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Optimizing the Percentage Use of Combined CFRP and Steel Tendons to Enhance Flexural Capacity of Unbonded Prestressed Concrete Beams

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ABSTRACT

The use of prestressed concrete beams is a critical element in modern structural design, offering enhanced load-carrying capacity, improved durability, and reduced deflection. Traditionally, steel tendons have been employed in prestressed concrete systems; however, their susceptibility to corrosion and heavy weight presents challenges in long-term performance. In recent years, Carbon Fibre Reinforced Polymer (CFRP) tendons have been proposed as a corrosion-resistant alternative, offering higher tensile strength and lighter weight, but they suffer from low strain capacity and limited bond behaviour with concrete. This study investigates an optimized design for unbonded prestressed concrete beams utilizing a combination of CFRP and steel tendons to overcome the limitations of each material. By integrating the corrosion resistance and lightness of CFRP with the high strain capacity and proven performance of steel, this hybrid system aims to enhance the flexural capacity and durability of prestressed concrete beams. Through a comprehensive series of numerical simulations and experimental tests, the paper explores the mechanical behaviour, load distribution, and failure modes of beams subjected to bending. Results demonstrate that the combined tendon system significantly improves the flexural strength and post-cracking behaviour compared to conventional steel-only prestressed beams. Additionally, the hybrid design reduces maintenance requirements and increases the longevity of the structure. The findings provide valuable insights for the optimized design of prestressed concrete beams, offering a more sustainable and cost-effective solution for modern infrastructure applications.

Keywords: OPTIMIZED DESIGN, FLEXURAL DESIGN, UNBONDED PRESTRESSED BEAMS, COMPOSITE TENDONS, CFRP & STEEL TENDONS,

1 INTRODUCTION

1.1 Background and Motivation

Fibre-reinforced polymers (FRP), particularly carbon fibre-reinforced polymers (CFRP), have emerged as promising alternatives to steel in various structural applications. CFRP tendons offer several advantages over steel tendons, including higher tensile strength-to-weight ratios, excellent corrosion resistance, and reduced maintenance costs. Despite these benefits, the brittle failure mode and lower modulus of elasticity of CFRP compared with steel pose significant design challenges. This has led to the use of composite tendons, combining CFRP and steel, to leverage the strengths of both materials

In the field of structural engineering, the design and construction of beams that can efficiently carry significant loads over long spans while minimizing structural depth are of paramount importance. Traditional prestressed concrete beams that utilize steel tendons for prestressing have been widely used owing to their high strength and ductility. However, the ever-increasing demand for more efficient and sustainable construction practices has necessitated the exploration of advanced materials and innovative design approaches.

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1.2 Research Problem

The primary challenge in the flexural strength of prestressed beams by using CFRP tendons is to optimize the use of CFRP and steel to enhance the structural performance while addressing the inherent limitations of each material. Specifically, this research aims to investigate how composite tendons can be utilized to increase the span-to-depth ratio of prestressed beams, leading to slenderer and efficient structural elements.

1.3 Significance of the Study

The flexural design of prestressed beams using composite fibre-reinforced polymer (FRP) tendons is a modern approach aimed at improving the durability, performance, and sustainability of concrete structures. Composite FRP tendons are increasingly used owing to their superior mechanical properties and resistance to environmental degradation compared with traditional steel tendons.

This research has significant potential to revolutionize the design of prestressed concrete beams. By effectively combining CFRP and steel tendons, it is possible to create structural elements that are not only stronger and more durable but also more efficient and sustainable. The findings of this study can lead to the development of new design standards and construction practices, promoting the wider adoption of composite tendons in the construction industry.

One general solution to the corrosion problem is to protect the reinforcement by reducing the voids of concrete. This can be achieved by increasing the amount of vibration or by using concrete admixtures.

Using CFRP Tendons, we can reduce the depth of the beam and increase the span-to-depth ratio.

1.4 Scope of the Research Work

1.4.1 Structural Behaviour Analysis: The scope includes the analysis of the flexural behaviour of prestressed beams, such as bending moments, deflections, cracking behaviour, and failure modes under static loading conditions.

*1.4.2 Design Parameters***:** This research explores various combinations and configurations of CFRP and steel tendons in terms of their placement, quantity, and cross-sectional areas.

1.4.3 Material Focus: This study focuses on the use of composite fibre-reinforced polymer (FRP) tendons, specifically Carbon Fibre Reinforced Polymer (CFRP) combined with steel tendons in prestressed concrete beams.

1.4.4 Experimental and Numerical Methods: Both experimental tests (such as laboratory-scale beam testing) and numerical simulations (such as finite element analysis) were conducted to validate the flexural performance of composite tendon-reinforced beams.

1.4.5 Standards and Guidelines: This study aims to align existing building codes and standards for the design of prestressed concrete beams, such as IS, ACI, Euro code, or AASHTO.

1.4.6 Design Optimization: This research explores the optimization of tendon layouts, prestressed levels, and anchorage details to maximize the structural performance of the beams.

1.4.7 Comparative Analysis: This study compares the performance of beams reinforced with composite tendons (CFRP and steel) with beams reinforced with traditional steel tendons and purely CFRP tendons. The comparison focuses on the flexural capacity and potential cost implications.

1.4.8 Geographical Context: This study primarily considers design practices applicable in regions with moderate climates where both CFRP and steel tendons are accessible.

1.4.9 Serviceability and Durability: This dissertation assesses the serviceability limits (deflection and cracking) and potential durability issues (such as corrosion of steel tendons and environmental degradation of CFRP tendons) under normal environmental conditions.

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1.4.10 Practical Implications: This dissertation discusses the practical implications of using CFRP-steel composite tendons in terms of cost, ease of construction, and potential benefits over conventional methods.

1.5 Literature

To overcome the limitations associated with the exclusive use of either CFRP or steel tendons, composite tendons that integrate both the materials have been proposed. The combination of CFRP and steel strands in a single composite tendon system seeks to capitalize on the strengths of each material while mitigating their respective weaknesses. CFRP provides high tensile strength and corrosion resistance, reducing the risk of environmental degradation, whereas steel contributes to ductility and energy absorption capacity, enhancing the overall toughness and deformability of the beam. This hybrid approach has the potential to enhance the flexural capacity & also durability of prestressed concrete beams, making them attractive options for modern construction.

Tianlai and Shuai concluded that external prestressing with CFRP tendons offers several advantages for strengthening concrete beams, including an enhanced flexural capacity, stiffness, and crack resistance. The design theory and formula developed in this study provide a reliable reference for practical engineering applications and offer an efficient method for bridge and infrastructure reinforcements.

Davood Askari developed a model to explore design recommendations for anybody clamp anchors and stressing devices, considering tendon stress at the ultimate and internal force distributions. This study demonstrates the effectiveness of the CFRP repair system in restoring and enhancing the structural integrity of damaged prestressed concrete beams.

Lucena and Aaron Paul I. Carabbacan concluded that CFRP tendons outperformed CFCC tendons in terms of tensile strength, with CFRP exhibiting a higher tensile capacity. Both CFRP and CFCC tendons perform similarly to traditional steel tendons in terms of serviceability and flexural behaviour, making them suitable for use in environments where corrosion resistance and long-term durability are critical.

The research by Etman et al. contributes significantly to the understanding of Steel Fibre Composite Bars (SFCBs) as an alternative to traditional steel and FRP reinforcement. The combination of a steel core with FRP coating is a promising solution for enhancing the durability of concrete structures in corrosive environments. However, the increased deflections and wider cracks associated with SFCBs suggest that they may not entirely replace steel but rather be used in specific applications where corrosion resistance is critical and higher deflections are permissible.

Zhang and Wang presented a comprehensive analysis of the mechanical behaviour of prestressed C-FRP Reinforced Concrete beams under two different prestressed introduction systems. Both methods improved the flexural performance of the beams although mechanical tensioning outperformed SMA wire heating recovery in terms of stiffness improvement and failure mode control. The proposed bending carrying capacity model accurately predicts the flexural response of the beams, making it a useful tool for engineers working with CFRP-strengthened structures.

Sha and Davidson verified the composite beam theory.

A mini-review by Abduljabbar and Abdulsahib provides a detailed examination of the flexural performance of hybrid FRP & Steel RC beams. By combining the strengths of both materials, the hybrid system offers an improved solution for modern structural applications, particularly in terms of balancing strength, ductility, and corrosion resistance.

The finite element model provides a useful tool for validating theoretical models and offers insights into the behaviour of prestressed members that are difficult to obtain experimentally.

Fatima El Meski and Mohamed H. Harajli provided significant view into the flexural behaviour of unbonded post tensioned Prestressed concrete beam combined with FRP composites. Experimental testing and numerical modelling demonstrated the effectiveness of FRP in increase the performance of proposed members. This design-oriented model offers a reliable method for calculating the flexural capacity of unbonded systems, thereby addressing a key gap in existing guidelines. This study contributes valuable knowledge to the field of structural strengthening, particularly for engineers dealing with post-tensioned systems in which unbonded tendons are used.

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Ebrahim et al. concluded that SFCBs significantly improve the flexural performance of UHPC beams. Key parameters such as the steel core area, reinforcement ratio, and FRP modulus play a dominant role in enhancing stiffness, moment capacity, and deflection control. This study confirms that SFCB-reinforced UHPC beams outperform beams reinforced with HSC and NSC in terms of strength and stiffness, making them an ideal choice for critical infrastructure applications.

The study by Ge et al. provided valuable insights into the flexural strength of RC beam reinforced with SFCBs. The experimental and theoretical frameworks established in this study lay the groundwork for future investigations on the application of SFCBs in structural engineering. By addressing the shortcomings of traditional reinforcement methods, SFCBs can significantly enhance the performance and longevity of concrete structures in various applications including marine and high-speed railway environments.

1.5.1 Research Gaps: The lack of ductility in CFRP tendons poses challenges for structural design, particularly in applications where overload conditions or impact loading might occur. Research is needed to improve the understanding of how CFRP tendons can be used in structures where ductility is critical or how to mitigate brittle failure modes.

There is limited knowledge on the stress transfer mechanisms, load-sharing, and failure modes of hybrid CFRP-steel tendons. Research is needed to model the interaction between CFRP and steel and optimize the proportion of each material in hybrid tendons.

Limited studies have focused on the bond behaviour of CFRP-steel hybrid tendons, particularly how the different materials interact within the concrete matrix under long-term loading and environmental conditions. Research is needed to develop reliable design methods for hybrid tendons in terms of bonding performance.

There is insufficient research on how to enhance the bond strength of CFRP tendons with concrete, especially in long-term applications and extreme environments. More work is needed to develop reliable bond enhancement techniques for CFRP tendons.

There is a need for more experimental data and models to predict the fatigue and creep behaviour of CFRP tendons in prestressed concrete, especially under varying environmental and loading conditions.

Further studies are needed to evaluate the long-term durability of CFRP tendons under a wider range of environmental conditions, especially in real-life scenarios where multiple stressors are present.

More research is needed on how to address the brittle failure modes of CFRP tendons, including hybridization with other materials or modifications to the structural design that can compensate for the lack of ductility.

Comprehensive design codes for CFRP tendons in prestressed concrete structures are still lacking, particularly in areas like long-term performance, bonding behaviour, and failure modes.

Development of design codes and guidelines for hybrid tendons is an important area of research. These codes should address key issues such as load sharing, fatigue behaviour, failure modes, and long-term durability.

More research is needed to perform life-cycle cost analyses comparing CFRP and steel tendons, especially for structures in environments where corrosion is a major concern. Additionally, the development of more cost-effective CFRP manufacturing processes is a key area of research. Limited studies have investigated the cost-effectiveness of CFRP-steel hybrid systems, including manufacturing, installation, and long-term maintenance costs. More research is needed to assess whether hybrid systems provide a good balance of performance and cost for various types of structures.

2. METHODOLOGY

2.1 Planning and Setup

Define the scope and objectives of the experimental and computational studies. Acquire necessary materials, equipment, and software. Develop detailed experimental plans and computational models.

2.2 Experimental Execution

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Prepare samples and conduct material characterization tests. Perform durability, fatigue, bond, and full-scale structural tests. Collect and analyse data from all experimental tests.

2.3 Computational Modelling and Simulation

Develop FEA models based on experimental results. Perform simulations for different loading conditions and environmental scenarios. Calibrate models using experimental data and refine as necessary.

2.4 Analysis and Optimization

Analyse results from experimental and computational studies. Perform optimization and probabilistic analyses to enhance design efficiency and reliability. Compare the performance of composite tendons with traditional steel tendons.

2.5 Reporting and Validation

Compile results into comprehensive reports. Validate computational models against experimental results. Provide recommendations for the practical application of composite tendons in prestressed concrete structures. By combining experimental and computational approaches, this methodology ensures a thorough understanding of the behaviour and performance of composite tendons in prestressed concrete structures, leading to optimized and reliable design solutions.

3 RESULTS

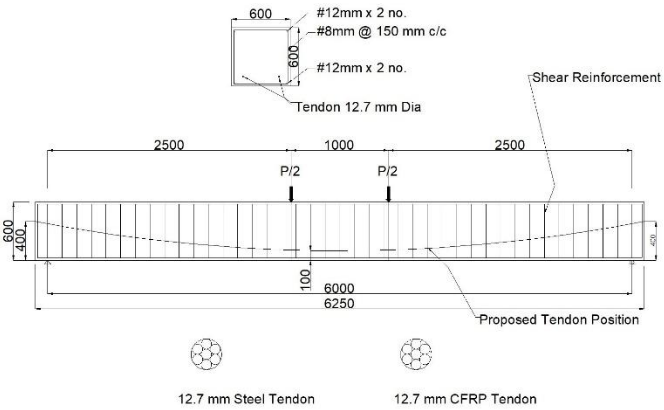

Figure 1 Beam Design & Case Study System

3.1 Compressive Strength of M35 after 28 Days

Table 1 Compressive Strength of M35 for 28 Days

Identification Mark	Age of Specimen	Weight	Density	Failure Load	Compressive Strength	Average Strength
	Days	kg	kg/m3	KN	N/mm2	N/mm2
Cube 4		8.789	2604.1	988.5	43.93	
Cube 5	28	8.821	2613.6	1002.5	44.55	44.23
Cube 6		8.81	2610	994.5	44.20	

Testing as per Beam size and Details shown in Figure 1,

Following is the results of analytical study for 7 different cases.

Beam Size=600mm x 600mm x 6000mm.

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Applied Load=350 KN at 2500 mm from left and 350 KN at 3500 mm from left support.

For Unbonded Prestressed concrete beam Friction and Anchorage Losses are taken as 0.

Concrete Material used M35.

CFRP Tendons 12.7 mm dia.

Modulus of Elasticity=150 KN/mm²

Minimum Yield Stress=2.1124 KN/mm²

Minimum Tensile Stress=2.327 KN/mm²

Steel Tendons 12.7 mm dia.

Modulus of Elasticity=196.5 KN/mm²

Minimum Yield Stress=1.6899 KN/mm²

Minimum Tensile Stress=1.8616 KN/mm²

3.2 case-1. analytical study by using 6 no. steel tendon and 0 No. CFRP tendon

Table 2 Analytical results from SAP2000

Particulars	Value	Unit
Max.B.M.	716493.77	KN.mm
Max.S.F.	318.99	KN.
Deflection	7.766831	mm
S11 max.	0.016946	KN/mm²
Torsion	71	KN.mm

3.3 case-2. analytical study by using 5 no. steel tendon and 1 no. cfrp tendons

Table 3 Analytical results from SAP2000

Particulars	Value	Unit
Max.B.M.	707488.86	KN.mm
Max.S.F.	317.38	KN.
Deflection	7.6697	mm
S11 max.	0.016561	KN/mm²
Torsion	4859	KN.mm

3.4 case-3. analytical study by using 4 no. steel tendon and 2 no. cfrp tendons

Table 4 Analytical results from SAP2000

Particulars	Value	Unit
Max.B.M.	698477.86	KN.mm
Max.S.F.	315.787	KN.
Deflection	7.572578	mm
S11 max.	0.016176	KN/mm²
Torsion	75.36	KN.mm

3.5 case-4. analytical study by using 3 no. steel tendon and 3 no. cfrp tendons

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Table 5 Analytical results from SAP2000

Particulars	Value	Unit
Max.B.M.	689460.78	KN.mm
Max.S.F.	314.184	KN.
Deflection	7.475342	mm
S11 max.	0.015792	KN/mm²
Torsion	7228	KN.mm

3.6 case-5. analytical study by using 2 no. steel tendon and 4 no. cfrp tendons

Table 6 Analytical results from SAP2000

Particulars	Value	Unit
Max.B.M.	680438.02	KN.mm
Max.S.F.	312.581	KN.
Deflection	7.37692	mm
S11 max.	0.015408	KN/mm²
Torsion	81.78	KN.mm

3.7 case-6. analytical study by using 1 no. steel tendon and 5 no. cfrp tendons

Table 7 Analytical results from SAP2000

Particulars	Value	Unit
Max.B.M.	671409	KN.mm
Max.S.F.	310.977	KN.
Deflection	7.278424	mm
S11 max.	0.015025	KN/mm²
Torsion	9659	KN.mm

3.8 case-7. analytical study by using 0 no. steel tendon and 6 no. cfrp tendons

Table 8 Analytical results from SAP2000

Particulars	Value	Unit
Max.B.M.	662373.72	KN.mm
Max.S.F.	309.373	KN.
Deflection	7.179851	mm
S11 max.	0.014642	KN/mm²
Torsion	90.33	KN.mm

4 CONCLUSION

Above analytical study shows that If we increase CFRP Tendons Bending moment, shear force, deflection reduce simultaneously. It also shows that the torsion increase due to instability in stresses of odd numbers of tendons. It is advisable to use even numbers of steel and CFRP tendons to balance the torsion effect. Also shows that equal numbers of Steel and CFRP tendons reduce bending moment, shear force, and deflection, also increase cost due to price of CFRP material. Results show that when we are using equal no. of steel and CFRP tendons in unbonded prestressed concrete beam will not affect major costing factor but also it increases span to depth ratio. If we require aesthetically to increase span to depth ratio without priority of costing, then this is the best way to achieve results as per requirements.

Table 9 Comparison of results from SAP2000

Particulars	Case 1	Case 4	Comparison
Max.B.M.	716493.77	689460.78	-3.7 %
Max.S.F.	318.99	314.184	-1.50 %
Deflection	7.766831	7.475342	-3.75 %
S11 max.	0.016946	0.015792	-6.8 %

Structure is more economical and more safe.

Also have more span to depth ratio.

5 FUTURE RESEARCH WORK

In continuing research on the flexural design of Prestressed beams by using Composite tendons (CFRP & Steel) to increase the span-to-depth ratio, several avenues of investigation can be pursued. This section outlines potential areas for further research that can enhance the understanding, application, and performance of these composite systems in structural engineering.

5.1 Experimental Validation

5.1.1 Full-Scale Testing: Full-scale tests were conducted on beams with varying configurations of CFRP and steel tendons to validate the theoretical and numerical models.

5.1.2 Long-Term Performance Studies: Investigate the long-term behaviour of composite Prestressed beams under sustained loads, considering creep, shrinkage, and relaxation effects over time.

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