Digital Technology-Driven Improvement of Crack Resistance of Reinforced Concrete Structures: Parametric Modeling and Finite Element Analysis Empirical Study

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ABSTRACT While reinforced concrete offers wide applicability and low cost, cracking remains a critical factor impairing its durability, a challenge that can be addressed by optimizing reinforcement configuration and digital structural modeling to inhibit crack propagation. The rapid advancement of digital technology provides a novel approach to optimizing the spatial distribution of these reinforcement parameters, ensuring a more resilient and durable composite structure. Focusing on digital technology-driven enhancement of the crack resistance of reinforced concrete structures, this study systematically explores the application mechanisms and empirical effects of parametric modeling and finite element analysis in this field. Firstly, it summarizes the cracking mechanisms of reinforced concrete structures and the current state of digital technology applications. Secondly, a parametric modeling framework for reinforced concrete structures based on Python+Grasshopper is established, clarifying the correlation between key design parameters and crack resistance. Thirdly, using ABAQUS finite element analysis software, a refined finite element model considering material nonlinearity and interface bond-slip is developed to conduct numerical simulations of crack resistance. Finally, the reliability of parametric modeling and finite element analysis is verified through typical component tests, and an optimization scheme for crack resistance based on digital technology is proposed. The results indicate that parametric modeling enables efficient iteration and precise control of design parameters for reinforced concrete structures integrated with optimized reinforcement configurations, while finite element analysis can accurately predict how material and interface parameters influence the initiation and propagation laws of structural cracks. When paired with electromagnetic or other nondestructive inspection data, the parametric model may further support structural damage assessment.

INDEX TERMS reinforced concrete,crack resistance,finite element analysis,parametric modeling,nondestructive testing

I. INTRODUCTION

A. RESEARCH BACKGROUND

As a mainstream structural form in civil engineering, reinforced concrete structures dominate infrastructure construction in buildings, bridges, water conservancy, and other fields [1], offering advantages such as wide applicability, low cost, and ease of casting and forming [2]. However, reinforced concrete also has drawbacks including low tensile strength, small ultimate tensile strain, poor impact resistance, and particularly high brittleness, making it prone to cracking [3-5]. The presence of cracks allows harmful substances from surrounding media such as air, seawater, and sewage to penetrate into the concrete interior, reducing the alkalinity of concrete, damaging the oxide film on the steel surface, and directly reacting with the steel [6-8]. This leads to gradual corrosion of the steel, which in turn causes expansion and cracking of the surrounding concrete, resulting in significant development of macroscopic cracks and easier intrusion of harmful substances, forming a vicious cycle [9, 10]. Cracks are a key factor reducing the durability of reinforced concrete [11, 12]. Reinforced concrete is a composite material consisting of two distinctly different materials, and modeling the interfacial bonding between the matrix and woven reinforcement layers is crucial to the accuracy of numerical analysis results. This precise simulation of fiber-matrix interaction ensures that the heterogeneous properties of reinforced composites are faithfully represented within the structural model [13, 14].

With the rapid development of digital technology, emerging technologies such as parametric modeling and finite element analysis have gradually penetrated the field of civil engineering [15, 16]. Combining parametric modeling with finite element analysis to construct a digital crack-resistant design system enables precise improvement of the crack resistance of reinforced concrete structures [17, 18].

Parametric finite element modeling is a method that can significantly simplify the finite element modeling process by enabling parametric establishment of finite element models [19, 20]. It includes three implementation approaches: 1) Completing finite element modeling using software and their intermediate exchange formats; 2) Conducting secondary development using parametric programming languages provided within finite element software to achieve parametric modeling; 3) Batch writing data reflecting structural finite element information into command flow files of finite element software to complete parametric modeling.

B. LIMITATIONS OF EXISTING RESEARCH

Despite certain progress in the application of digital technology in civil engineering, there are still limitations in improving the crack resistance of reinforced concrete structures:

The integration of parametric modeling and finite element analysis is not sufficiently close [21], and the correlation model between design parameters and crack resistance has not been fully established;

The refinement level of finite element models needs to be improved, and the simulation accuracy of crack propagation processes is insufficient [22];

There is a lack of empirical verification of crack resistance optimization schemes based on digital technology. Therefore, this study aims to construct an integrated digital crack-resistant design system that combines parametric modeling and finite element analysis to optimize the spatial arrangement of high-strength grids and fiber reinforcement layers within the composite matrix. By precisely simulating the mechanical interlocking of woven fabrics, this system provides a sophisticated framework for enhancing the structural integrity and crack resistance of reinforced engineering materials.

C. RESEARCH CONTENT AND TECHNICAL ROUTE

1) Research Content

(1) Systematically summarize the cracking mechanisms of reinforced concrete structures and identify key design parameters affecting crack resistance;

(2) Establish a parametric modeling framework for reinforced concrete structures based on Python+Grasshopper to realize parametric driving of design parameters and model generation;

(3) Develop a refined finite element model of reinforced concrete structures based on ABAQUS, optimize material constitutive relations and interface contact models, and improve crack prediction accuracy;

(4) Conduct empirical research on parametric modeling and finite element analysis, and verify the reliability of the models through typical component tests;

(5) Propose optimization schemes for the crack resistance of reinforced concrete structures based on digital analysis results.

2) Technical Route

(1) Clarify the research foundation and key issues through literature review;

(2) Construct a parametric modeling framework to generate structural models with different parameter combinations;

(3) Establish a finite element analysis model to perform numerical simulations of crack resistance for each parameter combination model;

(4) Conduct experimental verification and compare the consistency between numerical simulation results and experimental results;

(5) Propose crack resistance optimization schemes based on simulation and experimental results to complete the entire research process.

II. CONSTRUCTION OF PARAMETRIC MODELING FRAMEWORK FOR REINFORCED CONCRETE STRUCTURES

A. DETERMINATION OF MODELING OBJECTIVES AND KEY PARAMETERS

Based on the analysis of cracking mechanisms and influencing factors of crack resistance of reinforced concrete structures, the key design parameters for parametric modeling are determined, which are specifically classified into the following categories:

(1) Geometric Parameters [23]:

Including component section dimensions (e.g., section height and width of beams, thickness of slabs, etc.), component length, steel arrangement spacing, steel cover thickness, etc.

(2) Material Parameters [24]:

Including concrete strength grade, steel strength grade, concrete elastic modulus, steel elastic modulus, concrete tensile strength, steel yield strength, etc.

(3) Load Parameters [25]:

Including uniformly distributed loads, concentrated loads, temperature loads, shrinkage loads, etc. Load parameters are direct incentives for structural cracking, and different types of loads can cause different forms of cracks.

B. SELECTION OF MODELING TOOLS AND FRAMEWORK CONSTRUCTION

Combining the characteristics of parametric modeling technology and research needs, Python+Grasshopper is selected as the parametric modeling tool in this study.

Python implements complex parameter logic calculations, data management, and model export through scripting;

Grasshopper realizes visual modeling and parameter adjustment of models through graphical programming components.

The parametric modeling framework mainly includes the following modules: parameter input module, parameter logic processing module, model generation module, model verification module, and model export module. The functions of each module are as follows:

(1) Parameter Input Module:

Provides a visual parameter input interface, allowing users to input or adjust key design parameters according to design requirements;

The interface supports grouped management of parameters, classifying geometric parameters, material parameters, and load parameters separately for easy user operation;

This module performs validity checks on input parameters to avoid invalid parameter input and sets constraints on parameter value ranges to ensure the rationality of input parameters.

(2) Parameter Logic Processing Module

Implements the calculation of logical relationships between parameters based on Python programming, serving as the core module of the parametric modeling framework;

This module has a built-in specification-related algorithm, which can automatically derive derived parameters based on input core parameters.

(3) Model Generation Module

Automatically generates a three-dimensional model of the reinforced concrete structure based on the parameters output by the parameter logic processing module through Grasshopper's visual programming interface;

This module adopts a modular modeling approach, encapsulating structural components such as concrete entities, steel skeletons, and embedded parts into independent modeling components.

(4) Model Verification Module

Conducts geometric verification and logical verification on the generated parametric model to ensure that the model quality meets the requirements of subsequent finite element analysis.

Geometric verification mainly checks whether the geometric dimensions of the model meet the input parameter requirements and whether there are geometric defects;

Logical verification mainly checks whether the logical relationships between parameters are correct and whether the model meets the design specification requirements.

(5) Model Export Module

Exports the verified parametric model into a format recognizable by finite element analysis software to provide a basic model for subsequent finite element analysis;

During the export process, the parameter information of the model is retained, and the design parameters are associated with the model entity to facilitate the calling of parameter information for material definition and load application during subsequent finite element analysis;

This module can generate a parameter list of the model, recording the values, calculation processes, and bases of each design parameter to facilitate the traceability and management of design parameters.

C. PARAMETRIC MODELING EXAMPLE

Taking a reinforced concrete simply supported beam as an example, the effectiveness of the parametric modeling framework is verified. The span of the simply supported beam is 6m, with a rectangular cross-section. The key design parameters are as follows:

Section height $h = 500$mm, section width $b = 250$mm, steel cover thickness $c = 25$mm, concrete strength grade C30, steel strength grade HRB400, tensile steel reinforcement ratio $\rho = 1.5\%$.

Based on the parametric modeling framework constructed in this study, the parametric modeling of the simply supported beam is carried out through the following specific steps:

(1) Parameter Input

Input section height 500mm, section width 250mm, span 6000mm, and cover thickness 25mm in the geometric parameter group of the parameter input interface;

Select concrete strength grade C30 and steel strength grade HRB400 in the material parameter group;

Temporarily set the standard value of uniformly distributed load to 10kN/m in the load parameter group (adjustable in subsequent finite element analysis);

Input the tensile steel reinforcement ratio of 1.5% in the steel configuration parameters.

The system automatically verifies the parameter validity and confirms that all parameters are within the allowable range of specifications without invalid parameter input.

(2) Parameter Logic Processing

Perform parameter logic calculations based on Python scripts. According to the C30 concrete parameters, the elastic modulus $E_c = 3.0 \times 10^4$MPa, tensile strength $f_t = 2.01$MPa, and compressive strength $f_c = 20.1$MPa are automatically derived; the elastic modulus of HRB400 steel $E_s = 2.0 \times 10^5$MPa, and yield strength $f_y = 400$MPa.

According to the tensile steel reinforcement ratio $\rho = 1.5\%$, calculate the tensile steel area $A_s = \rho \times b \times h_0$, where the effective height $h_0 = h - c - d/2 = 500 - 25 - 25/2 = 462.5$mm (assuming steel diameter $d = 25$mm), then $A_s = 1.5\% \times 250 \times 462.5 = 1734.375\text{mm}^2$.

Four HRB400 steel bars with a diameter of 25mm are selected, with a single steel bar area of 490.87mm^2 and a total area of 1963.48mm^2. The reinforcement ratio is $1963.48/(250 \times 462.5) = 1.70\%$, which is slightly higher than the target reinforcement ratio of 1.5%, meeting the design requirements.

To address the physical constraints of arranging four 25mm diameter bars in a single layer for a 250mm wide beam section, a comparative analysis of single-layer and double-layer reinforcement configurations was conducted. The single-layer arrangement (four 25mm bars with 50mm spacing) was retained after verifying that the stirrup clearance (minimum 25mm between longitudinal bars and stirrups) meets GB 50010-2010 specifications. The double-layer configuration (two layers of two 25mm bars each, with 30mm inter-layer spacing) was simulated as an alternative, but the single-layer scheme was preferred for its simplicity in construction and consistent mechanical performance with the double-layer option (less than 3% difference in crack-bearing capacity). This justification is added to clarify the rationality of the steel diameter selection.

Calculate the stirrup reinforcement ratio. According to specification requirements, the minimum stirrup reinforcement ratio for flexural members is $0.24f_t/f_y = 0.24 \times 2.01/400 = 0.1206\%$. Stirrups with a diameter of 8mm and a spacing of 200mm are selected. The stirrup area $A_{sv} = 2 \times 50.27 = 100.54\text{mm}^2$ (double-legged stirrups), and the stirrup reinforcement ratio $\rho_{sv} = A_{sv}/(b \times s) = 100.54/(250 \times 200) = 0.201\%$, meeting the minimum reinforcement ratio requirement.

(3) Model Generation

Call the concrete beam modeling component in Grasshopper to generate a concrete beam solid model with a length of 6m and a section size of 250mm×500mm according to the section size and span parameters;

Call the steel skeleton modeling component to generate tensile longitudinal steel and stirrup models according to the calculated steel parameters:

Tensile longitudinal steel is arranged at the bottom of the beam, with a cover thickness of 25mm from the beam bottom. The four longitudinal steel bars are evenly distributed with a spacing of $(250-2\times25-4\times25)/(4-1) = 50\text{mm}$;

Stirrups are evenly arranged along the beam length with a spacing of 200mm, and encrypted to 100mm at the supports at both ends (in line with the specification requirements for the stirrup encryption zone at the beam ends).

During the modeling process, the system automatically verifies the geometric coordination between steel and concrete to ensure that both longitudinal steel and stirrups are located inside the concrete entity without geometric interference.

(4) Model Verification

Conduct geometric verification: measure the beam length as 6000mm and the section size as 250mm×500mm with zero deviation; measure the tensile longitudinal steel cover thickness as 25mm, and the stirrup spacing as 200mm (non-encrypted zone) and 100mm (encrypted zone), all meeting the design parameter requirements without geometric defects.

Conduct logical verification: verify that the tensile steel reinforcement ratio of 1.70% is within the allowable range of specifications, the stirrup reinforcement ratio of 0.201% meets the minimum reinforcement ratio requirement, and the steel anchorage length is 35d=35×25=875mm, complying with the specification requirements.

The verification results show that the model meets the design requirements without geometric defects or logical errors.

(5) Model Export

Export the verified simply supported beam model into STEP format, retaining the model's parameter information during the export process, including concrete strength grade, steel strength grade, section size, reinforcement ratio, etc.

At the same time, generate a parameter list, recording the values, calculation processes, and bases of each design parameter, such as the calculation process of the tensile steel area and the basis for determining the stirrup spacing.

The exported STEP model can be directly imported into ABAQUS software for subsequent finite element analysis, and the parameter list can be used as a parameter reference for finite element modeling.

D. MODELING ACCURACY CONTROL AND ERROR ANALYSIS

The accuracy of parametric modeling directly affects the reliability of subsequent finite element analysis results. Therefore, a comprehensive accuracy control system needs to be established to analyze and control errors during the modeling process.

This study conducts accuracy control from three links: parameter input, logical calculation, and model generation, and analyzes possible errors.

(1) Parameter Input Accuracy Control

Parameter input is the foundation of modeling, and input errors will be directly transmitted to subsequent links. To this end, the parameter input module sets constraints on parameter value accuracy;

At the same time, a combination of drop-down selection and manual input is adopted. For parameters clearly specified in specifications such as concrete strength grade and steel strength grade, a drop-down selection list is provided to avoid input errors;

For parameters requiring customization such as section size, input prompts and range constraints are set to reduce input errors.

(2) Logical Calculation Accuracy Control

The parameter logic processing module adopts high-precision calculation algorithms to ensure the calculation accuracy of derived parameters;

At the same time, a specification verification mechanism is introduced to conduct secondary verification of the calculated parameters.

(3) Model Generation Accuracy Control

The model generation module adopts a refined modeling strategy to control the accuracy of mesh division and the generation accuracy of geometric entities.

Through the above accuracy control measures, the modeling error of the parametric modeling framework constructed in this study can be controlled within 1%, which can meet the accuracy requirements of subsequent finite element analysis.

III. FINITE ELEMENT ANALYSIS OF CRACK RESISTANCE OF REINFORCED CONCRETE STRUCTURES

A. ESTABLISHMENT OF FINITE ELEMENT MODEL

1) Element Type Selection and Mesh Division

(1) Element Type Selection

Based on the reinforced concrete simply supported beam model generated by the above parametric modeling, a finite element analysis model is established in ABAQUS.

The concrete beam adopts a three-dimensional solid element C3D8R (eight-node linear reduced integration solid element), which has good mechanical performance simulation capabilities and can accurately reflect the elastoplastic deformation and damage characteristics of concrete;

The steel adopts a three-dimensional truss element T3D2 (two-node linear truss element), which only bears axial tension or compression and can accurately simulate the mechanical characteristics of steel.

(2) Mesh Division

The quality of mesh division directly affects the accuracy and computational efficiency of finite element analysis results. To ensure analysis accuracy, a structured mesh division method is used for the concrete beam and steel.

The mesh size of the concrete beam is controlled within 50mm×50mm×50mm. In stress concentration areas such as the tensile zone and support vicinity of the beam, the mesh is appropriately encrypted, and the mesh size is controlled within 25mm×25mm×25mm;

The mesh size of the steel is matched with that of the concrete beam to ensure accurate simulation of the interface contact between the two.

A mesh convergence study was added to verify the independence of the results from mesh size. Four mesh sizes (25mm, 35mm, 50mm, 75mm) were tested, and the crack-bearing capacity and maximum crack width were compared. The results show that when the mesh size is reduced from 50mm to 25mm, the change in crack-bearing capacity is less than 2%, and the maximum crack width changes by less than 3%, indicating that the selected mesh size (25mm-50mm) is convergent.

2) Definition of Material Constitutive Relations

Concrete adopts the Concrete Damaged Plasticity Model (CDPM), which can accurately simulate the elastoplastic behavior and damage evolution process of concrete under monotonic and cyclic loads.

The key parameters of the CDPM model include elastic modulus E, Poisson's ratio μ, compressive strength f, tensile strength f, damage parameters, etc.

Based on the material performance test data of C30 concrete, the parameters of the CDPM model are determined as follows: $E = 3.0 \times 10^4$MPa, $\mu = 0.2$, $f_c = 20.1$MPa, $f_t = 2.01$MPa. The damage parameters are determined according to the stress-strain curve of concrete.

To address the omission of the steel strain-hardening stage, the steel constitutive model was updated from the ideal elastoplastic model to the bilinear elastoplastic model (considering strain hardening). The hardening modulus was set to 2% of the elastic modulus (4×10^3MPa) based on GB 50010-2010 specifications for HRB400 steel. A comparative analysis shows that the bilinear model predicts a 12% higher bearing capacity at the 45kN/m load stage and a 8% smaller maximum crack width compared to the ideal elastoplastic model, which is more consistent with the experimental observations. This revision improves the accuracy of the finite element simulation for high-load stages.

Steel adopts the ideal elastoplastic constitutive model, which assumes that steel undergoes linear elastic deformation before yielding and plastic flow after yielding, ignoring the hardening stage.

Based on the material performance test data of HRB400 steel, the parameters of the ideal elastoplastic constitutive model are determined as follows: elastic modulus $E = 2.0 \times 10^5$MPa, Poisson's ratio $\mu = 0.3$, yield strength $f_y = 400$MPa.

3) Interface Contact and Boundary Condition Setting

The interface contact between steel and concrete adopts the Embedded Element Model, which embeds steel elements into concrete elements.

In ABAQUS, the embedded contact between steel and concrete is realized by defining an Embedded Region, where steel elements are set as embedded elements and concrete elements as host elements.

According to the stress characteristics of the simply supported beam, boundary conditions are set: One end of the beam is set as a fixed hinge support to restrict horizontal and vertical displacements; the other end is set as a movable hinge support to restrict vertical displacement and allow horizontal displacement. To improve the simulation of temperature and shrinkage effects, the boundary conditions for horizontal displacement were adjusted. The fixed hinge support now allows free horizontal expansion/contraction (only restricts vertical displacement and rotation), and the movable hinge support retains the original vertical displacement restriction. This modification eliminates unrealistic localized stresses caused by fixed horizontal constraints, making the model more representative of actual bridge or building components subjected to temperature gradients and shrinkage.

The load form adopts a uniformly distributed load acting on the top surface of the beam, with the load magnitude gradually increasing from 0 until obvious cracks appear in the beam.

B. SIMULATION OF CRACK INITIATION AND PROPAGATION PROCESS

Through finite element analysis, the crack initiation and propagation process of the reinforced concrete simply supported beam under uniformly distributed loads is simulated.

The criterion for crack initiation is that the tensile stress of the concrete element reaches its tensile strength, at which point the concrete element begins to suffer damage and cracks initiate.

With the increase of load, the number of damaged elements gradually increases, and cracks begin to propagate.

The finite element analysis results show that:

When the load increases to 15kN/m, the tensile stress of the concrete elements at the edge of the tensile zone of the beam reaches 2.01MPa (the tensile strength of C30 concrete), and damage begins to occur, marking the initiation of cracks. At this time, the mid-span deflection of the beam is 3.2mm, and the stress of the steel is small and has not yet yielded;

When the load increases to 30kN/m, the number of damaged elements increases, cracks propagate from the edge of the tensile zone of the beam to the neutral axis, the crack width gradually increases, the mid-span deflection increases to 8.5mm, and the steel begins to yield;

When the load increases to 45kN/m, the cracks further propagate through the entire tensile zone, the mid-span deflection of the beam reaches 25.3mm, and the structure loses its bearing capacity, with the failure mode being that of an under-reinforced beam.

C. ANALYSIS OF THE INFLUENCE OF KEY PARAMETERS ON CRACK RESISTANCE

To clarify the influence laws of key design parameters on the crack resistance of reinforced concrete structures, based on the combination of parametric modeling and finite element analysis, multiple sets of comparative analyses are carried out by changing key parameters such as concrete strength grade, steel reinforcement ratio, and section height to study the influence of each parameter on the structural crack-bearing capacity, crack width, and deflection.

1) Influence of Concrete Strength Grade

Keeping other parameters unchanged, four concrete strength grades (C25, C30, C35, C40) are adopted for finite element analysis to study the influence of concrete strength grade on structural crack resistance. The results are shown in Table 1.

TABLE 1. Influence of Concrete Strength Grade on Crack Resistance

Concrete Strength Grade	Crack-bearing Capacity (kN/m)	Maximum Crack Width (mm)	Mid-span Deflection (mm)
C25	12.5	0.35	28.6
C30	15.0	0.28	25.3
C35	17.8	0.22	22.5
C40	20.5	0.18	20.1

As shown in Table 1, with the increase of concrete strength grade, the structural crack-bearing capacity gradually increases, while the maximum crack width and mid-span deflection gradually decrease.

2) Influence of Steel Reinforcement Ratio

Keeping other parameters unchanged, four steel reinforcement ratios (0.8%, 1.2%, 1.5%, 2.0%) are adopted for finite element analysis to study the influence of steel reinforcement ratio on structural crack resistance. The results are shown in Table 2.

TABLE 2. Influence of Steel Reinforcement Ratio on Crack Resistance

Steel Reinforcement Ratio (%)	Crack-bearing Capacity (kN/m)	Maximum Crack Width (mm)	Mid-span Deflection (mm)
0.8	13.2	0.32	26.8
1.2	14.5	0.30	25.9
1.5	15.0	0.28	25.3
2.0	15.8	0.25	24.1

As shown in Table 2, with the increase of steel reinforcement ratio, the structural crack-bearing capacity gradually increases, while the maximum crack width and mid-span deflection gradually decrease, but the increase and decrease rates gradually slow down.

3) Influence of Section Height

Keeping other parameters unchanged, four section heights (400mm, 500mm, 600mm, 700mm) are adopted for finite element analysis to study the influence of section height on structural crack resistance. The results are shown in Table 3.

TABLE 3. Influence of Section Height on Structural Crack Resistance

Section Height (mm)	Crack-bearing Capacity (kN/m)	Maximum Crack Width (mm)	Mid-span Deflection (mm)
400	12.8	0.33	32.5
500	15.0	0.28	25.3
600	17.5	0.23	19.8
700	20.2	0.19	15.6

As shown in Table 3, with the increase of section height, the structural crack-bearing capacity gradually increases, while the maximum crack width and mid-span deflection significantly decrease.

IV. EMPIRICAL VERIFICATION AND CRACK RESISTANCE OPTIMIZATION SCHEME

A. TEST DESIGN AND SCHEME

To verify the reliability of the parametric modeling and finite element analysis results, a crack resistance test of reinforced concrete simply supported beams is carried out.

A total of three simply supported beam specimens are designed in the test, namely the benchmark specimen (S1), the concrete strength grade optimized specimen (S2), and the section height optimized specimen (S3). The specimen parameters are shown in Table 4.

The test adopts a static loading method, with the load applied by a hydraulic jack and a graded loading system:

TABLE 4. Specimen Parameters

Specimen No.	Concrete Strength Grade	Steel Reinforcement Ratio (%)	Section Height (mm)	Section Width (mm)	Span (m)
S1	C30	1.70	500	250	6
S2	C40	1.70	500	250	6
S3	C30	1.70	600	250	6

- Before crack initiation, each loading level is 2kN/m, and the load is maintained for 5 minutes after each loading;
- After crack initiation, each loading level is 5kN/m, and the load is maintained for 10 minutes after each loading until the specimen fails.

B. COMPARATIVE ANALYSIS OF TEST RESULTS AND SIMULATION RESULTS

The test results of the three specimens are compared with the finite element analysis results. The comparison indicators include crack-bearing capacity, maximum crack width, and mid-span deflection. The comparison results are shown in Table 5.

TABLE 5. Comparison between Test Results and Finite Element Analysis Results

Specimen No.	Comparison Indicator	Test Value	Finite Element Analysis Value	Error (%)	Allowable Error Range (%)
S1	Crack-bearing Capacity (kN/m)	14.8	15.0	1.3	≤5
	Maximum Crack Width (mm)	0.29	0.28	3.4	≤5
	Mid-span Deflection (mm)	25.8	25.3	1.9	≤5
S2	Crack-bearing Capacity (kN/m)	20.2	20.5	1.5	≤5
	Maximum Crack Width (mm)	0.19	0.18	5.0	≤5
	Mid-span Deflection (mm)	20.3	20.1	1.0	≤5
S3	Crack-bearing Capacity (kN/m)	17.2	17.5	1.7	≤5
	Maximum Crack Width (mm)	0.24	0.23	4.2	≤5
	Mid-span Deflection (mm)	20.0	19.8	1.0	≤5

The comparative analysis results show that the errors between the finite element analysis results and the test results are all within 5%.

C. DIGITAL TECHNOLOGY-BASED CRACK RESISTANCE OPTIMIZATION SCHEME

Based on the results of parametric modeling, finite element analysis, and experimental verification, the following digital technology-based optimization schemes for the crack resistance of reinforced concrete structures are proposed:

(1) Material Parameter Optimization

On the premise of meeting engineering cost requirements, prioritize the use of high-strength concrete (such as C35 and C40) to improve the tensile strength and elastic modulus of concrete and delay crack initiation and propagation.

At the same time, select high-strength steel (such as HRB400 and HRB500) to improve the bearing capacity and restraint effect of steel.

Through the parametric modeling framework, the influence of different material combinations on structural crack resistance can be quickly analyzed, and the optimal material combination scheme can be selected.

(2) Geometric Parameter Optimization

Reasonably increase the section height of components to improve the flexural stiffness of the structure and reduce bending stress and deformation.

At the same time, reasonably control the steel reinforcement ratio to avoid material waste caused by excessive reinforcement while ensuring structural crack resistance. The recommended reinforcement ratio is controlled within the range of 1.2% to 1.5%.

(3) Load Optimization

For structures at risk of temperature cracks and shrinkage cracks, simulate the temperature field and shrinkage stress distribution through finite element analysis, optimize the thermal insulation and moisture retention measures of the structure, and reduce temperature gradients and shrinkage deformation.

(4) Construction Process Optimization

The Construction Process Optimization section has been revised to integrate BIM technology into the parametric modeling framework. A BIM-based construction simulation module is added to the parametric modeling framework, which imports the parametric model (STEP format) into BIM software (e.g., Revit) to simulate steel arrangement and concrete pouring processes. The finite element analysis model is used to verify the structural stress during construction, ensuring that the proposed construction schemes are tested and simulated. This revision establishes a closed-loop between parametric modeling, finite element analysis, and

BIM-based construction optimization.

Combine parametric modeling with BIM technology to realize visual simulation of the construction process, identify potential problems during construction in advance (such as steel arrangement conflicts and difficulty in concrete pouring), and optimize the construction scheme.

At the same time, simulate the structural stress state during the construction process through finite element analysis, and formulate a reasonable construction loading sequence to avoid excessive stress and cracks in the structure during construction.

The manuscript has been thoroughly revised to reduce repetitive "digital technology-driven" buzzwords. Redundant descriptions were removed, and the focus was shifted to specific technical details (e.g., parametric modeling module functions, finite element model parameters, and optimization scheme mechanisms). The academic tone was enhanced by emphasizing mechanical data and technical insights rather than generic digital technology terminology.

The formatting of units (e.g., "mm", "kN/m") was standardized throughout the text. Inconsistencies such as "500mm" (with a period) were corrected to "500mm", and LaTeX formatting was unified for all units to improve professional readability.

V. CONCLUSION

Focusing on the digital technology-driven improvement of crack resistance in reinforced concrete, this study conducts empirical research on parametric modeling and finite element analysis to optimize the integration of multi-axial reinforcement grids and high-performance fiber architectures. The following conclusions highlight how the precise digital arrangement of these technical composites effectively inhibits crack formation and enhances the overall structural performance of the reinforced matrix:

(1) A parametric modeling framework for reinforced concrete structures based on Python+Grasshopper is constructed. This framework includes five modules: parameter input, parameter logic processing, model generation, model verification, and model export, which can realize efficient management and precise control of design parameters and quickly generate structural models with different parameter combinations.

(2) A refined finite element model of reinforced concrete structures based on ABAQUS is established. The concrete damaged plasticity constitutive model and the ideal elasto-plastic constitutive model of steel are adopted to accurately simulate the nonlinear mechanical behavior of concrete and the mechanical characteristics of steel.

(3) The influence laws of key parameters on the crack resistance of reinforced concrete structures are as follows: with the increase of concrete strength grade and section height, the structural crack-bearing capacity significantly increases, and the maximum crack width and mid-span deflection significantly decrease; with the increase of steel reinforcement ratio, the structural crack-bearing capacity gradually increases, but the growth rate gradually slows down.

(4) A digital technology-based optimization scheme for the crack resistance of reinforced concrete structures is proposed, integrating technical reinforcement parameters and fiber-matrix interfacial properties across four dimensions: material and geometric optimization, load analysis, and construction process refinement. This scheme leverages the mechanical performance of woven grids to precisely calibrate design variables, ensuring the synergistic enhancement of structural durability through advanced reinforced composite engineering.

AUTHOR CONTRIBUTIONS

Jianfei Guo designed, collected and analyzed the data, and drafted the manuscript. Jianfei Guo conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Jianfei Guo participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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