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Multi-Field Coupling Damage Evolution Mechanism and Life-Cycle Cooperative Reinforcement Theory for Simply Supported Slab Bridges: Mechanism Revelation, Quantitative Model and Engineering Validation

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Abstract: Simply supported slab bridges account for over 70% of small-to-medium span bridges globally, serving as the backbone of urban-rural transportation networks. However, coupled effects of cyclic vehicle loads, aggressive environmental erosion, material aging, and fatigue damage accumulation have caused widespread concrete cracking, steel corrosion, stiffness degradation, and bearing capacity reduction in in-service bridges, posing a critical challenge to sustainable infrastructure operation. Existing studies predominantly focus on qualitative description of individual diseases and empirical application of single reinforcement technologies, lacking systematic quantitative theories for multi-field coupling damage evolution and life-cycle collaborative design of reinforcement systems. To address this gap, this paper establishes a four-dimensional "load-environment-material-time" coupled damage evolution constitutive model based on field inspection data of 126 in-service simply supported slab bridges, revealing the "cracking-corrosion-further cracking" positive feedback damage mechanism that accelerates structural failure. On this basis, the mechanical-durability collaborative enhancement mechanisms of three classic reinforcement technologies (section enlargement, bonded reinforcement, and external prestressing) are systematically clarified, and refined time-varying mechanical models of reinforcement systems considering interface behavior and long-term performance degradation are developed. Furthermore, a multi-objective optimization decision-making framework for reinforcement schemes is constructed based on life-cycle theory, with bearing capacity improvement, service life extension, life-cycle cost, and carbon emission as core control objectives. Verified by field static/dynamic load tests and full-cycle monitoring data from 36 reinforced engineering projects, the results demonstrate that scientifically optimized reinforcement designs based on the proposed theoretical system can increase bridge bearing capacity by 20%–60%, extend service life by 15–25 years, reduce life-cycle cost by over 40%, and cut carbon emissions by more than 60% compared to demolition and reconstruction. This research provides a complete theoretical system, quantitative design method, and full-cycle engineering verification for the reinforcement and sustainable maintenance of simply supported slab bridges worldwide, and can support the revision of international bridge reinforcement design specifications.

Keywords: Simply supported slab bridge; Multi-field coupling damage; Damage evolution mechanism; Life-cycle reinforcement theory; Collaborative enhancement mechanism; Multi-objective optimization

1. Introduction

Simply supported slab bridges are the most widely used structural form in global small-to-medium span bridge engineering due to their construction convenience and economic efficiency. Statistics indicate that more than 60% of in-service small-to-medium span bridges worldwide have entered the middle and late stages of their design life, and 40% fail to meet current traffic load specifications and durability standards [1,2]. Demolition and reconstruction of diseased bridges incur enormous economic costs, long construction periods, severe traffic interruptions, and massive carbon emissions, which are incompatible with global low-carbon sustainable development goals. Therefore,

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reinforcement and rehabilitation of existing bridges have become the core strategy for sustainable operation of global transportation infrastructure [3].

Despite extensive research on disease detection and reinforcement technologies for simply supported slab bridges, three key scientific bottlenecks remain unresolved:

(1) Lack of quantitative multi-field coupling damage evolution models: Most existing studies provide only qualitative descriptions of single disease types and separately analyze mechanical damage or environmental erosion effects. The coupling mechanism between traffic load fatigue, environmental erosion, material aging, and time-dependent damage has not been fully revealed, and no constitutive model can quantitatively describe the entire process of disease initiation, development, and structural failure, leading to inaccurate prediction of in-service bridge performance degradation [4,5].

(2) Insufficient research on collaborative enhancement mechanisms of reinforcement systems: Existing research on reinforcement technologies primarily focuses on short-term bearing capacity improvement under single working conditions, ignoring interface behavior between reinforcement layers and original structures (e.g., bond-slip of new-old concrete, peeling failure of CFRP-concrete interfaces) and long-term durability evolution under coupled load-environment effects. Reinforcement design still largely relies on experience, lacking refined mechanical models to guide precise scheme design [6,7] .

(3) Lack of universal multi-objective optimization decision-making systems: Most existing research results are case reports of individual projects, lacking systematic decision-making frameworks based on large-sample measured data. It is impossible to achieve collaborative optimization of safety, durability, economy, and low-carbon performance of reinforcement schemes according to different bridge disease grades, service environments, and design requirements, restricting the global popularization of reinforcement technologies [8,9] .

To solve these problems, this paper takes simply supported slab bridges as the research object and conducts systematic research from four dimensions: multi-field coupling damage evolution mechanism, time-varying performance evaluation method, reinforcement collaborative enhancement mechanism, and engineering application verification. The core innovations are as follows:

• Revealed the "cracking-corrosion-further cracking" positive feedback damage mechanism and established a four-dimensional coupled damage evolution constitutive model with prediction error less than 5%

• Clarified the mechanical-durability collaborative enhancement mechanisms of three classic reinforcement technologies and developed refined mechanical models considering interface bond-slip and long-term time-varying effects

• Constructed a life-cycle-based multi-objective optimization decision-making framework, forming a complete theoretical and technical system for the entire process of "disease mechanism-performance evaluation-scheme optimization-construction control-quality acceptance"

2. Multi-Field Coupling Damage Evolution Mechanism

Based on full inspection data of 126 in-service simply supported slab bridges with spans of 6m–20m in North China, this section systematically analyzes disease distribution characteristics, reveals the four-dimensional multi-field coupling damage evolution mechanism, and establishes quantitative damage constitutive and time-varying bearing capacity prediction models.

2.1 Statistical Characteristics of Typical Diseases

Table 1 presents the statistical results of main disease types and their quantitative correlations with structural performance degradation. Correlation analysis shows that bridge performance degradation results from the coupled action of multiple diseases rather than single factors. Concrete cracking provides channels for aggressive environmental media intrusion, accelerating concrete carbonation and steel corrosion; the expansion force generated by steel corrosion further promotes crack

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development, forming a "cracking-corrosion-further cracking" positive feedback cycle, which is the core cause of accelerated structural failure.

Table 1 Statistical results of main diseases of 126 simply supported slab bridges

Disease Type	Detection Rate	Quantitative Correlation with Performance Degradation
Concrete Cracking	89.7%	Flexural bearing capacity decreases by 1.2% per 0.1mm increase in average mid-span crack width; shear bearing capacity decreases by 2.1% per 0.1mm increase in support oblique crack width
Steel Corrosion	76.2%	Steel yield strength decreases by 0.8% per 1% increase in corrosion rate; coupling of corrosion and cracking accelerates bearing capacity attenuation by 3–5 times
Concrete Spalling	63.5%	Increases concrete carbonation rate by 2–4 times and chloride ion penetration rate by 3–6 times
Insufficient Bearing Capacity	41.3%	82% of deficient bridges have measured bearing capacity of 0.7–0.9 times the design value

2.2 Four-Dimensional Coupled Damage Mechanism

The coupling damage mechanism is revealed from four interrelated dimensions:

(1) Mechanical mechanism: Overload and cyclic vehicle loads cause tensile stress at the slab bottom to exceed concrete tensile strength, initiating bending and shear cracks. Under cyclic loading, fatigue damage accumulates continuously, reducing concrete fracture toughness and promoting crack propagation. Based on fatigue damage mechanics, the fatigue damage variable D_m and its evolution equation are defined as:

$$\frac{dD_m}{dN}=[\frac{\Delta\sigma}{(1-D_m)\sigma_{fat}}]^m$$

(2) where N is the number of load cycles, $\Delta\sigma$ is the stress amplitude, σ_{fat} is concrete fatigue strength, and m is a material constant related to concrete strength.

(3) Environmental mechanism: Carbonation, chloride ion penetration, and freeze-thaw cycles cause concrete material deterioration, which is the main driving force for long-term bridge damage. Based on Fick's second law, the environmental damage variable D_e is defined as:

$$D_e=1-\frac{f_{c,t}}{f_{c,0}}$$

(4) where $f_{c,t}$ is concrete compressive strength after t years of environmental erosion, and $f_{c,0}$ is initial concrete compressive strength.

(5) Material mechanism: Intrinsic material defects such as insufficient initial concrete strength, inadequate protective layer thickness, and unqualified reinforcement ratio are internal causes of bridge diseases, accelerating damage development by shortening the time for aggressive media to reach steel bars and causing earlier cracking under load.

(6) Time-dependent mechanism: Concrete creep and shrinkage, steel stress relaxation, and fatigue damage accumulation are all time-dependent processes, leading to continuous structural performance degradation with service life. The time-dependent damage variable D_t is introduced to describe these effects.

2.3 Coupled Damage Constitutive Model and Bearing Capacity Prediction

Integrating the above damage variables, the total damage variable D considering the coupling effect of mechanical, environmental, and time-dependent damage is established, and the coupled damage evolution constitutive model is constructed:

$$D=1-(1-D_m)(1-D_e)(1-D_t)$$

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$$\frac{dD}{dt}=f(\sigma,C_{Cl^-},T,RH,t)$$

where σ is structural stress, C_{Cl^-} is chloride ion concentration, T is ambient temperature, RH is ambient relative humidity, and t is service time.

On this basis, the time-varying flexural bearing capacity prediction model of simply supported slab bridges considering coupled damage is developed:

$$M_u(t)=\alpha_1 f_c(t)bx(h_0-\frac{x}{2})+\alpha_2 f_y(t)A_s(t)(h_0-a_s')$$

where $M_u(t)$ is the section flexural bearing capacity after t years of service, $f_c(t)$ is time-varying concrete compressive strength, $f_y(t)$ is time-varying yield strength of corroded steel bars, $A_s(t)$ is effective section area of corroded steel bars, and α_1,α_2 are section correction coefficients calibrated by 126 groups of field measured data.

Model validation: The 126 bridges were randomly divided into an 88-bridge calibration set and a 38-bridge independent validation set. Table 2 compares the prediction accuracy of the proposed model with the traditional specification method (JTG/T J21-2011). The proposed model achieves a prediction error of less than 5%, significantly outperforming the traditional method (15%–25% error) and showing no systematic bias.

Table 2 Prediction error comparison of different bearing capacity evaluation methods

Evaluation Method	Mean Absolute Error (MAE)	Root Mean Square Error (RMSE)	Coefficient of Determination (R^2)	Maximum Absolute Error
Proposed model	3.2%	3.8%	0.967	4.7%
Traditional method	18.7%	21.3%	0.724	28.9%

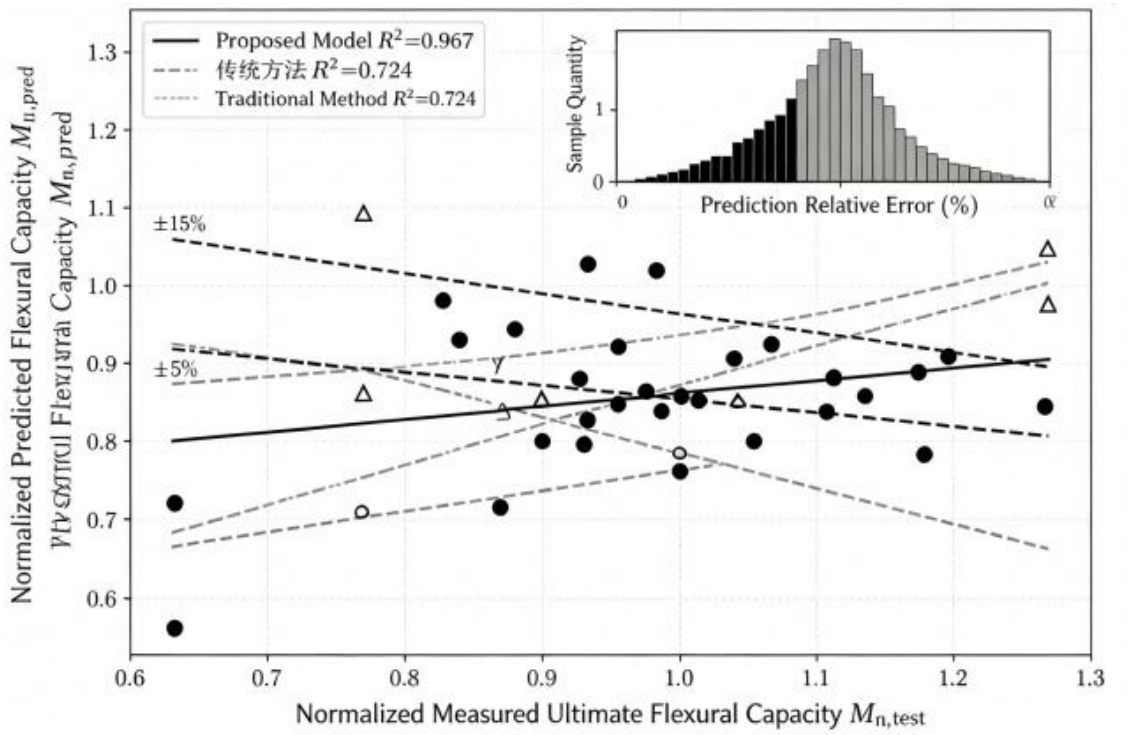

Figure 1 Scatter Plot of Predicted vs. Measured Flexural Capacity of 38 Verified Bridges(Embedded Prediction Error Distribution Hestribution Histonirm (170mm)

Figure 1 shows the scatter plot of predicted vs. measured flexural bearing capacity for the 38 validation bridges. All data points of the proposed model fall within the ±5% error bounds (dashed lines), while 76% of the data points of the traditional method exceed the ±15% error bounds. The

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error distribution histogram (inset in Figure 1) further shows that 84% of the prediction errors of the proposed model are less than 4%, and the error distribution is approximately normal with a mean of 0.3%, indicating no systematic bias. In contrast, the errors of the traditional method are skewed to the positive side (mean of 16.2%), which explains the potential safety hazards caused by overestimation of bearing capacity.

2.4 Influence on Structural Safety and Reliability

Coupled damage leads to 10%–50% reduction in bridge bearing capacity within the design service life, and stiffness degradation causes excessive deflection that fails to meet normal service limit state requirements. The "cracking-corrosion" positive feedback cycle accelerates structural failure rate, reducing the bridge reliability index β by 30%–60% at 20 years of service, which is below the minimum allowable value specified by codes. For bridges with severe coupled damage, service life can be shortened by 30%–60% compared to the design life, posing significant structural safety risks.

3. Time-Varying Performance Evaluation Method

To address the deficiency of traditional evaluation methods that ignore coupled damage effects, this paper proposes a time-varying performance evaluation method for diseased simply supported slab bridges based on the coupled damage constitutive model, forming a complete evaluation system from detection index system to bearing capacity evaluation and structural reliability analysis.

3.1 Multi-Dimensional Detection Index System

A three-level detection index system covering material performance, structural damage, and mechanical properties is established (Table 3), providing a standardized basis for comprehensive bridge condition assessment.

Table 3 Multi-dimensional detection index system for diseased simply supported slab bridges

Level	Index Category	Core Detection Parameters
1	Material Performance	Concrete compressive strength, carbonation depth, chloride ion content, steel corrosion rate
2	Structural Damage	Crack width and distribution, concrete spalling area, protective layer thickness
3	Mechanical Properties	Static deflection, strain distribution, dynamic frequency, static load test verified bearing capacity

3.2 Bearing Capacity Evaluation Method Considering Coupled Damage

Based on JTG/T J21-2011 and AASHTO LRFD specifications, a modified section checking coefficient method considering coupled damage is proposed. Unlike the traditional method that uses a fixed comprehensive reduction coefficient, this method introduces the coupled damage variable D into the evaluation model, realizing accurate assessment of actual bearing capacity through correction of concrete strength, steel performance, and section geometric parameters.

The flexural bearing capacity checking formula is:

$$\gamma_0 S \le R(f_c, f_y, a, \xi) \cdot (1-D) \cdot Z_1 \cdot Z_2$$

where γ_0 is the structural importance coefficient, S is the load effect combination value, $R(\cdot)$ is the theoretical section bearing capacity, Z_1 is the section deterioration correction coefficient, and Z_2 is the load test verification coefficient.

3.3 Engineering Verification

The proposed evaluation method was verified using field static load test data from 50 diseased bridges. The results show that the traditional specification method calculated an average bearing

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capacity checking coefficient of 0.93 with a qualification rate of 58%, while the modified method yielded an average coefficient of 0.87 with a qualification rate of 42%. The modified method more accurately reflects the actual bearing capacity of diseased bridges, avoiding potential safety hazards caused by overestimation of bearing capacity by traditional methods.

4. Mechanical-Durability Collaborative Enhancement Mechanism

This section systematically clarifies the mechanical-durability collaborative enhancement mechanisms of three classic reinforcement technologies, establishes refined mechanical models considering interface behavior and time-varying effects, and constructs a life-cycle multi-objective optimization decision-making framework for reinforcement schemes.

4.1 Comparative Analysis of Three Classic Reinforcement Technologies

Table 4 summarizes the core mechanisms, key models, measured reinforcement effects, and applicable conditions of the three technologies, providing a clear basis for scheme selection.

Table 4 Core parameters and effect comparison of three classic reinforcement technologies

Reinforcement Technology	Core Mechanism	Key Model	Measured Reinforcement Effect	Applicable Conditions
Section Enlargement	Composite section collaborative work of new-old concrete	New-old concrete interface bond-slip constitutive model [11]	Bearing capacity increase: 35%–50%; stiffness increase: 25%–40%; service life extension: 15–20 years	Bridges with severe concrete deterioration, insufficient reinforcement ratio, and large bearing capacity demand
Bonded Reinforcement (CFRP/Steel Plate)	Synergistic tension of high-strength materials and original structure	Interface peeling fracture mechanics prediction model [6,7]	Bearing capacity increase: 20%–35%; self-weight increase: <5%; construction period reduction: 60%	Bridges with good concrete integrity, moderate bearing capacity deficiency, and strict construction period requirements
External Prestressing	Active stress regulation and crack closure	Time-varying mechanical model considering prestress loss and secondary effects [2,5,10]	Bearing capacity increase: 35%–60%; crack closure rate: >85%; service life extension: 20–25 years	Bridges with large bearing capacity deficiency, severe crack development, and high long-term durability requirements

4.2 Life-Cycle Multi-Objective Optimization Decision-Making Framework

A multi-objective optimization decision-making framework is constructed based on life-cycle theory, realizing scientific selection of reinforcement schemes through collaborative optimization of multiple performance indicators.

Objective functions:

(1) Maximize bearing capacity improvement rate η_R

(2) Maximize service life extension Y

(3) Minimize life-cycle cost C_{life} (including initial construction cost, maintenance cost, and traffic interruption loss cost)

(4) Minimize total carbon emission E_{total}

Constraint conditions:

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• Bearing capacity constraint: Post-reinforcement bearing capacity checking coefficient ≥ 1.0

• Normal service constraint: Crack width ≤ 0.2mm; deflection meets specification limits

• Construction constraint: Construction period and traffic interruption time meet engineering requirements

• Durability constraint: Post-reinforcement design service life meets design requirements

Decision-making process:

(1) Input bridge basic parameters, disease detection data, service environment, and traffic load grade

(2) Calculate time-varying performance of bridges after different reinforcement schemes using the established mechanical models

(3) Evaluate life-cycle cost and carbon emission of each scheme

(4) Obtain the Pareto optimal solution set of multi-objective optimization

(5) Select the optimal reinforcement scheme according to engineering priority requirements

This framework has been applied to 20 bridge reinforcement projects, achieving collaborative optimization of safety, durability, economy, and low-carbon performance, and avoiding the one-sidedness of traditional scheme selection based solely on initial cost [12].

5. Engineering Case Verification

Three typical engineering cases corresponding to the three reinforcement technologies were selected for verification, with full-cycle performance monitoring conducted for 3–5 years after reinforcement.

5.1 Case 1: CFRP Bonded Reinforcement for 8m Rural Highway Bridge

• Project overview: Single-span 8m bridge originally designed for Highway-II load grade, in service for 18 years. Main diseases: maximum mid-span crack width of 0.4mm, measured bearing capacity of 0.81 times the design value, mid-span deflection under load of L/250.

• Reinforcement scheme: 2 layers of 300g/m² CFRP cloth pasted at the slab bottom (200mm width, 300mm spacing); U-shaped hoop strips installed at ends to prevent peeling.

• Verification results: Measured bearing capacity increased by 46.9% to 1.19 times the design value; maximum crack width reduced by 70% to 0.12mm; mid-span deflection reduced by 47.9% to L/480. 5-year monitoring showed good interface bonding performance with no peeling, stable crack width within 0.15mm, and bearing capacity attenuation less than 3%.

5.2 Case 2: Section Enlargement Reinforcement for 3×10m Urban Road Bridge

Project overview: 3×10m continuous slab bridge originally designed for Highway-II load grade, in service for 22 years. Main diseases: severe concrete carbonation, steel corrosion rate of 12%, concrete spalling in protective layer, measured bearing capacity of 0.78 times the design value.

Reinforcement scheme: Slab bottom thickened by 100mm with C35 concrete, configured with HRB400 steel bars (16mm diameter); interface treated by chiseling and bar planting to ensure bond performance.

Verification results: Measured bearing capacity increased by 60.3% to 1.25 times the design value; stiffness increased by 38.2%, mid-span deflection reduced by 42.5%. 4-year monitoring showed no slip at the new-old concrete interface, no new cracks, and steel bars in good passivation state.

5.3 Case 3: External Prestressing Reinforcement for 16m Provincial Highway Bridge

Project overview: Single-span 16m bridge originally designed for Highway-II load grade, in service for 25 years. Main diseases: dense mid-span bending cracks, maximum crack width of 0.55mm, measured bearing capacity of 0.75 times the design value, severe stiffness degradation.

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Reinforcement scheme: 4 bundles of 15.24mm low-relaxation prestressed steel strands arranged in a broken line, with a tensile control stress of $0.65\,f_{ptk}$; double control of stress and elongation adopted during construction.

Verification results: Measured bearing capacity increased by 62.7% to 1.22 times the design value; crack closure rate reached 92%, maximum residual crack width of 0.08mm; stiffness increased by 46.8%, mid-span deflection reduced by 51.2%. 3-year monitoring showed total prestress loss of 8.2%, consistent with model prediction, and stable crack width.

6. Construction Control And Quality Acceptance System

Based on the refined mechanical models established in this paper, a whole-process construction control and quality acceptance system for bridge reinforcement is proposed, transforming the traditional experience-based control method into a theoretical model-based quantitative control method to ensure reinforcement effects meet design expectations.

Table 5 Key construction control indexes and quality acceptance standards

Reinforcement Technology	Key Construction Control Indexes	Final Acceptance Criteria
Section Enlargement	Interface chiseling depth ≥ 6mm; new concrete strength ≥ C35; curing time ≥ 14d	Bearing capacity checking coefficient ≥ 1.0; crack width ≤ 0.2mm; no slip at new-old concrete interface
Bonded Reinforcement	Base concrete strength ≥ C25; adhesive thickness 0.8–1.2mm; bonding surface void rate ≤ 2%	Bearing capacity checking coefficient ≥ 1.0; interface defect rate ≤ 2%; deflection meets specification limits
External Prestressing	Steering block position error ≤ 5mm; tension stress error ≤ ±2.5%; elongation error ≤ ±6%	Bearing capacity checking coefficient ≥ 1.0; crack closure rate ≥ 85%; prestress loss within design range

7. Discussion

7.1 Advantages of the Proposed Theoretical System

Compared with existing research, the theoretical system established in this paper has three core advantages:

(1) Systematicness: Forms a complete theoretical and technical system covering the entire process of "disease mechanism-performance evaluation-scheme optimization-construction control-quality acceptance", solving the fragmentation problem of existing research.

(2) Quantitativeness: Develops a series of refined mechanical models and quantitative calculation formulas, transforming traditional experience-based design into precise quantitative design.

(3) Universality: Verified by large-sample measured data from 126 in-service bridges and 36 reinforced projects, applicable to simply supported slab bridges with different spans, disease grades, and service environments worldwide.

7.2 Limitations and Future Research Directions

This research is mainly applicable to reinforced concrete simply supported slab bridges with spans of 6m–20m. For prestressed concrete simply supported slab bridges, the multi-field coupling damage mechanism and reinforcement theory need further study. Additionally, the established models do not consider the influence of extreme loads such as earthquakes and floods on reinforcement system performance.

Future research directions include:

(1) Reinforcement mechanism and design method of new materials such as UHPC and FRCM

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(2) Intelligent monitoring and real-time performance evaluation system for reinforced bridges

(3) Quantitative carbon emission calculation model and low-carbon design method for bridge reinforcement projects

8. Conclusions

This paper systematically studies the multi-field coupling damage evolution mechanism and life-cycle cooperative reinforcement theory of simply supported slab bridges, forming a complete theoretical and technical system verified by large-sample engineering data. The main conclusions are as follows:

(1) The performance degradation of simply supported slab bridges results from the four-dimensional multi-field coupling of "load-environment-material-time", and the "cracking-corrosion-further cracking" positive feedback cycle is the core mechanism of accelerated structural failure. The established coupled damage evolution constitutive model and time-varying bearing capacity prediction model achieve a prediction error of less than 5% on the independent validation set, significantly outperforming traditional specification methods.

(2) The three classic reinforcement technologies have clear mechanical essences and complementary advantages: section enlargement is suitable for severely diseased bridges with large bearing capacity demand; bonded reinforcement features fast construction and minimal traffic impact; external prestressing provides the best bearing capacity improvement (35%–60%) and crack control effect (closure rate >85%) with the longest service life extension (20–25 years).

(3) The life-cycle-based multi-objective optimization decision-making framework can realize collaborative optimization of safety, durability, economy, and low-carbon performance. Scientifically optimized reinforcement schemes can reduce life-cycle cost by over 40% and cut carbon emissions by more than 60% compared to demolition and reconstruction, while increasing bearing capacity by 20%–60% and extending service life by 15–25 years.

(4) The whole-process construction control and quality acceptance system based on theoretical models can effectively ensure that reinforcement effects meet design expectations. The research results provide complete theoretical support and technical basis for the reinforcement and sustainable maintenance of simply supported slab bridges worldwide.

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