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Combined Strengthening of RCC Beam: Integrated Technique of External Prestressing and Concrete Jacketing

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***Abstract*—The structural rehabilitation of reinforced cement concrete (RCC) beams has become increasingly vital due to aging infrastructure, evolving load demands, and environmental deterioration. This study investigates a hybrid strengthening technique that combines external prestressing and concrete jacketing to enhance the performance of single-span rectangular RCC beams. The objective is to evaluate the effectiveness of this integrated method in improving ultimate load capacity, stiffness, ductility, and crack control under peak stress conditions. External prestressing introduces favorable compressive stresses that counteract tensile forces, thereby reducing crack initiation and propagation. Concrete jacketing, on the other hand, increases the cross-sectional area and provides confinement, which enhances both flexural and shear strength. To assess the comparative performance, five beam specimens were analyzed using three-dimensional finite element analysis (FEA) in Midas Civil software. These included unstrengthen beams, beams strengthened with individual techniques, and beams strengthened using the combined method. The results demonstrate that the hybrid approach significantly outperforms the individual techniques. Beams retrofitted with both external prestressing and concrete jacketing exhibited higher ultimate load capacity, improved load deflection behavior enhanced crack resistance and energy absorption. This synergistic effect underscores the practical advantages of integrated strengthening strategies, especially for retrofitting deficient RCC beams in seismic zones, bridges, and industrial structures. The present study provides a framework for future applications and encourages the adoption of combined techniques for sustainable infrastructure rehabilitation.**

***Index Terms*—Structural Deterioration, Infrastructure Upgrading, Seismic Strengthening, Beam Rehabilitation, Aging Infrastructure, Integrated Strengthening, Synergistic Performance.**

I. INTRODUCTION

The structural integrity of reinforced cement concrete (RCC) beams is a critical concern in modern civil engineering, especially in the context of aging infrastructure, increased service loads, and exposure to adverse environmental conditions. Over time, these factors contribute to deterioration in strength, stiffness, and serviceability, necessitating effective strengthening strategies to restore and enhance performance. Among the various retrofit techniques available, external prestressing and concrete jacketing have emerged as two of the most promising solutions due to their complementary benefits.

External prestressing introduces controlled compressive forces into the beam, counteracting tensile stresses and mitigating crack formation. This active technique not only improves flexural capacity but also enhances serviceability by reducing deflections and extending fatigue life. Concrete jacketing, on the other hand, is a passive method that increases the cross-sectional area and provides confinement, thereby improving shear strength, ductility, and overall load resistance. When applied together, these methods offer a synergistic strengthening effect, combining the advantages of both active and passive systems.

This study investigates the combined application of external prestressing and concrete jacketing on single- span rectangular RCC beams using three-dimensional finite element analysis (FEA) in Midas Civil software. Five beam configurations including unstrengthen, individually strengthened, and hybrid-strengthened specimens are analyzed under ultimate load conditions to evaluate improvements in load-carrying capacity, stiffness, and failure behavior. The findings aim to provide a comprehensive understanding of the integrated technique's effectiveness and its potential for widespread use in the rehabilitation of deficient structural elements, particularly in seismic zones and high load environments.

Strengthening of the structure involves increasing the load-carrying capacity of a structure or member to meet the present or future demands. It often involves adding or modifying structural element. Strengthening is primarily concerned with improving the structural performance of a building. It is an effective alternative to rebuilding or reconstruction of existing structures. Strengthening of structural element of existing building created many challenges in civil engineering during recent years. There are many researches that studied different methods of strengthening. Strengthening is required due to Increase in a load over a time, such as load from additional floors or heavier equipment. Deterioration factors like corrosion, cracking, or exposure to harsh environments can weaken beams. Sometime seismic retrofitting is carried out to ensure the structural integrity during earthquakes. Upgradation in building codes may also necessitate strengthening of existing structures.

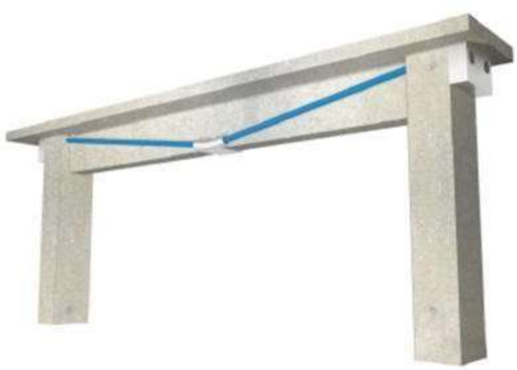

Fig 1: External Prestressed System of RCC beam External prestressing is a specialized method used to strengthen existing reinforced concrete beams by applying tension through tendons placed outside the concrete section. Unlike traditional bonded prestressing, these external tendons often steel cables or fiber-reinforced polymers are not embedded within the concrete but are anchored externally and run along the beam's surface in straight or draped profiles. This system enhances the beam's flexural and torsional capacity, reduces deflections, and mitigates cracking, making it especially valuable for structures facing increased load demands or deterioration due to age or environment

II. REVIEW OF LITERATURE

The use of external prestressing tendons (EPT) for strengthening reinforced concrete (RC) and prestressed concrete members has evolved into a versatile and effective structural retrofitting method. This technique has been extensively explored over the last few decades, focusing on improving flexural strength, stiffness, crack control, and deflection recovery in deteriorated or underperforming structural members.

Early investigations, such as the work by M. Harajli et al. (1999), developed a nonlinear analytical model to predict the behavior of RC members strengthened with external tendons. This study highlighted the significant role of second-order effects and tendon eccentricity changes during deformation. It concluded that while external tendons generally result in lower nominal flexural resistance compared to bonded tendons, moderate levels of prestressing significantly improve deflection recovery, serviceability, and load- carrying capacity. Similarly, Hanaa I. El-Sayad and Karim M. El-Dash (2001) focused on externally confined concrete members using prestressed steel straps. Their findings demonstrated that confinement effectiveness varied with cross-sectional shape, strap spacing, and positioning, especially at the corners of rectangular elements.

Expanding on the design considerations, Arlyawardena and Ghali (2002) distinguished between bonded and unbonded systems, emphasizing friction losses and tendon behavior at deviators. They proposed a modification to the NU girder series for weight reduction while employing both pretensioned and externally post-tensioned tendons. In a comprehensive evaluation of strengthening parameters, Ahmed Ghallab (2005) assessed the ultimate stress in external tendons made from both steel and FRP (Parafil ropes). The study compared prediction equations from Eurocode, ACI318, and BS8110, concluding that tendon profile, depth, and deviator configuration critically influence tendon stress development.

T. Aravinthan (2005) explored tendon layout optimization for flexural enhancement of continuous beams. His findings suggested that while confinement improved ductility, it had little effect on ultimate strength. Also, moment redistribution was dependent on tendon profile and loading conditions. Hakan Nordin et al. (2005) provided a comprehensive review of external prestressing methods, evaluating performance differences between bonded FRP laminates and unbonded tendons. Key advantages included ease of inspection and maintenance, particularly for retrofitting existing structures.

In later developments, S. Saibabu *et al.* (2009) introduced an innovative anchoring method for external prestressing using end-block shear transfer. Experimental and finite element results showed ductile behavior and reduced deformation in retrofitted girder ends, affirming the method's practicality for bridge strengthening. Ali J. S. *et al.* (2013) proposed a novel analytical approach to account for beam-tendon interaction at deviators by modeling global deformation compatibility, offering reliable predictions up to the elastic limit.

Addressing torsional behavior, Hakim Khalil A. *et al.* (2015) examined RC box beams with and without web openings, strengthened using horizontally and vertically applied external tendons. Results showed torsional strength improvements up to 58%, with vertical tendon application proving more effective, especially in mitigating the weakening effects of web openings.

The benefits of external prestressing in bridge applications were outlined by Hanbing Zhu and Yaxun Yang (2015), who emphasized stiffness improvement, crack reduction, and minimal disruption during retrofitting. Tianlai Yu et al. (2016) focused on externally prestressed beams using CFRP tendons, showing significant gains in stiffness and flexural capacity. Their results indicated tendon angle, reinforcement ratio, and applied stress levels as key influencing factors, while concrete strength had a minor effect.

A broad literature review by Harpreet Kaur and Jaspal Singh (2017) summarized technical insights into design, construction, and mechanical behavior of EPT systems. The authors emphasized that although external prestressing avoids friction losses seen in bonded systems, its behavior deviates from conventional assumptions like plane sections remaining plane due to unbonded tendon action.

In terms of modeling and simulation, Li Jun (2018) used ANSYS to simulate external prestressing effects in bridge retrofitting. The model incorporated material and geometric nonlinearities, offering accurate predictions on tendon stress distribution and deformation. Similarly, Jinhua Zou *et al.* (2019) evaluated how deviator number, tendon shape, and tension method affect T-beams. Beams with V- and U-shaped tendons performed better, and deviator placement significantly improved serviceability and stiffness.

In steel structures, Kamal Sh. Mahmoud et al. (2020) demonstrated that externally prestressed steel beams experienced improved yield load and stiffness, especially at higher tendon eccentricities. The yielding strain location shifted from the bottom flange to the top, reflecting the tendon's upward force. Sang-Hyun Kim *et al.* (2021) experimentally simulated aging by weakening concrete specimens and found that external prestressing restored over 200% of cracking load and improved load capacity, depending on reinforcement layout.

Addressing retrofitting for high-strength concrete beams, Ahmed M. El-Basiouny *et al.* (2021) evaluated beams with various opening dimensions. Numerical simulations of 70 beams led to a predictive formula for flexural capacity, with results indicating that opening height affected stiffness more than length. This study highlighted the critical influence of tendon layout and reinforcement coordination in achieving optimal retrofitting results.

Guo H. *et al.* (2024) provided a field-based analysis of long-term prestress loss in externally prestressed box girder bridges. Using advanced sensors and ABAQUS simulation, they found that most losses occurred immediately after tensioning and that longitudinal losses had the highest impact on mid-span deflection. External prestressing was shown to significantly reduce both sagging and reverse deflection, validating its efficacy in long-span structures.

Concrete jacketing is a widely adopted and effective technique for strengthening and retrofitting reinforced concrete (RC) structural members, especially in seismically vulnerable or aging buildings. It involves encasing existing members—columns, beams, or beam-column joints—with new concrete and additional reinforcement, thereby enhancing stiffness, strength, and ductility.

Md. Akhter Jamil *et al.* (2013) conducted one of the earlier studies focused on re-strengthening cracked RC beams using RCC jacketing. Through finite element analysis in ANSYS, the study evaluated both cracked and uncracked beams before and after jacketing. Results showed that jacketing reduces stress concentration at crack tips, significantly increases ultimate load capacity, and improves stiffness— affirming the viability of this method for retrofitting partially damaged components.

Further refinement in the analysis of jacketed RC beams was introduced by Alhadid *et al.* (2016), who emphasized the importance of accounting for interfacial slip between the existing concrete and the jacket. Most conventional models neglect this factor, resulting in inaccurate estimations of stiffness and strength. Their research developed a simplified analytical method incorporating nonlinear behavior of concrete and steel, and proposed an iterative algorithm to determine moment-curvature and load-deflection relationships. The study also derived slip modification factors to enhance the precision of capacity predictions.

Bandar F. Al Harbi *et al.* (2018) explored partial concrete jacketing, which is often necessitated by architectural constraints such as beams near building edges where full jacketing isn't feasible. Finite Element Modeling (FEM) using ANSYS software was used to study various configurations of partial jacketing. The study found that even partial jacketing significantly increased the load-bearing capacity and reduced reinforcement stress. These results align well with prior experimental findings, offering valuable insights for strengthening beams without altering their geometry drastically.

In strengthening beam-column junctions, Majumdar et al. (2019) demonstrated the widespread application of RC jacketing in high-rise structures. This study acknowledged the bond deterioration and reinforcement pull-out that occur during inelastic loading, especially in seismic zones. Numerical modeling in ABAQUS revealed that jacketed joints have greater energy dissipation and load-bearing capacity than their non-retrofitted counterparts. Due to practical constraints like drilling and placing joint confinement, the study also noted the incorporation of steel components within the jacket, adding complexity and effectiveness to the retrofitting process.

Expanding to column strengthening, Karim SH and Karim FR (2020) presented a critical review on RC column jacketing. They highlighted that although the technique has been extensively tested experimentally, there’s still a need for more efficient methods and better design strategies. Key variables include dowel bar integration (through drilled holes), surface preparation, and concrete type selection. These measures improve bond strength, crack resistance, and structural capacity. The study also addressed challenges in applying the method to structures under sustained or increasing loads common in multi-story buildings.

Addressing the design code and practical modeling aspects, Meenakshi Krishnan *et al.* (2020) focused on the application of IS 15988:2013 for retrofitting columns using concrete jacketing. The study provided a detailed ETABS modeling procedure for jacketed sections, aligning closely with physical behavior. It emphasized improvements in column flexural capacity and ductility, while also acknowledging a lack of clear retrofitting guidelines in Indian codes, thus serving as a practical reference for engineers

Despite the proven effectiveness of external prestressing combined with concrete jacketing for strengthening reinforced concrete (RC) beams, several critical research gaps remain. One major concern is the long-term durability of external tendons, particularly their susceptibility to corrosion under varying environmental conditions. Additionally, the bond behavior between old concrete, newly added jacketed concrete, and external tendons over time remains insufficiently understood. Fatigue performance under cyclic loading, especially in relation to tendon stress levels, bond conditions, and concrete properties, also warrants further study. Accurate nonlinear material models are needed to capture the complex behavior of both old and new concrete, steel reinforcement, and tendon-concrete interaction, especially under high stress and geometric nonlinearity. Seismic performance is another key area requiring evaluation through dynamic testing under diverse earthquake scenarios. Moreover, life-cycle cost analysis comparing this method with alternative strengthening techniques is essential for understanding long-term economic feasibility. Lastly, current design codes and standards must be updated to incorporate modern insights and provide comprehensive guidelines for using external prestressing in combination with concrete jacketing.

The primary aim of this study is to assess the effectiveness of combining external prestressing with reinforced concrete (RC) jacketing to significantly improve the flexural and shear capacity of existing RC beams. Six beams five strengthened and one control are evaluated with the following objectives: to enhance load-carrying capacity without altering beam geometry, maintain cost-efficiency through minimal material and labor use, preserve existing structural headroom, and conduct a comparative performance assessment to identify the most technically and economically optimal strengthening approach.

III. METHODOLOGY

The present work involves testing six beam specimens (five strengthened, one control) to evaluate the effectiveness of combining external prestressing with reinforced concrete jacketing in enhancing flexural and shear capacity. This study explores a less-common hybrid solution that aims to balance performance enhancement, constructability, and dimensional constraints. By avoiding significant enlargement of the beam section, it presents a potentially more efficient and application-friendly retrofitting option, particularly in low-clearance or weight-sensitive structures.

Experimental Methodology

Specimen Preparation

- Cast six simply-supported RC beams with identical original reinforcement and geometry. Cure for 28 days before any modifications.
- Designate one as an un strengthened reference and the other five for strengthening trials. Baseline Testing (Reference Beam)
- Load the reference beam under monotonic or cyclic loading until failure to capture baseline flexural and shear behaviour (load-displacement curves, crack patterns, ultimate capacity).

Strengthening Design and Execution

External Prestressing

- Tendon layout: Install external tendons along the length of the beam, draped to follow anticipated tension zones i.e., near soffit at midspan for positive bending, near soffit/top at supports for negative moments. Anchorage system: Use bearing plates bolted or welded onto concrete, fixed via anchor bolts or embedded steel plates per design.

Control eccentricity (1:5 slope) and ensure tendons remain elastic during angular rotations (3.5%).

- Tensioning procedure: Suspend hydraulic jacks aligned with tendon axes, insert strand and gripping wedges, tension to predetermined prestress force (e.g. 150 kN per strand), and lock off securely.

Reinforced Concrete Jacketing

- Surface preparation: Remove loose plaster/concrete, expose reinforcement, clean and roughen surfaces.
- Shear connectors: Drill holes (14 mm Dia, 75 mm deep @ 1000 mm c/c), clean and epoxy grout in shear dowels for mechanical interlock between new and old concrete.
- Reinforcement cage: Provide additional longitudinal and transverse reinforcement tailored to design; tie into existing bars using dowels or mechanical couplers.
- Bond coat: Apply epoxy or polymer-based bonding agent to the surface just prior to placing new concrete/mortar to ensure monolithic behavior.
- Formwork and Casting: Install watertight shuttering around the beam (3 sides if soffit inaccessible). Cast polymer-modified mortar or high-strength concrete to the specified jacket thickness (e.g. 20–100 mm). Use self-compacting or properly vibrated concrete.
- Curing: Wet curing for at least 3 days followed by air curing; remove props only after achieving required strength and bond.

Table 1: Experimental Beam Configurations and Research Objectives

Case No.	Beam ID	Description	Objective
	RB	Reference RCC beam with minimum reinforcement (no strengthening)	Determine baseline shear and flexural (moment) capacity

Table 2, 3, 4 & 5 shows the details about RB beam strengthened using combined concrete jacketing reinforcement and external prestressing

Case No.	Beam ID	Description	Objective
1.a	B1_0S_8T	Concrete Jacketing with 0 no's of strand and 2 no's of 8mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
1.b	B1_2S_8T	Concrete Jacketing with 2 no's of strand and 2 no's of 8mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
1.c	B1_4S_8T	Concrete Jacketing with 4 no's of strand and 2 no's of 8mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
1.d	B1_6S_8T	Concrete Jacketing with 6 no's of strand and 2 no's of 8mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
1.e	B1_8S_8T	Concrete Jacketing with 8 no's of strand and 2 no's of 8mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration

Table 2 Experimental Beam Configurations and Research Objectives – Case 1

Case No.	Beam ID	Description	Objective
2.a	B1_0S_10T	Concrete Jacketing with 0 no's of strand and 2 no's of 10mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
2.b	B1_2S_10T	Concrete Jacketing with 2 no's of strand and 2 no's of 10mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
2.c	B1_4S_10T	Concrete Jacketing with 4 no's of strand and 2 no's of 10mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
2.d	B1_0S_10T	Concrete Jacketing with 6 no's of strand and 2 no's of 10mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
2.e	B1_2S_10T	Concrete Jacketing with 8 no's of strand and 2 no's of 10mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration

Table 3 Experimental Beam Configurations and Research Objectives – Case 2

Case No.	Beam ID	Description	Objective
3.a	B1_0S_12T	Concrete Jacketing with 0 no's of strand and 2 no's of 12mm Dia r/f	Evaluate ultimate performance o full-strength hybrid configuration
3.b	B1_0S_12T	Concrete Jacketing with 2 no's of strand and 2 no's of 12mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
3.c	B1_0S_12T	Concrete Jacketing with 4 no's of strand and 2 no's of 12mm Dia r/f	Evaluate ultimate performance o full-strength hybrid configuration
3.d	B1_0S_12T	Concrete Jacketing with 6 no's of strand and 2 no's of 12mm Dia r/f	Evaluate ultimate performance o full-strength hybrid configuration
3.e	B1_0S_12T	Concrete Jacketing with 8 no's of strand and 2 no's of 12mm Dia r/f	Evaluate ultimate performance o full-strength hybrid configuration

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f

Table 4 Experimental Beam Configurations and Research Objectives – Case 3

Case No.	Beam ID	Description	Objective
4.a	B1_0S_16T	Concrete Jacketing with 0 no's of strand and 2 no's of 16mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
4.b	B1_0S_16T	Concrete Jacketing with 2 no's of strand and 2 no's of 16mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
4.c	B1_0S_16T	Concrete Jacketing with 4 no's of strand and 2 no's of 16mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
4.d	B1_0S_16T	Concrete Jacketing with 6 no's of strand and 2 no's of 16mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration
4.e	B1_0S_16T	Concrete Jacketing with 8 no's of strand and 2 no's of 16mm Dia r/f	Evaluate ultimate performance of full-strength hybrid configuration

Table 5 Experimental Beam Configurations and Research Objectives – Case 4

Note: This research is limited to the strengthening of single span rectangular RCC beam only, Also, Beam has been investigated exclusively under gravity loading; the effects of lateral loads have been intentionally excluded from the study.

IV.

STRUCTURAL MODELLING

Analytical and experimental studies were conducted on six beam configurations, ranging from unstrengthen to those strengthened with jacketing and/or external prestressing. Using MIDAS Civil, the structural behavior under self-weight and enhanced capacity was modeled, incorporating time-dependent effects and prestressing losses through construction-stage modeling, in accordance with IRC112. Each case was evaluated for bending, shear, and capacity, with results presented in tables and graphs to compare stiffness, cracking moment, ultimate load, and failure modes.

Reference Beam: Single beam is modelled in Midas civil software as reference beam

- Simple Support Boundary Condition is applied
- Only self-weight load is applied
- Bending Moment and Shear Force diagram is analysed
- 0.08 % minimum tension reinforcement and M25

Sr	Description	Value	Unit
1	Area	318000	mm^2
2	Moment of Inertia	9540000000	mm^4
3	CG distance from Top fibre	300	mm
4	CG distance from Bottom fibre	300	mm

grade of concrete provided

- Bending Moment capacity and shear force capacity worked out for reference.

Table 6: Section Property for RB i.e. Reference Beam with Minimum reinforcement

Case 1-RB with Combined Jacketing, 8mm Dia Reinforcement and External Prestressing:

In this Case, we have designed the beam for 5 sub cases

- For Jacketing M35 grade concrete is used
- M inim um reinf orce men

Sr	Description	Value	Unit
1	Area	138000	mm^2
2	Moment of Inertia	4140000000	mm^4
3	CG distance from Top fibre	300	mm
4	CG distance from Bottom fibre	300	mm

t (8 dia-2 no) is provided in jacketing.

- 0,2,4,6 and 8 No's of tendons are provided inside concrete jacketing for cases 1a,1b,1c,1d and 1e accordingly.
- 75% of ultimate prestressing force is applied
- Prestressing losses are calculated
- Bending Moment capacity and shear force capacity worked out.

Table 7: Section Property for Beam with Concrete Jacketing, Reinforcement and External Prestressing for Case 1 to Case 4

V. R

ESULTS AND DISCUSSION

Case 2-RB with Combined Jacketing, 10mm Dia Reinforcement and External Prestressing:

In this we have designed the beam for 5 sub cases

- For Jacketing M35 grade concrete is used
- Minimum reinforcement (10 dia-2 no) is provided in jacketing.
- 0,2,4,6 and 8 No's of tendons are provided inside concrete jacketing for cases 1a,1b,1c,1d and 1e accordingly.
- 75% of ultimate prestressing force is applied
- Prestressing losses are calculated
- Bending Moment capacity and shear force capacity worked out.

Case 3-RB with Combined Jacketing, 12mm Dia Reinforcement and External Prestressing:

In this we have designed the beam for 5 sub cases

- For Jacketing M35 grade concrete is used
- Minimum reinforcement (12 dia-2 no) is provided in jacketing.
- 0,2,4,6 and 8 No's of tendons are provided inside concrete jacketing for cases 1a,1b,1c,1d and 1e accordingly.
- 75% of ultimate prestressing force is applied
- Prestressing losses are calculated
- Bending Moment capacity and shear force capacity worked out.

Case 4-RB with Combined Jacketing, 16mm Dia Reinforcement and External Prestressing:

In this we have designed the beam for 5 sub cases For Jacketing M35 grade concrete is used

- Minimum reinforcement (16 dia-2 no) is provided in jacketing.
- 0,2,4,6 and 8 No's of tendons are provided inside concrete jacketing for cases 1a,1b,1c,1d and 1e accordingly.
- 75% of ultimate prestressing force is applied
- Prestressing losses are calculated
- Bending Moment capacity and shear force capacity worked out. The table 8 summarizes the structural performance improvements achieved through various strengthening techniques applied to a reference reinforced concrete (RCC) beam.

Structural Performance Improvements

The table 8 summarizes the structural performance of reinforced concrete beams that have undergone concrete jacketing with varying reinforcement sizes (8mm, 10mm, 12mm, and 16mm) and strand counts. The findings demonstrate a significant improvement in both moment and shear capacity, validating concrete jacketing as an effective retrofitting technique.

Here is a pointwise summary of the structural performance improvement for each reinforcement size compared to the reference RCC beam (RB), which has a Moment Capacity of 24.74 kNm and a Shear Capacity of 95.07 kN

8mm Reinforcement:

- Moment Capacity: The moment capacity shows a progressive increase with the number of added strands. The Concrete Jacketing and External Prestressing with addition of 0, 2, 4, 6, and 8 strands resulted in increases of 49.63 KN.m, 158.06 KN.m, 259.06 KN.m, 350.81 KN.m and 433.55 KN.m respectively, compared to the reference beam.
- Shear Capacity: Similarly, the shear capacity improved significantly with the addition of strands. The Concrete Jacketing and External Prestressing with addition of 0, 2, 4, 6, and 8 strands resulted in increases of 214.53 KN, 396.99 KN, 528.08 KN, 635.81 KN and 729.36 KN respectively, showcasing the effectiveness of the added reinforcement in resisting shear forces.

10mm Reinforcement

- Moment Capacity: The use of 10mm reinforcement resulted in a higher base capacity even with no added strands. The Concrete Jacketing and External Prestressing with addition of 0, 2, 4, 6, and 8 strands led to substantial improvements of 76.08 KN.m, 183.61 KN.m, 282.55 KN.m, 372.26 KN.m and 477.65 KN.m respectively, compared to the reference beam.
- Shear Capacity: The shear capacity saw similar trends, with improvements of 214.82 KN, 397.49 KN, 528.73 KN, 636.59 KN and 730.25 KN.

12mm Reinforcement

- Moment Capacity: Beams with 12mm reinforcement demonstrated a significant jump in moment capacity. The improvements were 208.2 KN.m for 0 strands, 214.2 KN.m for 2 strands, 310.6 KN.m for 4 strands, 397.83 KN.m for 6 strands and 475.94 KN.m for 8 strands, with the capacity increasing with each addition of strands.
- Shear Capacity: The shear capacity improvement followed a similar pattern, with an increase of 215.22 KN for 0 strands, 398.09 KN for 2 strands, 529.49 KN for 4 strands, 637.49 KN for 6 strands, and 731.28 KN for 8 strands.

16mm Reinforcement

- Moment Capacity: The 16mm reinforcement beams showed the highest capacity gains. Improvements were calculated at 189.01 KN.m for 0 strands, 288.3 KN.m for 2 strands, 378.29 KN.m for 4 strands, 459.07 KN.m for 6 strands, and 530.92 KN.m for 8 strands.
- Shear Capacity: The shear capacity also improved dramatically, with increases of 215.94 KN for 0 strands, 399.43 KN for 2 strands, 531.26 KN for 4 strands, 639.6 KN for 6 strands, and 733.68 KN for 8 strands.

Table 8: The structural performance improvements achieved through various strengthening techniques applied to a reference reinforced concrete (RCC) beam

Case No	Beam No	Description	Moment Capacity KN.m	Shear Capacity KN
	RB	Reference RCC Beam with minimum reinforcement	24.74	95.07
1a	B1_0S_8T	RB with concrete jacketing, 8mm reinforcement and No Strands	74.37	309.6
1b	B2_2S_8T	RB with concrete jacketing, 8mm reinforcement and 2 nos of Strands	182.80	492.06
1c	B3_4S_8T	RB with concrete jacketing, 8mm reinforcement and 4 nos of Strands	283.80	623.15
1d	B4_6S_8T	RB with concrete jacketing, 8mm reinforcement and 6 nos of Strands	375.55	730.88
1e	B5_8S_8T	RB with concrete jacketing, 8mm reinforcement and 8 nos of Strands	458.29	824.43
2a	B1_0S_10T	RB with concrete jacketing, 8mm reinforcement and No Strands	100.82	309.89
2b	B2_2S_10T	RB with concrete jacketing, 10mm reinforcement and 2 nos of Strands	208.35	492.56
2c	B3_4S_10T	RB with concrete jacketing, 10mm reinforcement and 4 nos of Strands	307.29	623.80
2d	B4_6S_10T	RB with concrete jacketing, 10mm reinforcement and 6 nos of Strands	397.00	731.66
2e	B5_8S_10T	RB with concrete jacketing, 10mm reinforcement and 8 nos of Strands	477.65	825.32
3a	B1_0S_12T	RB with concrete jacketing, 12mm reinforcement and No Strands	132.94	310.29
3b	B2_2S_12T	RB with concrete jacketing, 12mm reinforcement and 2 nos of Strands	238.94	493.15
3c	B3_4S_12T	RB with concrete jacketing, 12mm	335.34	624.56
3d	B4_6S_12T	RB with concrete jacketing, 12mm reinforcement and 6 nos of Strands	422.57	732.56
3e	B5_8S_12T	RB with concrete jacketing, 12mm reinforcement and 8 nos of Strands	500.68	826.35
4a	B1_0S_16T	RB with concrete jacketing, 16mm reinforcement and No Strands	213.75	311.01
4b	B2_2S_16T	RB with concrete jacketing, 16mm reinforcement and 2 nos of Strands	313.04	494.50
4c	B3_4S_16T	RB with concrete jacketing, 16mm reinforcement and 4 nos of Strands	403.03	626.33
4d	B4_6S_16T	RB with concrete jacketing, 16mm reinforcement and 6 nos of Strands	483.81	734.67
4e	B5_8S_16T	RB with concrete jacketing, 16mm reinforcement and 8 nos of Strands	555.66	828.75

The data clearly supports the thesis that Combined concrete jacketing and External Prestressing is a highly effective method for enhancing the load-bearing capacity of RCC beams. The findings show that both moment and shear capacity increase proportionally with the number and diameter of the additional reinforcing strands, with 16mm reinforcement demonstrating the most significant overall performance improvement. This validates the technique as a viable solution for retrofitting existing structures to meet increased load demands or to restore structural integrity.

(b) Flexural Performance

The Figure 2 demonstrates that combining Concrete Jacketing with External Prestressing is an effective method for enhancing the flexural capacity of reinforced concrete beams.

The bar graph, titled "Moment Capacity - RB v/s Combined Strengthening with 10 mm Dia R/f," illustrates the increase in moment capacity of reinforced concrete beams due to various strengthening techniques. The y- axis represents the Moment Capacity in kilonewton- meters (KN.m), while the x-axis, labelled "Axis Title," categorizes the beams based on their strengthening configuration.

The first bar, labelled RB, represents the "Reference Beam" or unstrengthen beam, showing a relatively low moment capacity of approximately 24.74 KN.m. This serves as the baseline for comparison. The subsequent bars represent beams strengthened with a combination of techniques, using 8 mm diameter reinforcement bars.

As the strengthening configuration progresses from B1_0S_8T to B5_8S_8T, there is a clear and significant increase in the moment capacity. The graph demonstrates that the strengthening techniques are effective in enhancing the load-bearing capability of the beams. The final configuration, B5_8S_8T, achieves the highest moment capacity, approaching 458.29 KN.m, which is a substantial improvement over the reference beam.

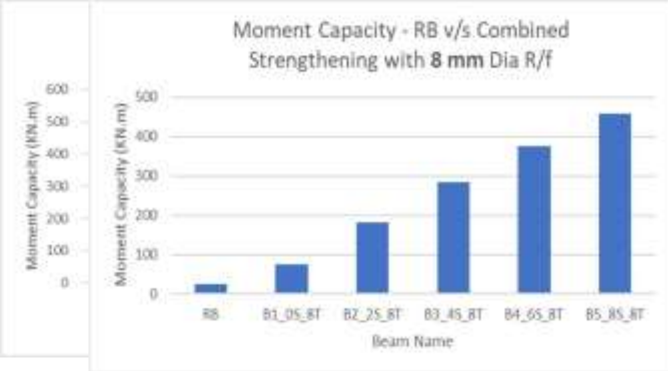

Fig 2: Moment Capacity for RB v/s Combined Strengthening with 8 mm Dia R/f

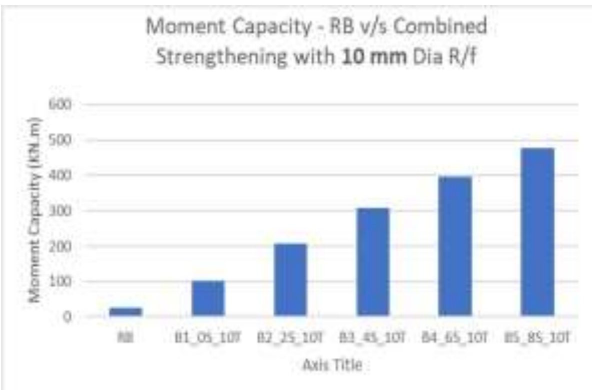

Fig 3: Moment Capacity for RB v/s Combined Strengthening with 10 mm Dia R/f

The bar graph, titled "Moment Capacity - RB v/s Combined Strengthening with 10 mm Dia R/f," illustrates the increase in moment capacity of reinforced concrete In Figure 3, The first bar, labelled RB, represents the "Reference Beam" or unstrengthen beam, showing a relatively low moment capacity of approximately 24.74 KN.m. As the strengthening configuration progresses from B1_0S_10T to B5_8S_10T, there is a clear and significant increase in the moment capacity. The graph demonstrates that the strengthening techniques are effective in enhancing the load-bearing capability of the beams. The final configuration, B5_8S_10T, achieves the highest moment capacity, approaching 477.65 KN.m, which is a substantial improvement over the reference beam. Fig 4: Moment Capacity for RB v/s Combined Strengthening with 12 mm Dia R/f

In Figure 4, The first bar, labelled RB, represents the "Reference Beam" or unstrengthen beam, showing a relatively low moment capacity of approximately 24.74 KN.m. As the strengthening configuration progresses from B1_0S_12T to B5_8S_12T, there is a clear and significant increase in the moment capacity. The graph demonstrates that the strengthening techniques are effective in enhancing the load-bearing capability of the beams. The final configuration, B5_8S_12T, achieves the highest moment capacity, approaching 500.68 KN.m, which is a substantial improvement over the reference beam.

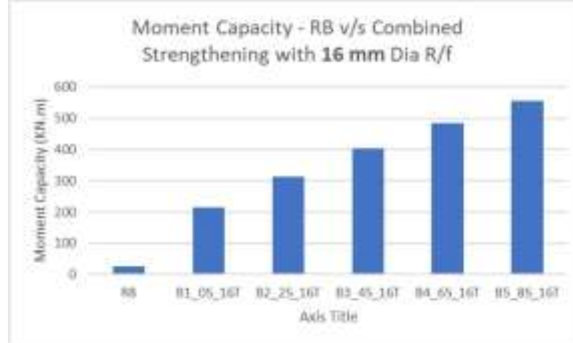

Fig 5: Moment Capacity for RB v/s Combined Strengthening with 16 mm Dia R/f

In Figure 5, The first bar, labelled RB, represents the "Reference Beam" or unstrengthen beam, showing a relatively low moment capacity of approximately 24.74 KN.m. As the strengthening configuration progresses from B1_0S_16T to B5_8S_16T, there is a clear and significant increase in the moment capacity. The graph demonstrates that the strengthening techniques are effective in enhancing the load-bearing capability of the beams. The final configuration, B5_8S_16T, achieves the highest moment capacity, approaching 555.66 KN.m, which is a substantial improvement over the reference beam.

Shear Performance

Figure 6 shows the bar graph, titled "Shear Capacity - RB v/s Combined Strengthening with 8 mm Dia R/f," presents the results for the shear capacity of reinforced concrete beams under various strengthening schemes. The graph's primary purpose is to demonstrate the efficacy of the proposed strengthening method in improving the shear resistance of the beams.The first bar, labelled "RB" (Reference Beam), establishes the control group, representing the shear capacity of the unstrengthen beam, which is shown to be approximately 95.07 KN. This value serves as the baseline for all subsequent comparisons. The following bars represent beams strengthened with combined techniques, using 8 mm diameter reinforcement, with labels such as B1_0S_8T, B2_2S_8T, B3_4S_8T, B4_6S_8T, and B5_8S_8T.

The graph clearly indicates a direct and significant correlation between the extent of strengthening and the resulting increase in shear capacity. A progressive increase in capacity is observed with each added strengthening component. The final bar, corresponding to the most comprehensive strengthening configuration (B5_8S_8T), demonstrates the maximum achieved shear capacity, reaching over 824 KN. This represents that 729.36 KN increase over the reference beam's capacity.

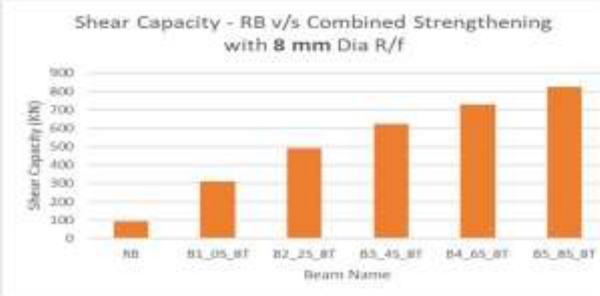

Fig 6: Shear Capacity for RB v/s Combined Strengthening with 8 mm Dia R/f

In Figure 7, The first bar, labelled "RB" (Reference Beam), establishes the control group, representing the shear capacity of the unstrengthen beam, which is shown to be approximately 95.07 KN. This value serves as the baseline for all subsequent comparisons. The following bars represent beams strengthened with combined techniques, using 10 mm diameter reinforcement, with labels such as B1_0S_10T, B2_2S_10T, B3_4S_10T, B4_6S_10T, and B5_8S_10T.

The graph clearly indicates a direct and significant correlation between the extent of strengthening and the resulting increase in shear capacity. A progressive increase in capacity is observed with each added strengthening component. The final bar, corresponding to the most comprehensive strengthening configuration (B5_8S_10T), demonstrates the maximum achieved shear capacity, reaching over 825.32 KN. This represents that 730.25 KN increase over the reference beam's capacity.

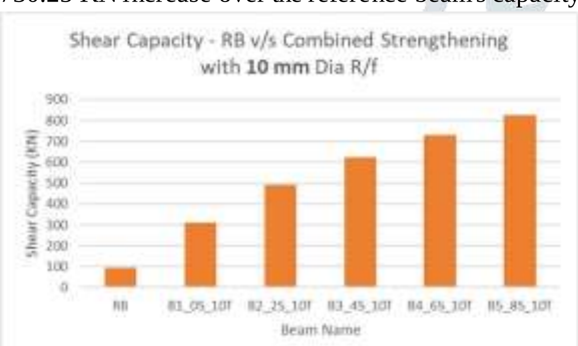

Fig 7: Shear Capacity for RB v/s Combined Strengthening with 10 mm Dia R/f

In Figure 8, The first bar, labelled "RB" (Reference Beam), establishes the control group, representing the shear capacity of the unstrengthen beam, which is shown to be approximately 95.07 KN. This value serves as the baseline for all subsequent comparisons. The following bars represent beams strengthened with combined techniques, using 12 mm diameter reinforcement, with labels such as B1_0S_12T, B2_2S_12T, B3_4S_12T, B4_6S_12T, and B5_8S_12T.

The graph clearly indicates a direct and significant correlation between the extent of strengthening and the resulting increase in shear capacity. A progressive increase in capacity is observed with each added strengthening component. The final bar, corresponding to the most comprehensive strengthening configuration (B5_8S_12T), demonstrates the maximum achieved shear capacity, reaching over 826.35 KN. This represents that 731.28 KN increase over the reference beam's capacity.

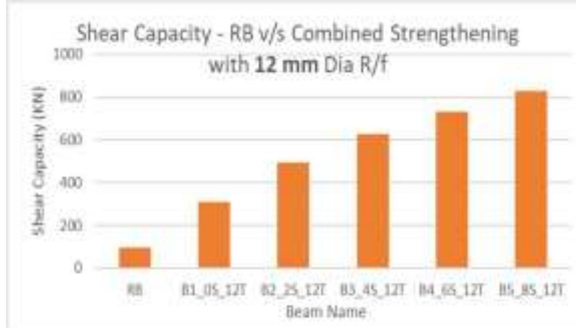

Fig 8: Shear Capacity for RB v/s Combined Strengthening with 12 mm Dia R/f

In Figure 9, The first bar, labelled "RB" (Reference Beam), establishes the control group, representing the shear capacity of the unstrengthen beam, which is shown to be approximately 95.07 KN. This value serves as the baseline for all subsequent comparisons. The following bars represent beams strengthened with combined techniques, using 16 mm diameter reinforcement, with labels such as B1_0S_16T, B2_2S_16T, B3_4S_16T, B4_6S_16T, and B5_8S_16T.

The graph clearly indicates a direct and significant correlation between the extent of strengthening and the resulting increase in shear capacity. A progressive increase in capacity is observed with each added strengthening component. The final bar, corresponding to the most comprehensive strengthening configuration (B5_8S_16T), demonstrates the maximum achieved shear capacity, reaching over 828.75 KN. This represents that 733.68 KN increase over the reference beam's capacity.

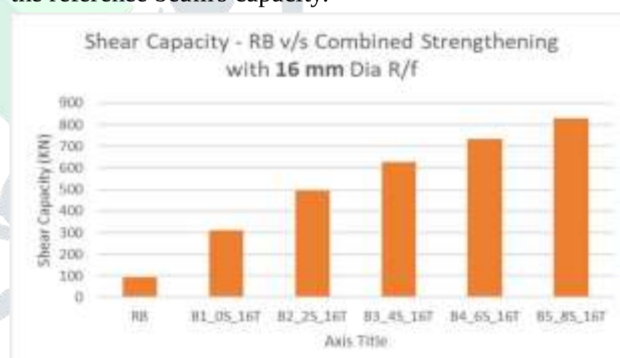

Fig 9: Shear Capacity for RB v/s Combined Strengthening with 16 mm Dia R/f

Overall, the data illustrates that hybrid strengthening methods especially those combining jacketing and prestressing deliver superior shear performance, dramatically improving capacity while keeping utilization ratios impressively low. The present study focuses on the combined strengthening of reinforced concrete (RCC) beams using external prestressing and concrete jacketing, aimed at enhancing load-carrying capacity and serviceability of existing structures. With aging infrastructure and increased design demands, there is a growing need for effective retrofitting solutions.

In this study, RCC beams were subjected to two strengthening techniques: (1) External prestressing, which introduces beneficial compressive forces to counteract tensile stresses, and (2) Concrete jacketing, which increases cross-sectional area and confinement.Compared to beams strengthened by either technique alone, the combination yielded superior structural behavior, including higher load-carrying capacity, delayed crack formation, and better energy absorption. This dual technique provides an efficient and economical solution for retrofitting aging or deficient concrete beams, especially in structures where downtime and invasive techniques must be minimized.

VI. CONCLUSION

The structural integrity of reinforced concrete (RC) beams is crucial for infrastructure safety and durability. Aging, increased loads, environmental effects, and design limits necessitate effective strengthening methods. Concrete jacketing and external prestressing are proven techniques to enhance flexural and shear performance. This study evaluates six retrofit scenarios, from baseline to advanced jacketing and prestressing combinations using Midas Civil software and IRC112 standards under self- weight loading. Results show a clear improvement in structural capacity, validating these methods for future design and rehabilitation.

Major Contributions from the present work:

- The baseline beam (Case RB) safely supported self- weight with moderate flexural and low shear utilization.
- The study demonstrates that substantial enhancement of a beam's load-carrying capacity is achievable without demolition by employing a combined strategy of Concrete Jacketing and External Prestressing. The chosen methodology, which involved a 150mm increase in concrete on both sides of the existing beam, proved effective. This approach not only preserved the original structure but also significantly improved its strength. It is a practical and efficient structural retrofitting technique to adopt. This non- intrusive method can be a viable alternative to costly and time-consuming demolition and reconstruction.
- The graphs on Moment Capacity Efficiency and Shear Capacity Efficiency address the objective of ensuring cost-effectiveness. The efficiency metric (Rs./kN.m for moment and Rs./kN for shear) is a direct measure of how much capacity is gained per unit of cost. A lower value indicates higher efficiency. The B1 series of beams is the least efficient. In contrast, the B5 series demonstrates the highest efficiency. This significant difference highlights that certain strengthening conditions provide far greater performance per rupee spent. A similar trend is observed for shear capacity. The B1 series is the least efficient, while the B5 series proves to be the most cost-effective solution. The results shows that the cost- effectiveness and operational efficiency are not uniform across all strengthening solutions. The method employed in the B5 series is demonstrably superior, providing a far more favorable return on investment in terms of both moment and shear capacity.
- It demonstrates that chosen strengthening method, which involved combined concrete jacketing and external prestressing, was executed with a 150mm increase in concrete only on the sides of the beam. Critically, no alteration was made to the beam's depth. It is a highly effective retrofitting technique that strengthens the beam without compromising critical architectural and functional clearances. This is particularly valuable for buildings where maintaining headroom is essential, such as in basements, parking garages, or industrial facilities. The successful implementation of this method proves that it's possible to enhance a structure's capacity while respecting its original design constraints and avoiding the significant disruptions associated with other, more invasive strengthening techniques.
- Technical Superiority

While the Total Cost Comparison graph shows that the B5 beams are among the most expensive in absolute terms, their high-capacity gain makes them significantly more efficient.

- Optimal Balance: The key finding is that the B5 series achieves the best balance between cost and performance. The moment and shear efficiency graphs provide the evidence for this, as the low cost-per-unit-capacity ratio proves that the extra expense for materials and labor in the B5 series is justified by a disproportionately large increase in load-carrying capacity. The other beam series, while perhaps cheaper upfront, are not as efficient. These improvements reflect enhanced capacity, ductility, safety margins, and design flexibility, confirming the reliability of combined retrofit strategies, especially in seismic or critical structures.

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