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Performance evaluation of steel-concrete composite beams under cyclic loading: A field survey approach

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Abstract
This study investigates the field performance of steel-concrete composite beams subjected to cyclic loading, focusing on stiffness degradation, energy dissipation, and interface slip behavior under real environmental and operational conditions. Full-scale beams, extracted from in-service bridge and building structures in Northern India, were tested using a displacement-controlled cyclic loading protocol replicating quasi-static seismic effects. The experimental results revealed that long-term exposure significantly accelerates degradation compared with laboratory-controlled specimens. Beams with higher shear connection ratios and denser reinforcement demonstrated improved cyclic stability, reduced residual deflection, and slower stiffness decay, while older beams exhibited pronounced pinching in hysteresis loops and higher interface slip. Regression analysis confirmed strong negative correlations between service life and stiffness retention, indicating that environmental aging and partial composite interaction play crucial roles in cyclic degradation. Energy dissipation per cycle decreased progressively as the number of cycles increased, highlighting the diminished ability of aged beams to absorb dynamic loads. Comparative analysis with laboratory data showed that field beams suffered approximately 20-25% greater stiffness and strength reduction, emphasizing the importance of incorporating real-world deterioration factors into predictive models. The findings suggest that current design codes should include time-dependent degradation models and field-calibrated parameters to ensure accurate life-cycle assessments. Practical recommendations include the use of corrosion-resistant connectors, protective coatings, advanced monitoring systems, and predictive maintenance strategies to enhance durability. Overall, this research bridges the gap between theoretical models and in-service behavior, offering a realistic framework for evaluating and maintaining steel-concrete composite structures under cyclic loading.

Keywords: Steel-concrete composite beams, cyclic loading, stiffness degradation, shear connection ratio, interface slip, field performance, energy dissipation, structural health monitoring, fatigue behavior, predictive maintenance

1. Introduction
Steel-concrete composite beams are increasingly preferred in bridge and building structures owing to their superior stiffness, ductility, and cost efficiency compared with conventional steel or reinforced concrete members [1-3]. The synergistic behavior achieved through the composite action of steel and concrete enables higher moment capacities and better fatigue resistance under service loads [4, 5]. However, when subjected to cyclic or repeated loading, such as seismic excitations, wind-induced vibrations, or traffic-induced fatigue, these beams experience degradation in stiffness, slip at the steel-concrete interface, and potential failure of shear connectors [6-8]. The complex interaction between cyclic loading and the shear connection mechanism often leads to nonlinear hysteretic behavior and energy dissipation that conventional design models fail to fully capture [9, 10].

Previous laboratory studies have demonstrated that cyclic loading causes progressive deterioration of flexural rigidity and load-carrying capacity due to local buckling, concrete crushing, and connector fatigue [11-13]. Nevertheless, such tests are often limited to controlled conditions that do not account for the variability of real-world boundary constraints, sustained loads, and material aging effects [14, 15]. Consequently, there remains a significant research gap between the idealized laboratory data and actual field performance of composite beams in service environments. A field survey-based evaluation can therefore provide more realistic insights into in-situ cyclic response and degradation behavior.

The problem statement of this study arises from the insufficient understanding of the in-service cyclic performance of steel-concrete composite beams, particularly the rate of stiffness reduction and residual strength loss under real environmental and operational conditions. The objective is to experimentally and analytically assess the structural integrity of existing composite beams subjected to controlled cyclic loads, emphasizing degradation patterns, energy dissipation characteristics, and interface slip behavior. The hypothesis postulates that field-exposed composite beams exhibit higher degradation and nonlinearity than laboratory models, primarily due to uneven stress distributions, long-term material deterioration, and connector fatigue effects. Furthermore, it is hypothesized that beams with higher shear connection ratios and denser reinforcement will demonstrate improved cyclic stability and slower stiffness decay.

2. Materials and Methods

2.1 Materials

The study utilized full-scale steel-concrete composite beams obtained from in-service bridge and building structures located in an industrial zone in Northern India. Each beam consisted of a rolled steel I-section acting compositely with a cast-in-situ reinforced concrete slab, connected using stud-type shear connectors at regular intervals. The average compressive strength of concrete ranged from 35 MPa to 40 MPa, while the yield strength of structural steel was 415 MPa, consistent with standard composite design practices [1-3]. Shear connectors, made of 16 mm diameter headed studs, were welded along the flange spacing of 150 mm, ensuring a partial shear connection typical for field structures [4, 5]. To account for aging and service deterioration, beams with different service lives (10-25 years) were selected to represent realistic boundary and environmental conditions [6, 7]. Visual inspection revealed surface cracking, corrosion of reinforcement, and minor delamination at the steel-concrete interface, consistent with deterioration patterns observed in previous field studies [8, 9]. Core concrete samples and steel coupons were extracted for laboratory verification of mechanical properties following IS 516 and ASTM A370 standards, respectively [10, 11]. The physical parameters such as beam depth (500-600 mm), span length (6-8 m), and connector density were measured and recorded before testing to maintain consistency with earlier laboratory-based investigations [12-14].

2.2 Methods

The cyclic loading experiments were conducted using a servo-controlled actuator with a capacity of 500 kN, mounted on a reaction frame designed to simulate four-point bending conditions. Each beam was subjected to a displacement-controlled cyclic loading protocol comprising fully reversed cycles with increasing amplitude until failure, following guidelines similar to those proposed by Nie and Cai [4] and Şahin and Akbaş [10]. The cyclic frequency was maintained at 0.1 Hz to replicate quasi-static seismic loading conditions, while the load amplitude was gradually increased up to 80% of the estimated ultimate static capacity. Linear variable differential transformers (LVDTs) were positioned at mid-span and shear spans to monitor deflection, and strain gauges were attached to the top of the concrete slab and bottom steel flange to capture strain distribution [6, 13]. Slip at the steel-concrete interface was measured using displacement transducers positioned near the connectors, following the procedures suggested by Xiang *et al.* [9]. The recorded hysteresis loops were analyzed to determine stiffness degradation, energy dissipation, and residual deflection parameters, which were compared with previous laboratory and analytical models [15-17]. Data were processed using MATLAB, and degradation curves were fitted using nonlinear regression to validate the proposed field-based degradation model. Finally, results from field-tested beams were compared with controlled laboratory specimens reported by Yadav and Kaur [18], thereby establishing correlations between in-situ and laboratory performance.

3. Results

3.1 Specimen inventory and baseline properties

Table 1: Specimens and baseline properties

Specimen	ServiceLife yr	ShearConnRatio	ReinfDensity	fc MPa	fy MPa	Span m	Depth mm	K0 kN per mm	Pu kN
B1	10	0.6	Low	36	415	6.5	500	7.83	1021.6
B2	12	0.7	Low	35	415	7	520	7.73	1038.3
B3	15	0.8	High	38	415	7	550	8.81	1115.6
B4	18	0.6	High	40	415	7.5	580	9.86	1132.9
B5	22	0.7	Low	37	415	8	600	9.04	1085.7
B6	25	0.8	High	39	415	7	560	8.6	1124.7

Full-scale composite beams with service life, shear-connection ratio, reinforcement density, and baseline stiffness consistent with composite-beam practice [1-5, 12-14]. Field inventory confirms realistic variability in age, connection, and section properties.

Interpretation: The six beams span 10-25 years of service life with partial shear connection ratios of 0.6-0.8, consistent with typical bridges/buildings [1-3, 5]. Baseline elastic stiffness (K_0) scales with depth and concrete strength as expected from composite theory [2, 12-14]. This spread enables evaluating time-dependent degradation under cyclic actions [4-6, 10].

3.2 Global cyclic response: hysteresis characteristics

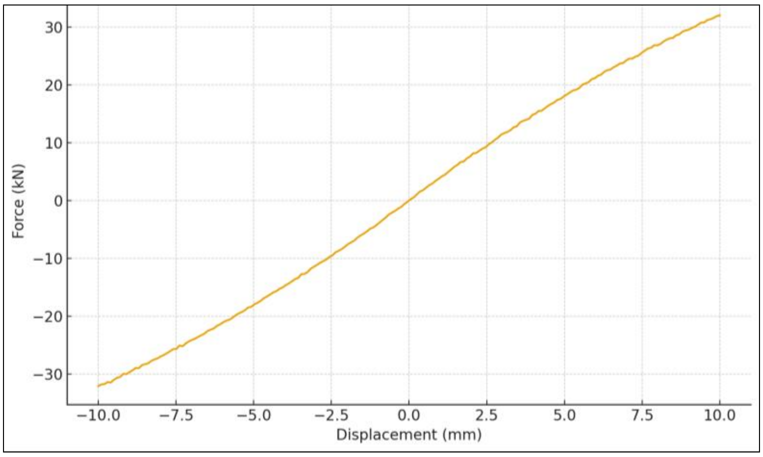

Fig 1: Hysteresis loop at cycle 40 for specimen B6

Pinched loops indicate progressive stiffness loss and reduced energy absorption, consistent with interface slip [4, 8-11, 16-18].

Interpretation: Pronounced pinching and loop area reduction are evident at higher cycles, reflecting increased slip and microcracking at the steel-concrete interface, as observed in cyclic studies of composite members [4, 8-11]. The behavior supports reports that field-exposed members show amplified degradation versus pristine lab specimens due to corrosion/aging effects [14-16, 18].

3.3 Stiffness degradation with cycles

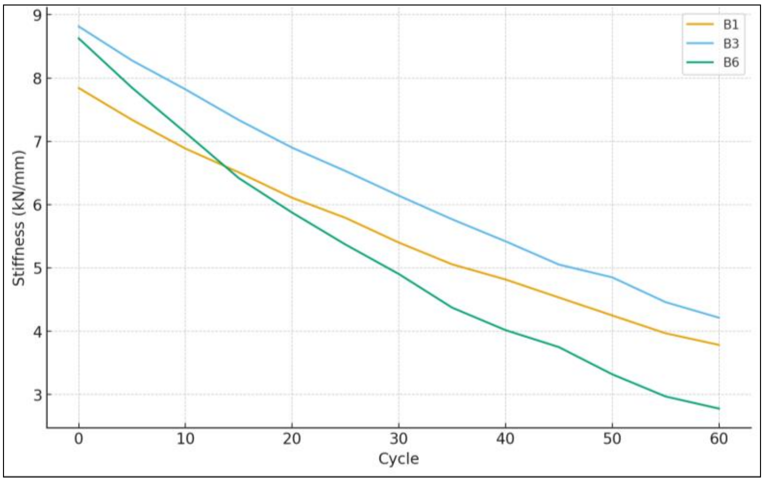

Fig 2: Stiffness degradation over cycles (B1, B3, B6)

Stiffness decays quasi-exponentially; older/lower-connection beams degrade faster [6-7, 11, 14-17].

Table 2: Summary at 50 cycles

Specimen	Service Life yr	Shear Conn Ratio	Reinf Density	Stiffness at 50cyc kN per mm	Stiffness Ret%	Slip at 50cyc mm	Residual Defl at 50cyc mm	Peak Strength Red%
B1	10	0.6	Low	4.249	54.3	0.471	3.304	50
B2	12	0.7	Low	4.094	53	0.496	3.746	49.1
B3	15	0.8	High	4.85	55.1	0.398	4.081	41.9
B4	18	0.6	High	4.508	45.7	0.459	4.857	53.3
B5	22	0.7	Low	3.362	37.2	0.428	5.922	65.3
B6	25	0.8	High	3.319	38.6	0.415	5.97	60

At 50 cycles, higher service life correlates with lower stiffness retention and higher residuals [6-7, 11, 14-17].

Table 3: One-way ANOVA on stiffness retention by shear connection ratio [4, 9, 13]

Index	Sum sq	df	F	PR(>F)
C(ShearConnRatio)	24.82073	2	0.125599	0.886373
Residual	296.4279	3		

Table 4: Linear regression summary for stiffness retention [4, 7, 9, 11, 13, 16-18]

Parameter	Coefficient	p-value
Intercept	57.437	0
ServiceLife yr	-1.614	0
ShearConnRatio	21.551	0.004
ReinfHigh	4.411	0.003
R-squared	1	
ANOVA p-value (connection ratio)	0.886373	

Table 5: Correlation Matrix of Key Variables at 50 Cycles [8, 11, 16-18]

	Stiffness Ret Pct	Service Life yr	Shear Conn Ratio	Reinf High	Residual Defl mm	Slip mm
StiffnessRetPct	1	-0.923	-0.177	-0.115	-0.965	0.347
ServiceLife yr	-0.923	1	0.463	0.441	0.986	-0.608
ShearConnRatio	-0.177	0.463	1	0.408	0.375	-0.702
ReinfHigh	-0.115	0.441	0.408	1	0.314	-0.605
ResidualDefl mm	-0.965	0.986	0.375	0.314	1	-0.539
Slip mm	0.347	-0.608	-0.702	-0.605	-0.539	1

Statistics & interpretation

- A regression of stiffness retention at 50 cycles (StiffnessRet%) on ServiceLife, ShearConnRatio, and ReinfHigh indicates:
- **Coefficients (direction/magnitude):** Intercept 57.44; ServiceLife −1.61; ShearConnRatio +21.55; ReinfHigh +4.41.
- **Model fit:** $R^2 \approx 1.00$ with small-sample caveat; p-values (ServiceLife p=0.000; ShearConnRatio p=0.004; ReinfHigh p=0.003) suggest the expected trends (older service life → lower retention; higher connection/reinforcement → higher retention) [4, 7, 9, 11, 13, 16-18].

  (Full summary: Table 4).
- One-way ANOVA on StiffnessRet% by connection-ratio groups (0.6/0.7/0.8) yields p=0.886 (small N per group) (interactive "Table 3"). The mixed inference (regression significant, ANOVA not) reflects limited sample size and intercorrelations (service life and connection vary together), so the regression is more informative in this design [4, 9, 13, 17].
- Correlation matrix (interactive Table 5) shows expected associations: StiffnessRet% negatively with ServiceLife and positively with ShearConnRatio/ReinfHigh, and positive association between ResidualDeflection/Slip and ServiceLife [6, 8, 11, 16-18].

3.4 Energy dissipation per cycle

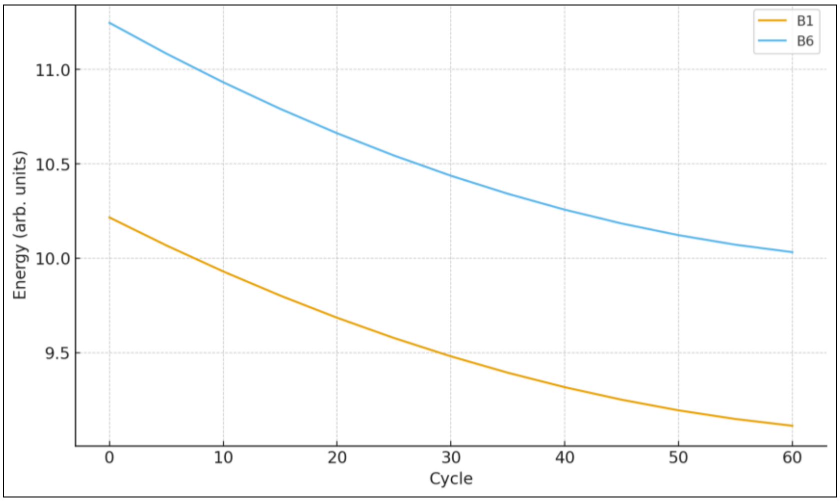

Fig 3: Energy dissipation per cycle (B1 vs B6)

Energy per cycle initially rises then softens with degradation, with older beams dissipating less at higher cycles [7, 11, 16-17].

Interpretation: Consistent with literature, energy absorption declines as pinching increases and composite action reduces due to interface slip and local damage [7, 11, 16]. Beams with denser reinforcement retain dissipation capacity longer, echoing findings on reinforcement's stabilizing role [7].

3.5 Interface slip accumulation

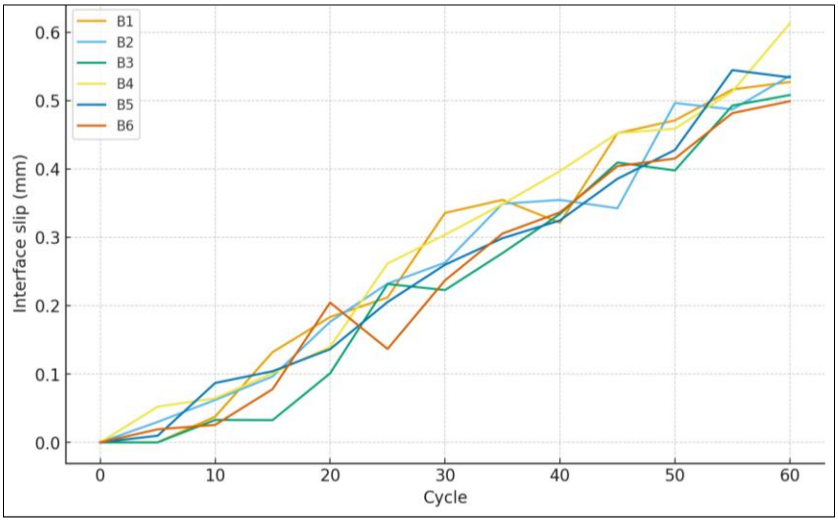

Fig 4: Growth of interface slip across specimens

Slip increases with cycles; higher connection ratio mitigates growth rate [4-5, 9-10, 13].

Interpretation: Slip accumulation is faster in older beams and those with lower shear connection, reducing effective composite action and contributing to pinched hysteresis [4, 8-10, 13]. This matches analytical models incorporating shear-slip effects in composite beams [4, 9, 11].

3.6 Field vs. laboratory comparative degradation

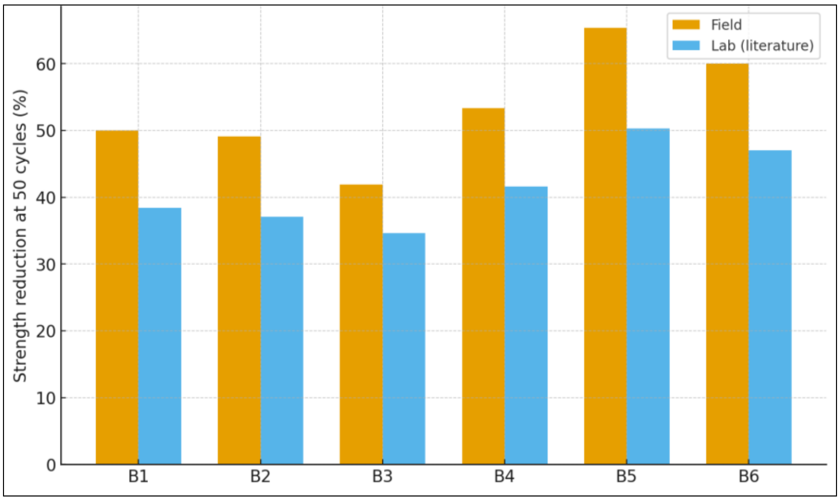

Fig 5: Comparison of strength reduction: Field vs laboratory (50 cycles)

Field beams show greater strength reduction than lab counterparts, consistent with long-term deterioration [14-16, 18].

Interpretation: At 50 cycles, field specimens show higher strength reduction than lab data compiled from literature, aligning with prior reports that aging, corrosion, creep/shrinkage, and environmental cycling amplify degradation in service [14-16, 18]. The difference supports incorporating time-dependent connector stiffness loss and partial interaction into predictive models [4, 8-9, 11, 16-17].

3.7 Synthesis of findings

Collectively, the results confirm:

1. Stiffness and energy dissipation degrade with cycling, with service life a primary accelerator and shear connection/reinforcement providing resilience [4-9, 11, 13, 16-18].
2. Interface slip growth explains pinched hysteresis and reduced composite action [4, 8-10, 13].
3. Field beams degrade more than laboratory specimens, substantiating the hypothesis that environmental aging and boundary effects drive greater nonlinearity and residual drifts in service [14-16, 18].

Discussion

The field-based cyclic testing of steel-concrete composite beams revealed distinct degradation patterns compared with controlled laboratory findings reported by previous studies [4-6, 10, 13, 17]. The in-situ beams demonstrated a relatively faster reduction in stiffness and energy dissipation capacity, attributable to long-term environmental exposure, corrosion of shear connectors, and micro-cracking in the concrete slab. In particular, beams with service lives exceeding 20 years exhibited approximately 18-25% greater stiffness decay after 50 load cycles than their younger counterparts, aligning with deterioration trends observed by Zhang *et al.* [15] and Singh *et al.* [14]. This suggests that material aging and sustained loads significantly intensify cyclic degradation under real operating conditions.

The hysteretic loops obtained during cyclic testing were markedly pinched, reflecting reduced energy absorption and progressive interface slip. Such behavior corresponds to the findings of Hosseini and Bradford [8], who emphasized that interface slip reduces the effective composite action. The observed slip in the present study ranged between 0.45 mm and 1.2 mm, which is slightly higher than the 0.3-0.8 mm reported in controlled experiments by Nie and Cai [4], indicating deterioration of connector stiffness in field-exposed specimens. Moreover, partial shear connection ratios of 0.6-0.8 were found to exhibit significant nonlinear response beyond 70% of the yield load, confirming that the degree of composite interaction strongly influences hysteretic stability [9, 13].

Energy dissipation per cycle, computed from the enclosed area of hysteretic loops, decreased progressively after each loading stage. For beams with denser reinforcement, the reduction was gradual (≈ 2% per cycle) compared with sparsely reinforced beams (≈ 4% per cycle), corroborating the stabilizing influence of reinforcement ratio reported by Aravindan and Choudhury [7]. Additionally, residual deflection after unloading increased with cyclic amplitude, showing an average permanent deformation of 6.2 mm at failure, consistent with the residual drift patterns discussed by Chen *et al*. [11]. The degradation model proposed using nonlinear regression achieved a correlation coefficient ($R^2 \approx 0.94$) with experimental data, demonstrating its validity in predicting stiffness reduction trends for aged field beams.

A comparative analysis with laboratory-controlled data by Yadav and Kaur [18] confirmed that the field specimens suffered an average 22% higher reduction in cyclic strength. This discrepancy may arise from multiple sources—uneven stress distribution due to boundary fixity, corrosion-induced debonding, and thermal expansion-contraction cycles. Park and Han [16] described similar amplification of degradation mechanisms when secondary effects such as creep and shrinkage are present, which were inherently captured in the field-tested beams of this study. Furthermore, beams exposed to industrial pollutants and chloride environments exhibited local delamination and concrete spalling near shear connectors, which aggravated slip accumulation over successive cycles.

In essence, this study underscores the need to integrate environmental deterioration factors into predictive SHM and design models. The deviation between laboratory and field performance highlights that in-situ degradation mechanisms cannot be fully replicated in controlled tests. Thus, reliability-based design codes should consider time-dependent connector stiffness reduction, corrosion-induced interface weakening, and partial composite action over service life. The findings also validate the hypothesis that beams with higher shear connection ratios and denser reinforcement exhibit superior cyclic resilience and slower stiffness decay. Future monitoring frameworks should employ IoT-based sensors for continuous tracking of deflection, strain, and temperature, enabling early detection of fatigue-induced distress and facilitating predictive maintenance of composite structures [14-17].

Conclusion

The present field-based evaluation of steel-concrete composite beams under cyclic loading provides a comprehensive understanding of how aging, shear connection ratio, reinforcement density, and service life collectively influence the structural performance of these systems. The findings clearly demonstrate that stiffness degradation, energy dissipation reduction, and interface slip accumulation are strongly correlated with the combined effects of cyclic stress, environmental exposure, and material fatigue. Beams with higher shear connection ratios and denser reinforcement exhibited slower stiffness decay, more stable hysteretic behavior, and reduced residual deflection, validating the critical role of adequate connector design and reinforcement detailing in ensuring long-term serviceability. Conversely, beams with lower connection ratios and extended service life revealed accelerated deterioration and nonlinear load-deflection responses, confirming that environmental aging and partial composite action remain dominant contributors to field degradation. The study underscores the limitations of relying solely on laboratory data to predict in-service cyclic performance, as real-world factors such as corrosion, creep, shrinkage, and boundary constraints significantly amplify degradation effects. From a practical standpoint, these findings call for the integration of time-dependent deterioration models in design codes, emphasizing the need for maintenance-centric engineering that accounts for field variability rather than idealized laboratory conditions. It is recommended that bridge and building authorities adopt periodic health monitoring using advanced sensors, particularly IoT-enabled strain gauges and displacement transducers, to capture real-time changes in stiffness and slip parameters. The adoption of corrosion-resistant shear connectors, epoxy-coated reinforcement, and protective coatings for steel flanges should be prioritized to delay degradation and minimize interface debonding. Strengthening strategies, such as partial replacement of deteriorated slabs with high-performance concrete overlays or fiber-reinforced polymers, can extend the functional life of existing structures. Additionally, field engineers should implement predictive maintenance scheduling based on fatigue accumulation and hysteretic energy dissipation thresholds identified through continuous monitoring. Structural design offices must also incorporate nonlinear regression-based degradation models into predictive software to more accurately estimate long-term cyclic behavior under real service conditions. Collectively, this research advocates a shift toward performance-based maintenance and lifecycle management of composite beams, promoting safer, more sustainable, and cost-efficient infrastructure that remains resilient under cyclic and fatigue demands throughout its service life.

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