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Microscopic Modeling Techniques for Steel Fiber Reinforced Concrete: Applications and Future Directions

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

This article reviews micro-modeling methods for steel fiber-reinforced concrete (SFRC), including finite element, discrete element, and computational fluid dynamics approaches, to analyze its mechanical and structural behavior. The models offer predictive insights on stress response, crack propagation, and durability in SFRC, particularly in high-stress structural applications. This study discusses the limitations of current modeling practices, such as high computational demand and parameter determination challenges, and suggests future improvements to enhance simulation accuracy and scalability. This review aims to support the advancement of SFRC in structural engineering applications.

Keywords: Steel fiber reinforced concrete; micro modeling; micro mechanical modeling; finite element simulation; discrete element method.

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1. INTRODUCTION

With the continuous improvement of the performance requirements of concrete materials in the construction industry, steel fiber reinforced concrete as a new type of composite material has gradually attracted attention. Researchers try to mix various types of fibers in concrete to improve the tensile properties of FRC, such as steel fiber, synthetic fiber, carbon fiber, glass fiber and natural fiber (Zhang et al., 2022). The research shows that the concrete material mixed with steel fiber has better resistance to explosion and impact load than the concrete material mixed with other fibers Steel fiber reinforced concrete (SFRC) is a composite material by adding steel fibers to concrete to enhance its tensile strength and crack resistance (Guofan, 1999). The addition of steel fibers significantly improves the tensile strength of concrete and reduces brittleness. Steel fiber can effectively restrain the crack propagation of concrete. SFRC shows better toughness and energy absorption ability when subjected to impact or dynamic load, and improves the toughness, crack resistance and impact resistance of concrete, so it has a wide application prospect in structural engineering. However, the mechanical behavior of steel fiber reinforced concrete is affected by the complexity of its internal microstructure, and the traditional macro model is often unable to accurately capture its real performance. Therefore, the meso modeling method came into being and became an important tool for the research and optimization of steel fiber reinforced concrete (Shengli, 2018).

Through in-depth analysis of the microstructure of concrete, meso modeling can reveal the mechanical properties, flow behavior and crack propagation mechanism within the material. Using numerical simulation techniques, such as discrete element method (DEM), computational fluid dynamics (CFD) and finite element analysis (FEA), researchers can effectively simulate the effect of the distribution, shape and orientation of steel fibers in concrete matrix on the material properties. These methods not only provide support for theoretical research, but also provide reliable design basis for practical engineering application.

2. MESO MODELING METHOD OF STEEL FIBER REINFORCED CONCRETE

2.1 Finite Element Method

Finite element method is a common numerical simulation tool, which can be used for the meso modeling of steel fiber reinforced concrete. By establishing a meso model including steel fiber and matrix, and considering the macro stress and the interaction between fibers, the finite element simulation can predict the mechanical behavior and failure mode of concrete. In addition, it can also optimize the concrete ratio and structural design to meet the specific engineering requirements. Before finite element simulation, it is necessary to establish appropriate mathematical models. The selection depends on the research purpose and mechanical behavior. Common models include linear elastic, elastoplastic and damage models (Jiawei, 2020). When establishing the model, the interface effect, distribution and orientation of fiber and matrix should be considered (Jihong et al., 2015).

The simulation needs to build an accurate numerical model (Yujun et al., 2013), including geometric model, material model and boundary conditions. According to the research requirements, you can choose 2D plane stress, 3D solid model or discrete element model. It is also necessary to determine a series of material parameters, such as the elastic modulus, Poisson's ratio and tensile strength of the concrete matrix, as well as the length, diameter and volume fraction of steel fibers. The accuracy of these parameters is crucial to the simulation results, which are usually obtained through experimental tests or literature research. Finite element simulation reveals the failure mechanism and stress response of steel fiber reinforced concrete (Wancheng and Chun'an 2004). By simulating the loading process, the tension of steel fiber, interface shear and crushing of concrete can be observed, which is of great significance for optimizing the ratio and structural design.

Through accurate model establishment, parameter determination and failure mechanism analysis, finite element simulation can predict the stress response and failure process of concrete. Future research should focus on improving the simulation method, improving the accuracy and reliability of the results, so as to promote the application of steel fiber reinforced concrete (Zhang et al., 2022). The simulation can also predict the mechanical properties, such as stress-strain curve, tensile strength, compressive strength, flexural strength and crack width, and provide the basis for structural design and optimization, and carry out sensitivity analysis. The accuracy of the simulation results needs to be verified by comparing with the experimental results to evaluate the reliability of the model.

2.2 Discrete Element Method

The discrete element method discretizes the steel fiber reinforced concrete system into a group of particles, representing the concrete matrix, steel fiber, etc. The shape and size of particles can be selected according to the actual situation, usually using spherical or polyhedron. The position, velocity, angular velocity and other status information of particles will be tracked and updated. In the simulation, the interaction force between particles is the basis of calculation. The contact force model is based on the contact area, stiffness and deformation, while the friction model describes the friction behavior between particles.

Steel fiber plays a reinforcing role in steel fiber reinforced concrete, which significantly affects its mechanical properties. Fiber mechanics model is used to describe the stress-strain behavior of steel fiber. The common models include spring model, elastic-plastic model and fracture model. The spring model regards the steel fiber as a linear elastic material, and connects the fiber and matrix particles through the spring. The elastic-plastic model considers the elastic and plastic behavior of the steel fiber, and more accurately describes its stress-strain response (Kelai, 2018). The fracture model is used to simulate the fracture process of steel fiber, considering the fracture strength and toughness. The fiber matrix interface plays a role in connecting and transferring force in steel fiber reinforced concrete. The interface model is divided into rigid and non rigid models. The former assumes that the interface has no slip, while the latter considers slip and shear behavior (Zhang et al., 2011, Naderi and Zhang 2020).

The material behavior can be described by appropriate particle model (Ramadoss et al., 2023). The elastic-plastic or strength softening model can be used for concrete matrix, and the spring model or elastoplastic model can be used for steel fiber. The numerical simulation of steel fiber reinforced concrete by discrete element method can observe the interaction, displacement and failure process between particles, and analyze the tensile failure of steel fiber, crushing failure of concrete and shear failure between particles. The simulation results are helpful to predict the mechanical properties and failure characteristics of steel fiber reinforced concrete.

2.3 Computational Fluid Dynamics Method

The CFD method is based on the basic equations of fluid dynamics (such as Navier Stokes equation) (Yan te al., 2022), and simulates the fluid movement through numerical methods. In the research of steel fiber reinforced concrete, CFD is mainly used to analyze the fluidity, filling and anti separation properties of concrete. Compared with the traditional experimental method, CFD can quickly obtain a large number of data in a variety of working conditions, and provide a reliable basis for material design and construction process optimization.

In the process of modeling, a suitable rheological model is selected to describe the flow characteristics of SFRC. Ensure that the rheological parameters (such as yield stress, plastic viscosity) are obtained through experiments, and accurately set the physical properties of the material, including density, viscosity, etc., to ensure that they are consistent with the actual material. Create an accurate geometric model, simulate the actual construction environment (such as pouring mold, mixer, etc.), reasonably divide the calculation grid, and ensure that there is sufficient resolution in key areas (such as places with rapid changes in flow) to capture details. Appropriate grid optimization techniques (such as local encryption) can be used. Set reasonable boundary conditions (such as inlet, outlet, wall conditions, etc.) to ensure that the simulated flow characteristics conform to the actual situation. Select appropriate initial conditions to reflect the state of concrete before mixing and pouring, and ensure that the physical state at the beginning of simulation is reasonable. The simulation results were compared with the experimental data to verify the accuracy of the CFD model. If necessary, multiple experiments can be carried out to adjust the model parameters. The post-processing tool of CFD software is used to visually analyze the flow field, velocity field and pressure field, and identify the flow characteristics and possible problems. If necessary, considering the interaction between fluid and solid particles, the fluid discrete element method (DEM) coupling simulation is used to more accurately reflect the flow and mechanical properties of concrete.

3. APPLICATION OF STEEL FIBER REINFORCED CONCRETE MESO MODELING

The meso modeling application of steel fiber reinforced concrete covers many aspects, such as mechanical properties, fluidity, crack development, fatigue evaluation and so on. Through careful numerical simulation, researchers can deeply understand the micro mechanism inside the material, so as to provide theoretical support for the design and application of concrete (Pros et al., 2012). These applications not only help to optimize the performance of existing materials, but also provide important guidance for the development of new steel fiber reinforced concrete.

3.1 Mechanical Properties

Through meso modeling, the distribution and orientation of steel fibers in the concrete matrix can be simulated, and its influence on the tensile strength, compressive strength and flexural strength of concrete can be analyzed (Caifeng, 2018).

Wang Biao (2021) regarded rockfill concrete as a composite material formed by the combination of rockfill and self compacting concrete. He used Matlab and ANSYS/LS-DYNA software to build a three-dimensional finite element model, and then carried out the numerical simulation of dynamic compression test and dynamic splitting tensile test of rockfill concrete model on this basis. The effects of strain rate, bond strength of rockfill concrete and stone particle size on the compressive strength and splitting tensile strength of rockfill concrete are discussed and analyzed.

Xiangwei liang (2018) and others successfully established and verified the three-dimensional mesoscale model through finite element method based on Delaunay triangulation. In this method, the fiber and concrete are modeled separately, and connected with the sliding line contact, which can truly reflect the interface behavior of fiber and mortar, so as to achieve high fidelity of numerical simulation. A model with high computational efficiency and accuracy is proposed. In addition, the model has the potential to deal with small specimens cut from SFRC blocks. A three-dimensional mesoscale model is proposed. Uniaxial compression, bending tension and splitting tension were simulated to verify the correctness of the model. The influence of steel fiber on the performance of steel fiber reinforced concrete was studied.

A. Orbe et al. (2014) Established the correlation between fiber orientation prediction and bending properties of composites in SFRC. Using CFD method, Bingham plastic model was realized in uniform fluid to predict fiber orientation. By analyzing the velocity fields of the fluid in the simulated continuous time step, and connecting these fields with the bending strength (before and after cracking) of the prismatic specimen extracted from the wall, the acceptability of the expected direction is confirmed.

3.2 Liquidity and Workability

Meso modeling can simulate the flow characteristics of fresh concrete and analyze the influence of steel fiber on the workability of concrete. Using CFD to simulate the flow behavior of concrete paste, the fluidity of different proportions and its operability in the construction process were studied.

F. Kolar í K et al. (2015) Proposed a numerical model for predicting the orientation state of steel fibers, and outlined the method of discretization with finite element method, using the probability distribution of fiber angle to describe the direction of fiber, and the fiber angle changes with the change of flow. The correctness of the model is verified by experiments, and the numerical algorithm for predicting fiber orientation is proposed. R. Deeb. (2014) proposed a simple method to evaluate the orientation and distribution of short steel fibers in self compacting concrete during flow. In this paper, the three-dimensional Lagrangian smoothed particle hydrodynamics (SPH) method is used to simulate the flow of self compacting fiber reinforced concrete. This method is simpler and more suitable for simulating the flow of self compacting fiber reinforced concrete and monitoring the distribution and orientation of fibers in the flow process of self compacting fiber reinforced concrete. Probability density function (PDF) is introduced to represent the three-dimensional orientation variables of fibers. In addition, the orientation variables of each fiber on any two-dimensional section are calculated by using the geometric data obtained from three-dimensional simulation.

Guodong cao (2022) and others established the mechanical model of steel fiber under the action of magnetic field in edem, and simulated the magnetic field orientation and slump of steel fiber reinforced concrete by discrete element method, and compared it with the experiment. The error between numerical results and experimental results is less than 5%, which verifies the effectiveness of the model. The influence of magnetic induction intensity and duration on the orientation of steel fiber and the influence of orientation on mortar flow were analyzed.

3.3 Fracture and Crack Development

Meso modeling can be used to simulate the process of crack formation and propagation, and study the inhibition effect of steel fiber on crack propagation. XFEM (extended finite element method) or phase field method is used to simulate the generation and development of cracks and evaluate the reinforcement effect of steel fiber under different conditions.

Jiaging wang conducted an experimental and Numerical Study on the flexural fracture behavior of steel fiber reinforced rubber self compacting concrete (SRSCC). Based on its volume, waste tire rubber aggregate (10%, 15% and 25%) was used to replace the fine aggregate of SRSCC sample, and micro steel fiber was introduced, with the addition ratio of 0.2% of the volume of the whole mixture. In the finite element model, the tension softening function is used to predict the bending fracture behavior of the corresponding specimens, and the numerical simulation results are basically consistent with the experimental results. In general, the experimental data and numerical simulation model can reveal the detailed fracture behavior of srscc, and provide reference for future material design.

Pierre rossi (2017) proposed a finite element model to analyze the crack process of SFRC beams under two-point loading. The validated numerical model is a probabilistic explicit crack model. Evaluate the influence of the degree of redundancy of the mechanical system on the mechanical properties (bearing capacity and crack process) of the beam.

3.4 Damage and Durability Assessment

Through the meso model, the fatigue behavior of steel fiber reinforced concrete under cyclic loading is analyzed, and its durability and long-term performance are studied. Combined with fatigue analysis model and microstructure simulation, the performance change of concrete under long-term load is evaluated.

Xu et al. (2012) developed a two-dimensional mesoscale model using the finite element software ANSYS. The model is composed of end hook, spiral fiber, aggregate and mortar matrix, which is used to simulate the impact compression/tensile load of SFRC under different strain rates. The influence of fiber content and fiber shape on the dynamic increase factor (DIF) of SFRC and the failure mechanism were revealed. In addition, in order to better simulate and understand the dynamic material properties and failure mechanism of SFRC, many researchers have proposed various three-dimensional (3D) mesoscale models (Liang and Wu 2018), including different phase components, such as fiber, aggregate and cement mortar.

Fang Q (2013) used the material model in LS-DYNA to describe the material characteristics of steel fiber under high rate load, which is suitable for simulating metal materials under high strain rate. At the same time, the stress and strain of the material and the fracture damage of the material are considered. The corresponding material parameters include damage parameters, shear modulus, temperature parameters, specific heat, Poisson's ratio and mass density. In order to study the effect of fiber content on the dynamic properties of SFRC, a series of meso simulations of dynamic compression, dynamic tension and contact detonation were carried out.

4. CONCLUSIONS

The meso simulation of steel fiber reinforced concrete has some limitations in research and application, but also has some future development directions. The limitations and future development direction of steel fiber reinforced concrete meso simulation are introduced in detail below:.

5. Limitation

① Model complexity: the meso simulation of steel fiber reinforced concrete involves multiple scales and various physical processes, and the complexity of the model is high. The current meso simulation method can not fully cover all the characteristics and behaviors of steel fiber reinforced concrete, which needs to be further improved. ② Parameter determination: a large number of material parameters need to be estimated and determined in the meso simulation, such as the mechanical properties of particles, fiber distribution and fiber matrix interface properties. The accuracy of these parameters has an important impact on the reliability and accuracy of the simulation results, but there are still some difficulties in the determination and estimation of the parameters. ③ Large amount of calculation: because the meso simulation of steel fiber reinforced concrete involves a large number of particle interactions, it requires a large amount of calculation resources and time. This limits the scale and application of meso simulation..

6. FUTURE DIRECTIONS

① Model improvement: the meso simulation of steel fiber reinforced concrete needs to be further improved to more accurately describe the behavior and failure mechanism of materials. For example, we can introduce a more refined fiber model and improve the model of interaction force between particles to improve the accuracy of simulation results. ② Parameter determination and verification: it is necessary to strengthen the determination and verification of steel fiber reinforced concrete material parameters to improve the reliability of simulation results. Through the comparison of experimental and field observation data, the model parameters can be better determined, and the simulation results can be verified. ③ Multi scale simulation: the behavior of steel fiber reinforced concrete is affected by many scale factors, which is of great significance from micro scale to macro scale. Future research can develop multi-scale simulation methods, combining meso simulation with macro simulation, to more comprehensively understand and predict the performance and behavior of steel fiber reinforced concrete. ④ Practical engineering application: the effective application of meso simulation results in the field of practical engineering is the future development direction. The combination of meso simulation and structural analysis can provide guidance for the design and construction of steel fiber reinforced concrete structure, and improve the performance and durability of the project.

In conclusion, although there are some limitations in the meso simulation of steel fiber reinforced concrete, the accuracy and reliability of the simulation results can be improved through the development of model improvement, parameter determination and multi-scale simulation, and the research and application of steel fiber reinforced concrete can be promoted. The success of practical engineering application will be one of the important goals of future development.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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