Prefabricated Steel-CFRP Hybrid Strengthening Technique for Enhancing the Flexural Capacity of Floor Slabs in Old High-Rise Buildings in Kunming, Yunnan

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Abstract

Aged reinforced-concrete floor slabs in pre-2000 high-rise buildings in Kunming suffer from inadequate flexural capacity, stiffness, and ductility due to updated load codes, functional upgrades, and heightened seismic demands. Traditional methods such as section enlargement are unsuitable for Kunming's compact, headroom-limited residential buildings owing to heavy wet work, long construction times, and added self-weight. This study experimentally investigated the flexural behavior of eighteen floor-slab specimens retrieved from a decommissioned high-rise building in Kunming, strengthened by six schemes: unstrengthened control, 2 mm and 4 mm bonded steel plates, one and two layers of CFRP fabric, and a hybrid system (2 mm steel plate + one CFRP layer). Monotonic static loading tests were conducted per GB 50367-2013 (Ministry of Housing and Urban-Rural Development of China [MOHURD], 2013) and GB/T 50152-2019. (MOHURD, 2019) Results showed that all schemes significantly improved flexural capacity: steel plates achieved 80.0–126.1% enhancement, CFRP fabrics 74.1–128.2%, while the hybrid system yielded the highest improvement of 163.7%, exceeding the sum of individual contributions and demonstrating a synergistic effect. The hybrid specimens exhibited progressive ductile failure with the best balance of stiffness, ductility, and crack control. The hybrid scheme with 2 mm steel plate and one CFRP layer was recommended as the optimal solution, providing practical guidance for seismic-resistant retrofitting of aged high-rise buildings in Kunming.

Keywords: Old high-rise buildings; floor slab strengthening; bonded steel plate; CFRP; hybrid reinforcement; flexural capacity

Introduction

Pre-2010 high-rise residential buildings in Kunming exhibit deficient floor-slab flexural capacity—only 70–85% of current code demands—owing to updated load standards (MOHURD, 2012), duplex conversions, and Grade 7 seismic fortification requirements (0.10 g PGA) in the Sichuan–Yunnan seismic belt(Fardis, 2018). While bonded steel plates (Ciampa et al., 2023) and CFRP fabrics are established strengthening techniques (Li et al., 2011; Li et al., 2019), and their hybrid combination offers synergistic benefits with progressive ductile failure (Gong et al., 2021), most prior studies addressed beams or laboratory-cast specimens rather than aged two-way slabs (Altemen et al., 2024; Han et al., 2023; Nguyen et al., 2025) under Kunming's specific climate, seismic, and spatial constraints. This study aimed to: (1) determine load-capacity enhancement and stiffness variation of aged RC slabs strengthened with bonded steel plates, CFRP fabrics, and their hybrid system; (2) identify failure modes and strain development of each scheme; and (3) compare ductility, crack control, and constructability to recommend an optimal configuration for Kunming's conditions. A laboratory experimental programme was conducted using aged slab specimens retrieved from a decommissioned building to provide practical design guidance for high-rise floor-slab retrofitting (Fardis, 2018; MOHURD, 2021) in the region.

Research Methodology

1. **General** This study employed a controlled laboratory experiment to compare the flexural performance of aged RC floor slabs strengthened by bonded steel plates, CFRP fabrics, and a steel–CFRP hybrid system. All procedures followed (MOHURD, 2013), (MOHURD, 2019), and (MOHURD, 2020), and were conducted at the Structural Engineering Laboratory of Kunming University of Science and Technology using a 300 kN hydraulic-jack reaction frame.
2. **Materials** The substrate slabs (3000 × 1000 × 120 mm, C30 concrete with measured strength of 34.6 MPa, Φ8@150 bidirectional reinforcement) were retrieved from a decommissioned 33-storey residential building constructed in 1998 in Kunming's Xishan District. Strengthening materials included Q235B steel plates (2 mm and 4 mm thick, sandblasted to Sa2.5), T700 unidirectional CFRP fabric (tensile strength ≥3,400 MPa, elastic modulus ≥230 GPa), Grade A two-component modified epoxy adhesive (bond strength ≥3.5 MPa), and fluorocarbon topcoat resin for UV protection.
3. **Strengthening Scheme Design:** Eighteen specimens were divided into six groups of three: unstrengthened control (B0), 2 mm bonded steel plate (SP2), 4 mm bonded steel plate (SP4), one-layer CFRP (C1), two-layer CFRP (C2), and hybrid 2 mm steel plate plus one CFRP layer (H1). All strengthening was applied to the tension face after identical substrate preparation, with seven-day curing at 25 ± 2 °C (MOHURD, 2013).
4. **Experimental Program:** Substrate surfaces were ground to expose sound aggregate, cleaned, and dried to below 4% moisture. Steel plates were bonded with epoxy under 0.4 MPa pressure (Ciampa et al., 2023); CFRP was applied by wet lay-up with primer, impregnating resin, and air removal; the hybrid group received steel-plate bonding followed by CFRP overlay after surface roughening. Monotonic four-point bending was applied over a 2,800 mm simply supported clear span, with load steps of 5 kN (control) or 10 kN (strengthened groups) held for ten minutes, terminated at 85% post-peak load. Eight strain gauges and four LVDTs per specimen recorded strain distribution and deflection at 1 Hz (MOHURD, 2019).
5. **Data Analysis:** Mean values and standard deviations of cracking load, yield load, ultimate capacity, mid-span deflection, and crack width were calculated for each group. Results were expressed as relative improvement rates against the control group (B0). Load–deflection curves, strain distributions, and crack patterns were analyzed for stiffness, ductility, and crack control. Statistical significance was evaluated at 95% confidence with outliers eliminated by the Grubbs criterion, using Excel, Origin, and SPSS.

Results

1. **Failure Modes and Experimental** B0 failed in ductile flexure with insufficient capacity. SP2 and SP4 exhibited semi-ductile failure with 32–48% higher cracking loads but eventual end-peel debonding. C1 and C2 achieved high stiffness yet failed brittlely by crack-induced debonding without yield warning. H1 showed the most favorable progressive ductile failure—steel yielded first as a deformation warning while CFRP delayed debonding (Gong et al., 2021)—making it optimal for seismic-zone retrofitting (Fardis, 2018).
2. **Bearing Capacity and Stiffness** All schemes significantly improved flexural capacity: SP2 and SP4 by 80.0% and 126.1%; C1 and C2 by 74.1% and 128.2%. H1 achieved the highest enhancement of 163.7%, exceeding the sum of individual contributions and confirming a synergistic effect (Altemen et al., 2024; Gong et al., 2021). Initial stiffness ranked H1 > SP4 > C2 > SP2 > C1 > B0. CFRP groups showed the smallest ultimate deflection but brittle failure, whereas H1 combined high capacity with appropriate deflection for Grade 7 seismic demand (Fardis, 2018). The load–midspan deflection curves (Figure 1) confirmed H1's sustained post-peak descending branch, the most favorable response for seismic-prone applications.
3. **Strain Distribution and Crack Development** Strain profiles remained approximately linear in the elastic stage for all groups. Steel-plate strains reached yield steadily before failure; CFRP strains rose rapidly to ultimate elongation before brittle debonding. In H1, both materials acted cooperatively—steel yielded first and transferred load to CFRP without early debonding, carrying approximately 70% of the bending moment while CFRP carried approximately 85% of the shear force (Gong et al., 2021). Average crack widths were 0.62 mm (B0), 0.30–0.35 mm (SP2/SP4), 0.25–0.28 mm (C1/C2), and only 0.23 mm (H1) at service load, satisfying durability and seismic requirements (MOHURD, 2013).
4. **Overall Performance Evaluation** H1 (2 mm steel + one CFRP layer) delivered the most balanced performance: 163.7% capacity enhancement, progressive ductile failure with yield warning, 0.23 mm average crack width, and <15 mm added thickness with minimal wet work. As shown in Figure 2, the enhancement was super-additive, exceeding the sum of individual contributions and confirming cooperative steel–CFRP action (Altemen et al., 2024; Han et al., 2023). This combination of capacity, ductility, crack control, and constructability made H1 the preferred scheme for Kunming's Grade 7 seismic requirements (MOHURD, 2013)..

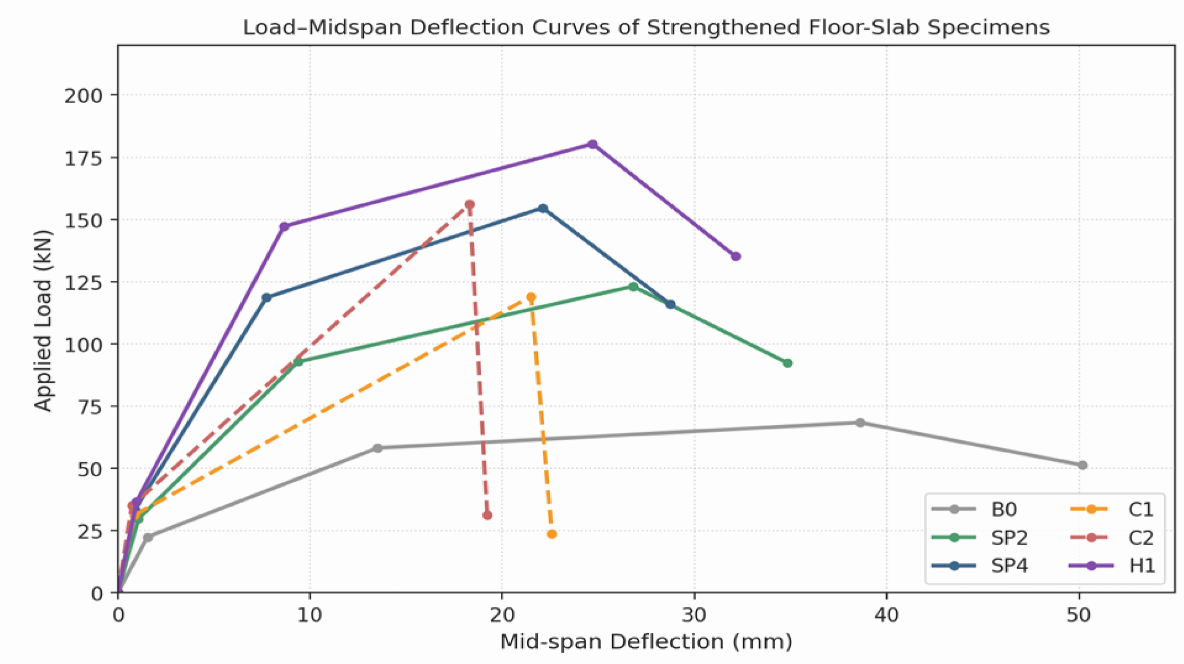

Figure 1. Load–Midspan Deflection Curves of Strengthened Floor-Slab Specimens

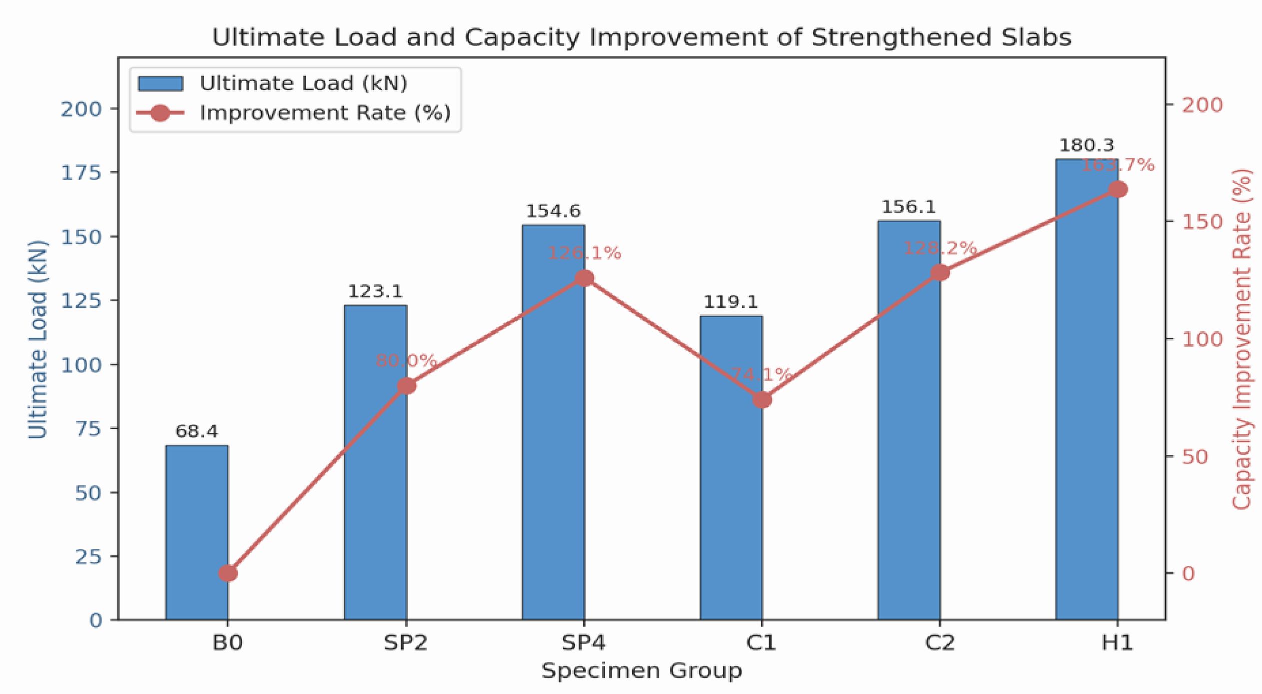

Figure 2. Ultimate Load and Capacity Improvement Rate of Strengthened Floor-Slab Specimens

Conclusions

This study was limited to monotonic static loading on specimens from a single building, requiring further field verification. Results showed that all strengthening schemes significantly enhanced flexural capacity: steel plates by 80.0–126.1%, CFRP by 74.1–128.2%, and the hybrid system (2 mm steel + one CFRP layer) by 163.7% with progressive ductile failure, 0.23 mm average crack width, and minimal added thickness. The hybrid system's superiority arose from synergistic steel–CFRP interaction: steel provided stiffness and ductile yielding while CFRP contributed tensile strength and crack bridging, together delaying debonding (Gong et al., 2021; Nguyen et al., 2025). The prefabricated configuration also reduced wet work, carbon footprint, and on-site disruption compared to traditional methods, providing practical guidance for seismic-resistant retrofitting(Fardis, 2018) of aged high-rise floor slabs in Kunming's Grade 7 fortification zone (MOHURD, 2013).

Future Work

Future work focuses on four areas: (1) recommending the hybrid system of 2 mm Q235B steel plate with one layer of T700 CFRP (Group H1) for floor-slab retrofitting in Kunming, with strict construction quality control; (2) investigating long-term performance under actual service and seismic conditions, including fatigue, freeze–thaw, humidity, and UV exposure; (3) studying the effects of different steel grades, CFRP fibre architectures, and anchorage methods, as well as applicability to two-way and continuous slabs; and (4) conducting life-cycle cost–benefit analysis to support policy formulation and promote practical implementation in seismic-prone regions of southwestern China.

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