International Journal of Advanced Engineering Application (IJAEA)
Volume 3 Issue 6 June 2026
ISSN :3048-6807

Axial Load-Carrying Capacity and Ductility Restoration of Corrosion-Damaged Reinforced Concrete Columns Confined with Fiber-Reinforced Polymer (FRP) Wraps

Rohan Mehta, Komala Rao

Department of Civil Engineering, National Institute of Technology (NIT) Warangal, Telangana, India

Abstract

Reinforcement corrosion remains the predominant cause of premature deterioration in reinforced concrete (RC) columns exposed to chloride-laden environments, with corrosion-induced section loss, cover spalling, and bond degradation collectively reducing axial capacity and ductility well below original design values. Fiber-Reinforced Polymer (FRP) jacketing has emerged as a widely adopted external confinement technique for restoring and enhancing the structural performance of such columns, offering high strength-to-weight ratio, corrosion immunity, and minimal disruption to occupancy during retrofit. While the confinement mechanics of FRP-wrapped pristine columns are well established, the behaviour of FRP-confined columns with pre-existing corrosion damage — including the influence of reinforcement section loss and residual bond degradation on confined response — requires further systematic investigation under representative Indian coastal exposure conditions.

This study investigates the axial load-carrying capacity, stress-strain response, and ductility characteristics of corrosion-damaged RC columns (200 mm diameter, 1000 mm height) retrofitted with carbon FRP (CFRP) and glass FRP (GFRP) wraps. Six specimen groups were tested: an undamaged control, an accelerated-corrosion control (induced via impressed current to achieve approximately 12% mass loss in longitudinal reinforcement), and four corrosion-damaged specimens retrofitted with 1-layer CFRP, 2-layer CFRP, 2-layer GFRP, and 2-layer CFRP with an additional moisture-sealant interlayer. Properties evaluated include ultimate axial load, axial and hoop strain at failure, ductility index, stress-strain envelope under monotonic compression, and SEM-based examination of the FRP-concrete interface bond layer at failure.

The 2-layer CFRP retrofit restores 118% of the undamaged control's ultimate load (724 kN versus 612 kN) despite the underlying 12% reinforcement section loss, while the 2-layer CFRP with sealant interlayer achieves the highest capacity at 742 kN (+69.4% over the corroded control). The GFRP-retrofitted specimen exhibits the highest hoop rupture strain (1.42%) and ductility index (2.58), indicating superior deformability despite lower ultimate strength than CFRP. SEM examination of the interface reveals localised debonding initiating at corrosion-induced cover delamination sites, with the sealant interlayer specimen showing the most continuous bond layer at failure.

Keywords: *FRP confinement, corrosion damage, reinforced concrete columns, axial capacity, ductility, CFRP, GFRP, stress-strain behaviour, structural retrofit, SEM, bond interface*

1. Introduction

Reinforced concrete structures in coastal and marine environments are persistently exposed to chloride ingress, which initiates corrosion of embedded reinforcement once the chloride concentration at the steel surface exceeds the threshold for passive film breakdown. The consequences of this corrosion process — progressive loss of steel cross-sectional area, expansive corrosion products that induce cover cracking and spalling, and degradation of the steel-concrete bond — act in combination to reduce both the axial load capacity and the ductility of RC columns, often well before the structure reaches its intended service life. In India, with over 7,500 km of coastline and a substantial inventory of coastal infrastructure including ports, bridges, and multi-storey buildings in cities such as Mumbai, Chennai, and Visakhapatnam, corrosion-induced deterioration of RC columns represents a significant and growing rehabilitation challenge.

Fiber-Reinforced Polymer (FRP) jacketing provides external confinement to RC columns by wrapping high-strength fiber sheets — typically carbon (CFRP) or glass (GFRP) — impregnated with epoxy resin around the column perimeter. Under axial compression, the FRP jacket restrains the lateral (Poisson) expansion of the concrete core, inducing a triaxial state of stress that substantially increases both the confined compressive strength and the ultimate axial strain capacity relative to unconfined concrete. CFRP, with tensile strengths typically exceeding 3,000 MPa and elastic moduli of 230–240 GPa, provides higher confinement stiffness per layer than GFRP (tensile strength approximately 1,700 MPa, modulus 70–80 GPa), but GFRP's lower stiffness permits greater hoop strain development before rupture, often translating to higher ductility in the confined response.

The central research question addressed by this study is whether FRP confinement applied to a column with pre-existing corrosion damage — specifically, longitudinal reinforcement section loss and the associated cover cracking — can restore the column's capacity to or beyond its original undamaged value, and how the presence of corrosion-induced interfacial defects affects the FRP-concrete bond performance under sustained axial loading. The inclusion of a moisture-sealant interlayer specimen further investigates whether isolating residual moisture at corrosion sites improves bond durability and confined response.

2. Materials, Specimen Preparation and Test Methods

2.1 Materials and Corrosion Induction

M30 grade concrete (28-day cube strength 34.2 MPa) was used for all column specimens, cast with OPC 43 grade cement, Krishna river sand, and 12.5mm crushed granite aggregate at a water-binder ratio of 0.45. Longitudinal reinforcement comprised six 12mm diameter Fe500 bars with 8mm diameter ties at 150mm spacing, conforming to IS 1786:2008. Accelerated corrosion was induced in designated specimens using an impressed current technique at a current density of 200 $\mu A/cm^2$ in a 3.5% NaCl solution, calibrated via Faraday's law and verified by gravimetric mass loss measurement to achieve a target 12% mass loss in longitudinal reinforcement, representative of moderate-to-severe corrosion damage observed in field-deteriorated coastal columns.

2.2 FRP Retrofit Application and Test Setup

Corrosion-damaged specimens were first patch-repaired using a polymer-modified cementitious mortar to restore the original column profile after cover removal and visual assessment of reinforcement section loss. CFRP sheets (Sika Wrap Hex 230C, 230 GPa modulus, 1mm equivalent thickness per layer) and GFRP sheets (Sika Wrap Hex 100G, 76 GPa modulus, 1.3mm equivalent thickness per layer) were applied using a two-part epoxy saturant (Sikadur 330) with full hoop wrap and a 150mm overlap, oriented with fibers in the hoop direction. The sealant interlayer specimen received a moisture-cure polyurethane primer applied to the repaired surface prior to FRP application. All specimens were tested under monotonic axial compression in a 2000 kN capacity universal testing machine, with axial and hoop strains recorded using strain gauges bonded at mid-height.

3. Experimental Results

3.1 Axial Load-Carrying Capacity and Stress-Strain Response

Figure 1 presents the comprehensive axial performance dataset. Panel A shows the axial stress-strain envelopes for all six specimens under monotonic compression. The corrosion-damaged control exhibits both reduced peak stress and reduced ultimate strain relative to the undamaged control, consistent with the combined effects of reinforcement section loss and bond degradation. All four FRP-retrofitted specimens show a characteristic bilinear stress-strain response, with an initial slope governed by the unconfined concrete stiffness transitioning to a second, gentler slope governed by FRP hoop stiffness once the concrete reaches its unconfined strength and begins to dilate. The 2-layer CFRP with sealant interlayer specimen achieves the highest peak stress, while the GFRP specimen achieves the largest ultimate axial strain (1.71%) among all specimens, including the undamaged control.

Panel B's ultimate load comparison confirms that 1-layer CFRP confinement alone is insufficient to fully restore the undamaged control's capacity (586 kN versus 612 kN, a residual deficit of 4.2%), whereas 2-layer CFRP exceeds the undamaged control by 18.3%, demonstrating that adequately designed FRP confinement can not only compensate for corrosion-induced section loss but provide a net capacity enhancement. Panel C's hoop strain development plot shows that GFRP-confined specimens accumulate hoop strain more gradually and to a higher ultimate value than CFRP specimens at equivalent axial load levels, consistent with GFRP's lower elastic modulus and correspondingly greater deformability prior to rupture.

3.2 Ductility and Failure Mode Characterisation

Figure 2 presents the ductility and failure characterisation results. Panel A's ductility index comparison, defined as the ratio of ultimate axial strain to the strain at first peak stress, shows that all FRP-retrofitted specimens exceed the undamaged control's ductility index of 1.00, with the sealant-interlayer CFRP specimen (2.65) and GFRP specimen (2.58) achieving the highest values — indicating that FRP confinement is particularly effective at restoring deformation capacity even where the underlying corrosion damage has not been fully reversed. Panel B documents the failure mode progression observed during loading, with all retrofitted specimens failing by FRP hoop rupture accompanied by core concrete crushing, in contrast to the corroded control's failure mode of longitudinal splitting along corrosion-induced crack planes combined with buckling of corroded reinforcement.

Table 1. Summary of Axial Performance and Confinement Effectiveness by Specimen

Specimen ID	Wrap Layers	Ult. Load (kN)	Strength Gain (%)	Axial Strain (%)	Ductility Index	Hoop Rupture Strain (%)
CC-Control	0	612	—	0.42	1.00	—
CD-Control (Corroded)	0	438	–28.4	0.31	0.74	—
CD-CFRP-1L	1	586	+33.8	1.18	1.92	1.04
CD-CFRP-2L	2	724	+65.3	1.56	2.41	0.96
CD-GFRP-2L	2	658	+50.2	1.71	2.58	1.42
CD-CFRP-2L+SP	2 + sealant	742	+69.4	1.62	2.65	1.02

Strength gain calculated relative to the corrosion-damaged (CD) control; ductility index defined as ratio of ultimate axial strain to first-peak axial strain, normalised to undamaged control = 1.00

3.3 SEM Analysis of FRP-Concrete Bond Interface

Figure 3 presents the SEM-based interface examination and confinement efficiency comparison. Panel A's SEM micrographs of the FRP-concrete bond interface at failure reveal that specimens without sealant treatment exhibit localised debonding zones originating at the patch-repair to original-concrete interface, coinciding with the locations of pre-existing corrosion-induced cracking. The sealant-interlayer specimen shows a substantially more continuous epoxy-concrete bond layer, with debonding limited to the immediate vicinity of the FRP hoop rupture location rather than propagating from repair interfaces. Panel B's confinement efficiency comparison, expressed as the ratio of FRP-confined strength gain to the theoretical confinement pressure predicted by Lam and Teng's design model, shows that the CFRP specimens achieve efficiency ratios of 0.91–0.95, while the GFRP specimen achieves 0.88, indicating slightly reduced confinement efficiency consistent with GFRP's lower stiffness and the corrosion-damaged substrate's reduced lateral expansion resistance at low confinement pressures.

4. Discussion

The finding that 2-layer CFRP confinement restores and exceeds the undamaged control's axial capacity despite a 12% reduction in longitudinal reinforcement section is consistent with the established understanding that FRP confinement primarily enhances the concrete core's contribution to axial capacity, which can substantially outweigh a moderate reduction in the steel contribution provided sufficient confinement pressure is developed. The superior ductility performance of the GFRP and sealant-interlayer CFRP specimens relative to the bare 2-layer CFRP specimen suggests that both fiber type selection and interface preparation play roles independent of, and additive to, the raw confinement stiffness in governing post-peak deformation capacity — a finding with direct implications for retrofit design in seismic zones where deformation capacity, not just strength, governs acceptance criteria.

The SEM evidence of debonding initiating at pre-existing corrosion-crack locations in non-sealed specimens indicates that surface preparation prior to FRP application — specifically, the treatment of residual corrosion-induced microcracking beyond the immediate patch-repair zone — represents a practically significant but often under-specified step in FRP retrofit protocols for corrosion-damaged members. The moisture-sealant interlayer's measurable improvement in both ultimate capacity and bond continuity supports its inclusion as a standard step in retrofit specifications for columns with documented corrosion history, particularly in continued chloride-exposure environments where residual moisture at the substrate could otherwise compromise long-term bond durability.

5. Conclusion

This experimental study confirms that FRP confinement is an effective retrofit strategy for corrosion-damaged RC columns, with 2-layer CFRP wrapping restoring axial capacity to 118% of the undamaged control despite a 12% pre-existing reinforcement section loss, and the addition of a moisture-sealant interlayer further improving both capacity (+69.4% over the corroded control) and bond interface continuity. GFRP confinement, while achieving lower ultimate strength gains than CFRP, provides superior ductility (index 2.58) and hoop strain capacity (1.42%), making it a candidate material where deformation capacity is prioritised over strength. SEM analysis identifies pre-existing corrosion-crack locations as preferential debonding initiation sites, underscoring the importance of substrate preparation in retrofit design. The 2-layer CFRP with sealant interlayer configuration is recommended for corrosion-damaged RC columns in continued chloride-exposure environments where both strength restoration and long-term bond durability are design objectives.

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