriorated and cracks will occur. Under low temperature conditions, the hydration rate of concrete will slow down, thus affecting its strength development. If fresh concrete is frozen at temperatures around -10°C, the hydration reaction and strength development will stop. If the tensile strength of the concrete is not sufficient to resist the expansion force caused by freezing after it is set, and it is affected by low temperature, the expansion caused by freezing will cause irrecoverable irregular cracks and strength loss. Frost damage within 24 hours after concrete is poured can reduce its 28-day compressive strength by approximately 50%, while also causing surface spalling and reduced durability. Under low temperature conditions, the surface temperature of the concrete structure decreases significantly faster than the interior, resulting in a large temperature gradient and resulting temperature stress. If the tensile strength of the concrete is not enough to resist this stress, irregular cracks will appear on the surface. Most of these cracks are recoverable, but they may gradually expand under load and become a channel for corrosive substances to enter the interior of the concrete. This significantly reduces the long-term durability of concrete.

The frost durability of concrete is related to its age at the first freeze-thaw cycle, but there is no linear relationship between frost resistance at early ages and frost resistance after multiple freeze-thaw cycles. The key factors that really affect frost resistance are the tensile strength of the concrete and the degree of saturation of the pores. If concrete is exposed to low temperatures during its early age, a single freeze-thaw cycle can cause irreversible performance degradation due to insufficient tensile strength and highly saturated pores. In cold areas or harsh environments, it is necessary to ensure that the concrete structure can still work stably at low temperatures, so the study of the mechanical properties of concrete under low temperature conditions has become particularly important. The behavior of concrete at low temperatures is directly related to its application in such environments, especially in polar construction, bridges, tunnels and other infrastructure in cold regions.

2. Survey of Contemporary Numerical Approaches

2.1. Finite element modeling

This method is built on common techniques where we break down the area into different parts and use shape functions to estimate how values change between points. In a regular mechanics problem, we define the main equations for a structural simulation by putting together different elements like the overall stiffness matrix, the mass matrix, and the force vector from each part. Specifically, we figure out how stiff each part is compared to how flexible it is, showing how the material behaves in different directions (you can pick 2D or 3D simulations based on what you need).[3]

Finite element analysis (FEA) can model concrete structures by simulating load-induced cracking and analyzing the behavior of reinforced concrete (RC) elements. Performing finite element analysis involves employing numerical material models to replicate the stress-strain characteristics of concrete subjected to tension and compression, encompassing considerations for damage properties. These models can generate stress-strain curves and take into account strain-softening conditions. Leveraging finite element analysis proves invaluable in assessing current reinforced concrete structures, especially in cases where comprehensive test results are lacking. This is particularly pertinent in the modeling of plastic damage in finite-element applications. Furthermore, FEA can be used to analyze RC shell structures through a layered approach and the three-dimensional stress yield function of concrete. This approach ensures accuracy and convergence properties even on coarse meshes, and can be extended to model other material layers, such as reinforcements for retrofit purposes.[4] An efficient elastoplastic model for the analysis of reinforced concrete shells. Finite element analysis can also model 3D printed structures by using finite elements to reproduce experimental tests, allowing analysis of printing speed and its effect on stress and displacement. Utilizing Computational Modeling for Analyzing Structural Elements with Cement Composites in 3D Printing. Furthermore, the integration of Finite Element Analysis (FEA) with high-performance computing enables the analysis of extensive and intricate systems, considering nonlinear material deformations. This encompasses modeling the failure of concrete components and treating nodal reactions as external loads. The suggested approach is applicable to the numerical analysis of reinforced concrete structures, showcasing distinctive features in the modeling of such structures using the Finite Element Method.[5] The prediction of reinforced concrete structures behavior using finite element analysis involves incorporating the nonlinear characteristics of steel bars and the deformation of concrete. This method allows for forecasting the performance of these structures and enables comparison of the results with experimental data.

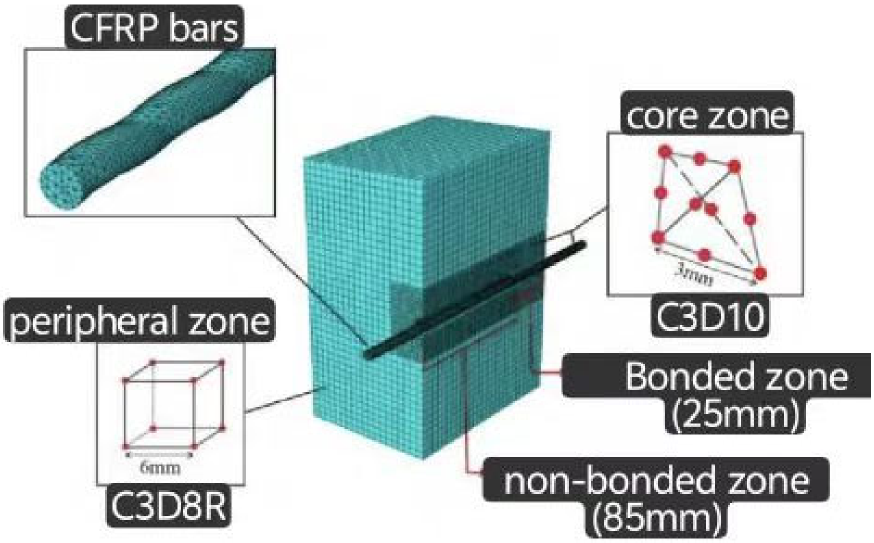

Figure 1. Xie's numerical model.

Xie and colleagues conducted a finite element modeling study on the bond performance between CFRP bars and concrete under low temperatures. In the study, the concrete specimens measured 150 mm × 150 mm × 110 mm, with a bond length of 25.0 mm (equivalent to 5 times the diameter of the CFRP bar) between the CFRP bar and concrete. The rib width of the CFRP bar was 9.0 mm, and the rib spacing was 4.0 mm. In the finite element model, the CFRP bar was modeled in detail, with the actual dimensions of the surface transverse ribs shown in Figure 2. To save computational time, the finite element model divided the concrete into a core zone and a peripheral zone. The concrete core zone and CFRP bar were meshed using ten-node modified quadratic tetrahedral elements, while the concrete peripheral zone was meshed using eight-node linear hexahedral elements. After conducting a mesh sensitivity analysis, the mesh size of 3 mm was chosen for both the concrete and CFRP bar, balancing computational efficiency and accuracy. The experimental results showed that the numerical model, which considered the surface characteristics of the CFRP bar, effectively represented the stress transfer between the CFRP bar and concrete. Additionally, the model accurately reflected the damage conditions and bond failure mechanisms between the CFRP bar and concrete under low temperatures.[20]

Finite element analysis, therefore, offers a comprehensive approach to understanding and evaluating the behavior of reinforced concrete structures.

2.2. Discrete element method

The Discrete Element Method (DEM) is a numerical simulation technique widely used in fields such as granular materials and geotechnical engineering, representing solid materials as numerous discrete particles, each possessing its unique motion state and mechanical attributes.[6] By modeling the interactions among particles, incorporating aspects like collision, friction, and contact, DEM investigates material behavior under mechanical loading, revealing both microscopic motion and macroscopic behavior in the particle system. This method provides detailed insights into complex phenomena such as internal structure, deformation, and fracture of particle systems, thereby aiding in the optimization of engineering design and the understanding of material behavior. Moreover, DEM is applicable for modeling concrete behavior, accurately assessing cracks and simulating crack characteristics in non-reinforced concrete flexural testing. This capability is highlighted in the "Discrete Element

Method Approach to Simulate Cracks in Four-Point Flexural Test," showcasing its potential in analyzing concrete behavior. Furthermore, DEM has been employed to unveil the interplay between pore structure, cement slurry properties, and mechanical properties in foamed concrete, as evidenced by the "Experimental Study and 3-D Meso-Scale Discrete Element Modeling on the Compressive Behavior of Foamed Concrete.". The integration of lattice discrete element method (LDEM) with acoustic emission (AE) technology has been employed for the analysis of concrete slabs and pre-cracked sandstone beams.[8] This approach provides a comprehensive understanding of the damage process in quasi-brittle materials, as exemplified in the study "Truss-like Discrete Element Method Applied to Damage Process Simulation in Quasi-Brittle Materials." The Discrete Element Method (DEM), in conjunction with bonding and cohesive contact models, has been employed to replicate the cementation process of clays. This approach unveils the impact of clay structure on deformation and failure processes, exemplified in "Discrete Element Method Modeling of Structural Clay."[9] Furthermore, DEM has been utilized to simulate concrete properties during the Uniaxial Compressive Test, validating numerical models and examining crack initiation and failure processes, as demonstrated in "Discrete Element Modeling of Concrete Behavior under Uniaxial Compressive Test."[10]

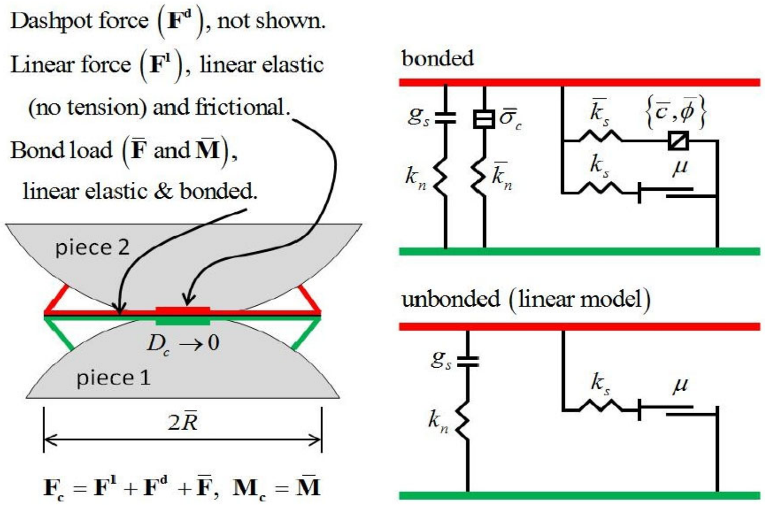

Figure 2. The constitutive relationship diagram of the linear parallel bond model

Xu demonstrated in his paper that the discrete element method (DEM) offers significant advantages in calculating freeze-thaw damage in concrete materials. The method provides accurate results, is time-efficient, and overcomes the limitations of traditional indoor freeze-thaw tests. In his experiment, Xu used PFC3D software and employed the linear parallel bond model to simulate the mechanical behavior of cement concrete. Unlike traditional linear models, the linear parallel bond model requires specific parameters to define the bonding behavior, including normal stiffness, shear stiffness, elastic modulus, parallel bond normal stiffness, parallel bond shear stiffness, parallel bond elastic modulus, parallel bond tensile strength, parallel bond cohesion, parallel bond friction angle, bond radius, and bond gap. When constructing the micromechanical model, Xu assumed that the concrete material (the study object) consists of three components: cement paste particles, voids (closed volume), and effective water-filled particles (open volume). The cement paste particles are connected by bonds to form the material's solid strength, while water particles are randomly distributed within the concrete. Upon freezing, the expansion of these water particles causes damage and rupture of the cement paste bonds. To ensure the model's representativeness and prevent overly uneven distribution of water particles, the representative volume element (RVE) of the concrete was set at 1 cm^3.The radius of the cement paste particles (gray spheres) ranges from 0.3×10-3 to 1.0×10- 3.The radius of the water particles (blue spheres) ranges from 0.2×10 -3 to 0.3×10 - 3.The experiment ultimately derived a four-factor expression for the freeze-thaw equivalent coefficient of concrete with different strengths through multifactor analysis. The fitting results were all within a reasonable margin of error, indicating a high level of accuracy.[21]

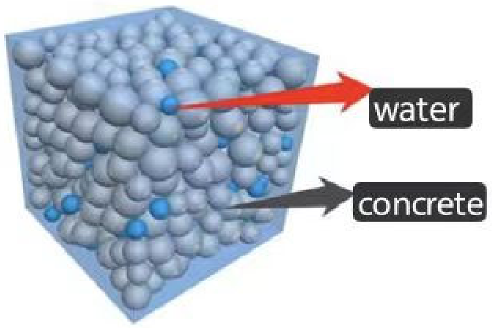

Figure 3. Microscopic freeze-thaw model of concrete

2.3. Boundary element method

The Boundary Element Method (BEM) has a wide range of applications in modeling concrete, including analyzing concrete slabs, studying concrete cracks, and assessing building raft foundations. It is also used to obtain the mechanical response of concrete and conduct crack growth analysis. This approach is particularly valuable for combining virtual crack models and simulating the nonlinear behavior of concrete cracks. Additionally, BEM has been applied to concrete fracture testing through Bayesian model updating, illustrating its efficacy in modeling various aspects of concrete behavior. It plays a pivotal role in concrete engineering by facilitating detailed modeling of concrete slabs and conducting probabilistic mechanical modeling to explore the creep behavior of concrete. These applications demonstrate the versatility and importance of BEM in the field of concrete engineering.[10]Additionally, BEM is applied for in-depth analysis of crack propagation in concrete, providing profound insights. Remarkably, in concrete fracture testing, the ingenious integration of Bayesian model updating and the Boundary Element Method reveals crucial characteristics of concrete during the fracture process. This comprehensive and innovative methodology offers robust tools and theoretical foundations for concrete material research and structural analysis.[12]

2.4. Finite difference method

Finite Difference Method (FDM) serves as a technique for numerically solving differential equations by dividing space and time into discrete grid points, establishing differential approximations, and converting differential equations into algebraic equations. First, mesh the area to be studied; then, use Taylor series expansion and other methods to replace the differential operator with a difference operator to obtain a discrete approximate equation; Specify the problem's boundary conditions to ensure the numerical solution remains valid and accurate at the boundaries; Finally, the obtained algebraic equations are solved to obtain numerical solutions at discrete grid points. The finite difference method is simple and intuitive. It is suitable for heat conduction, fluid dynamics, structural mechanics and other fields. It is a common method for solving numerical simulation problems of differential equations.

The finite difference method is a numerical analysis approach applicable in constructing mathematical models for concrete. By employing the finite difference method, the partial differential equation can be discretized, enabling the numerical simulation and analysis of the concrete's sound field. Research shows that the finite difference method can be applied to establish a mathematical model of the sound field of concrete, conduct ultrasonic numerical simulations of concrete models with different internal defect sizes, and analyze the received ultrasonic signals from the time domain and frequency domain. This shows that the finite difference method has certain application potential in concrete damage analysis. Ultrasonic damage analysis of concrete using finite difference time domain method[15]

2.5. finite volume method

The finite volume method is a numerical simulation technique applicable to the numerical simulation of concrete. This method involves partitioning the computational domain into non-overlapping control volumes and integrating the differential equation over each control volume to derive the discrete form of the equation. It has been effectively utilized in simulating diffusion transport and blast resistance in concrete. Notably, in contrast to the finite element method and the finite difference method, the finite volume method discretizes the control volume rather than the unit or node. This distinction is exemplified in the simulation and analysis of chloride ion diffusion transport in concrete using the finite volume method.[17]

2.6. Cohesive zone model

The Cohesive Zone Model (CZM), also known as the fictitious crack or Dugdale-Barenblatt model, is extensively used for modeling the behavior of concrete and other quasi-brittle materials. Unlike linear elastic fracture mechanics (LEFM) theory, CZM takes into account the mechanical behavior of materials, especially in the presence of inelastic deformations, and is therefore more suited for describing fracture phenomena in materials such as concrete and cement composites. This model has proven effective in simulating concrete fracture under uniaxial tension and accurately representing the stress and fracture behavior of concrete across different loading conditions.[18]

The Cohesive Zone Model (CZM) is a numerical approach extensively employed in fracture mechanics to simulate the initiation, propagation, and interaction of cracks within materials, particularly in brittle materials such as concrete or composites. It characterizes the response of a cohesive zone or the region of material surrounding the crack tip, presuming the material within the cohesive zone to behave as an elastic-plastic material. The cohesive stress represents the force resisting crack propagation and gradually diminishes as the crack propagates, simulating the crack opening process. This model is frequently utilized in the examination of brittle materials, notably in areas like concrete or composites.

Cohesive zone models, often utilized alongside finite element methods, are essential for simulating crack propagation in structures and materials. These models offer significant value in predicting both crack initiation and propagation, providing crucial insights into the fracture behavior of materials, and facilitating the optimization of designs to bolster structural integrity.

The Cohesive Zone Model (CZM) is utilized in concrete modeling to capture a range of phenomena, including concrete cracking, fracture, and the rehabilitation and reinforcement of reinforced concrete structures. This entails methods that focus on mechanically characterizing the bond in the aggregate-mortar interface transition zone (ITZ) and characterizing fracture properties between material elements. Consequently, the CZM is proficient in simulating the fracture failure process in reinforced concrete structures and analyzing the distribution of cracks in reinforced concrete beams, considering various reinforcement ratios and spiral stirrup inclination angles. [19]

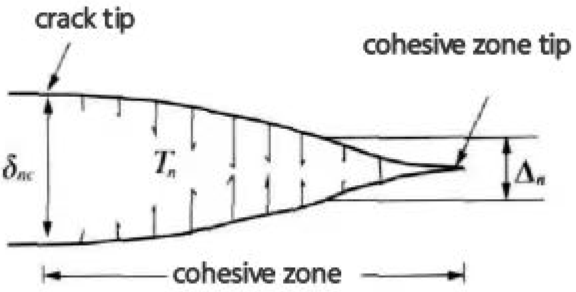

Figure 4. The schematic diagram of the cohesive tensile stress distribution on the cohesive zone surface

Chen and colleagues conducted a numerical simulation of fracture failure in a simply supported concrete beam under dynamic loading. They applied the principle of dynamic virtual work, time stepping, and a bilinear cohesive zone model, and developed a program code for dynamic analysis of the beam by combining conventional finite element methods with cohesive zone models. Utilizing the powerful pre- and post-processing capabilities of the commercial software ABAQUS, they verified that the size of the cohesive elements should be controlled to within half of the cohesive zone length. Within the cohesive zone, due to the high stress state near the crack tip, a material point (before failure) can open by a distance Δ (after failure). On the surface of the cohesive zone, there is a distributed tensile stress TTT, which is a function of the crack opening distance Δ. The relationship between the distributed tensile stress TTT and the opening distance Δ defines the constitutive law for the cohesive zone surface.[22]

3. Conclusion

This article deeply discusses various numerical simulation methods such as finite element method, finite difference method, discrete element method, boundary element method and finite volume method. Each of these methods has unique characteristics and application scope, providing a basis for studying the response of concrete structures under conditions. Through systematic analysis of these methods, we found that different numerical simulation techniques have their own advantages and disadvantages when dealing with the mechanical behavior of concrete at low temperatures, and they need to be reasonably selected and optimized according to the nature of the specific problem and the research objectives. For example, the cohesive zone model is more suitable for crack research and needs to be used in conjunction with finite elements. Discrete elements have outstanding advantages in calculating freeze-thaw damage. The boundary element method has advantages in analyzing mechanical response and crack growth. In the future, with the further improvement of computing power and the continuous improvement of numerical algorithms, these methods will play a more important role in the field of concrete engineering and provide better solutions for low-temperature environments. The design, optimization and performance prediction of concrete structures provide more accurate and reliable technical support. Through in-depth understanding and application of numerical simulation technology, we have laid a solid theoretical foundation for promoting the development of concrete mechanics and continue to promote continuous progress in this field.

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