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INCREASE FLEXURAL STRENGTH OF POST-TENSIONED PRESTRESSED CONCRETE BEAMS BY USING UNBONDED COMPOSITE TENDONS (CFRP & STEEL) A REVIEW

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ABSTRACT
This review investigates the potential of CFRP-steel composite tendons to enhance the flexural performance of prestressed concrete beams. CFRP strands offer high tensile strength, lightweight characteristics, and excellent corrosion resistance, whereas steel strands are ductile and cost-effective. The combination of these materials in composite tendons aims to optimize the structural behaviour and durability of prestressed beams. This study provides a comprehensive overview of the current state of research on the mechanical properties, bond performance, and failure mechanisms of prestressed concrete beams reinforced with CFRP-steel composite tendons. Additionally, it examined the influence of different design parameters, such as tendon configuration, pre-tensioning levels, and anchorage systems, influence the flexural capacity and serviceability of the beams. This review also discusses the challenges associated with practical implementation, including long-term durability, fatigue behaviour, anchoring, and cost implications. Through a critical analysis of experimental studies, analytical models, and numerical simulations, this study identifies gaps in existing knowledge and proposes future research directions to improve the understanding and application of composite tendons in prestressed concrete design. The insights presented herein are intended to guide structural engineers and researchers in developing more efficient and sustainable prestressed concrete systems.

Keywords:
Flexural Design, Prestressed Beams, Composite FRP Tendons, CFRP & Steel Strands,

Abbreviations

CFRP	Carbon fiber-reinforced polymer
FRP	Fiber-reinforced polymer
CFCC	Carbon Fiber Composite Cable
RC	Reinforced Concrete
SMA	Shape Memory Alloy
SFCB	Steel-FRP Composite Bars
PC	Prestressed Concrete
UHPC	Ultra-high-performance concrete
HSC	High-strength concrete
NSC	Normal strength concrete

I. Introduction
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.

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.

1.1 Research Problem

The primary challenge in the flexural design of prestressed beams using composite FRP 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.

1.2 Significance of the Study

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 traditional solution to the corrosion problem is to protect the reinforcement by reducing the porosity of concrete. This can be achieved by increasing the amount of cement or by using concrete admixtures.

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.

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

Composite Tendons created from CFRP and Steel Strands are a new approach to reduce the span-to-depth ratio of prestressed concrete beams. The demand for advanced materials and innovative design approaches in civil engineering has led to significant advancements in the flexural design of prestressed concrete beams. Traditionally, steel tendons have been used for prestressing, owing to their high tensile strength and ductility. However, issues related to corrosion, high weight, and long-term maintenance costs have prompted the exploration of alternative materials. Carbon fibre-reinforced polymer (CFRP) tendons have emerged as a promising solution because of their superior properties such as high strength-to-weight ratio, excellent corrosion resistance, and low relaxation losses. Despite these advantages, CFRP tendons have limitations including brittleness and high initial cost, which can affect the overall performance and economic feasibility of prestressed concrete structures.

II. 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 improve both the flexural capacity and durability of prestressed concrete beams, making them attractive options for modern construction.

2.1 CFRP and CFCC Tendons

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.

This study provides valuable insights into the application of CFRP tendons in external prestressing of concrete beams. It combines both experimental testing and theoretical modelling, offering a well-rounded approach to understanding the flexural behaviour of CFRP-strengthened beams. While it addresses key variables, such as the tendon bending angle, reinforcement ratio, and concrete strength, the study also contributes to the ongoing development of design guidelines for CFRP tendon applications in civil engineering.

This study fills a gap in the understanding of the flexural performance of beams strengthened with CFRP tendons and provides a solid foundation for future studies, particularly for bridge reinforcement. Davood Askari developed a model to explore design recommendations for unibody 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. He aims to provide a comprehensive overview of the research on the flexural behaviour of prestressed concrete beams reinforced with CFRP-steel composite tendons. This study discusses the mechanical properties, bond characteristics, and failure modes associated with these composite tendons and their impact on the overall flexural performance of beams. The influence of key design parameters such as tendon configuration, prestressing levels, and anchorage systems was critically examined. Additionally, this study addresses the challenges of implementing composite tendons, including long-term durability, fatigue performance, and cost considerations, as well as the post-tensioning process, which are essential for their broader adoption in practical applications.

Furthermore, this review synthesizes findings from experimental investigations, analytical models, and numerical simulations to provide insights into the current state of knowledge and to identify gaps that warrant further research. By highlighting the advantages, limitations, and future research needs of CFRP-steel composite tendons in prestressed concrete design, this study aims to guide structural engineers and researchers in developing more efficient, durable, and cost-effective solutions for the construction industry.

This introduction sets the stage for an in-depth discussion of the potential of CFRP-steel composite tendons in enhancing the performance of prestressed concrete beams, and contributes to ongoing efforts to improve sustainability and innovation in civil engineering practices. 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. Furthermore, the composite-bonding wedge anchorage system was identified as the most effective anchorage mechanism for both CFRP and CFCC tendons, ensuring that the tendons can fully utilize their tensile strength without premature bond failure. This system demonstrates that FRP tendons can be anchored effectively, providing confidence in their use in prestressed concrete structures.

This study provides engineers with valuable insights into the properties and performance of CFRP and CFCC tendons, highlighting their suitability for use in prestressed concrete structures, particularly in environments where corrosion resistance is a priority. These findings suggest that CFRP tendons are a superior option for high-tensile applications owing to their greater tensile strength, whereas CFCC tendons still provide adequate performance in less demanding scenarios. Additionally, the anchorage system described in this article ensures that engineers can effectively utilize the full capacity of FRP tendons, making them a viable alternative to traditional steel in many applications.

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Zhang and Wang presented a comprehensive analysis of the mechanical behaviour of prestressed CFRP-strengthened RC beams under two different prestressed introduction methods. 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.

2.2 FRP & SFCB Tendons

Sha and Davidson successfully verified the composite beam theory for predicting the transfer length in FRP-prestressed concrete members by using finite element analysis.

1. The results demonstrate that the bond-slip behaviour between the FRP tendons and concrete is a critical factor in determining the transfer length, and the friction coefficients must be carefully selected for accurate modelling.
2. 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.

The findings of this study have direct applications in the design of FRP-prestressed concrete structures, such as bridges and buildings. The ability to accurately predict transfer lengths using both theoretical and finite element methods ensures that engineers can design reliable and durable structures that take full advantage of the high strength and corrosion resistance of FRP materials. This study also emphasizes the importance of understanding the bond behaviour in prestressed systems to improve the design and serviceability of such structures.

This study contributes significantly to the field of civil engineering by combining analytical and numerical approaches to validate the critical aspects of FRP-prestressed concrete design. By integrating finite element modelling with composite beam theory, the authors provided a more comprehensive understanding of the transfer length and bond behaviour in pretensioned concrete members. These results are highly relevant for the development of design guidelines and practical applications for the construction of prestressed concrete structures.

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.

The analytical study accompanying the experimental work provides validated formulas for predicting beam performance, which can be applied in practical design scenarios.

A mini-review by Abduljabbar and Abdulsahib provides a detailed examination of the flexural performance of hybrid FRP/steel-reinforced concrete 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. However, the review also underscores the need for further research, particularly regarding the long-term behaviour of hybrid beams, the bond between FRP and concrete, and the optimization of reinforcement ratios.

Fatima El Meski and Mohamed H. Harajli provided significant insights into the flexural behaviour of unbonded post-tensioned PC members strengthened with FRP composites. The combination of experimental testing and numerical modelling demonstrated the effectiveness of FRP in enhancing the performance of these members. The developed 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.

This study successfully addressed a critical gap in the field of FRP strengthening for unbonded post-tensioned members. By combining the experimental results with numerical analysis, the authors provided a comprehensive framework for understanding the flexural behaviour of these systems. The

design-oriented model proposed in this study will be particularly useful for practicing engineers because it offers a practical method for calculating the flexural capacity of unbonded systems using FRP composites.
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 findings also suggest that future research should focus on optimizing the design of SFCBs, particularly in relation to the inner steel core and FRP wrapping modulus, to further improve the structural performance of reinforced concrete beams.
This paper provides a comprehensive numerical study of the flexural behaviour of UHPC beams reinforced with SFCBs. The combination of steel and FRP offers a balanced approach to address the challenges of durability, ductility, and flexural strength in modern concrete structures. This research presents clear evidence of the advantages of SFCBs over traditional reinforcement methods, making them a valuable resource for engineers and designers to implement innovative reinforcement solutions in high-performance concrete structures.
The study by Ge et al. provided valuable insights into the flexural performance of concrete beams 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.
Further experimental and computational studies are essential to fully understand the structural behaviour of SFCB-reinforced elements. Investigations into the long-term performance under cyclic loading and environmental conditions as well as the development of design codes for SFCB applications are critical for advancing this innovative reinforcement technology.

2.3 FRP Composite Tendon

El Meski and Harajli found a combination of experimental results with an analytical model and showed that the developed procedure provides a reliable design approach for evaluating the flexural capacity of unbonded post-tensioned members strengthened with an external FRP. It adheres to the ACI standards and enhances the understanding of FRP’s role of FRPs in concrete strengthening, particularly in post-tensioned applications.
This research is critical for advancing the use of FRP composites in structural strengthening, especially in applications where unbonded tendons are involved, and where control of failure modes such as FRP debonding is essential for safe design practices.
This review highlights the importance of the ACI Committee 440 recommendations for ensuring safe and efficient strengthening of concrete members using FRP composites.
The study by El Meski and Harajli offers valuable insights into the flexural behaviour of unbonded post-tensioned concrete members strengthened with external FRP composites. The experimental results demonstrate that FRP composites effectively increase both the load capacity and stiffness of unbonded members, albeit at the cost of reduced deformation capacity. Moreover, the study highlights the challenges associated with calculating the strains and stresses in unbonded tendons, which are critical factors in extending FRP strengthening guidelines to these systems.
Overall, this study contributes to the broader effort to develop standardized guidelines for using FRP composites in unbonded post-tensioned systems, addressing a critical gap in current design codes, and making strides toward more robust and efficient retrofitting solutions.
Dolan proposed a robust framework for the flexural design of prestressed concrete beams by using FRP tendons. This highlights the importance of considering FRP’s unique mechanical properties of FRPs, particularly their brittleness and linear elasticity. The proposed design methodology, validated

by experimental data, provides a reliable approach for engineers seeking to employ FRP tendons in environments that require non-corrosive materials. However, owing to the lack of ductility, careful attention must be paid to the strength reduction factors and failure modes in the design.
This study provides a solid foundation for the use of FRP tendons in prestressed concrete structures, addressing both the theoretical and practical aspects of design.

III. Conclusion

The above study showed that many types of tendons are used in various types of beams and slabs. They used steel-FRP, CFCC, and CFRP tendons. This study confirms that CFRP tendons are a high-performance option, particularly suited for applications that require high tensile strength and corrosion resistance. The difficulty in providing a proper anchoring system while using CFRP tendons was a crucial aspect of this study. The tensile strengths of the steel and CFRP strands were different. The externally prestressed CFRP tendons exhibited an increase in beam strength. Most studies have focused on RC beams with externally prestressed CFRP tendons. This review paper deals with internal prestressed Composite Tendons Created from CFRP and steel strands.

References

[1] Ahmed AA, Khan M-I, Masmoudi R, Hassan M (2022) Flexural strength of post-tensioned concrete-filled fibre-reinforced polymer rectangular tube beams. PCI Journal 67.4-02.
[2] Bizualew MG, Wondimu T (2024) Strength Evaluation and Optimization of Anchorage Zones for Post-Tensioned Prestressed Concrete Beams. 10.2139/ssrn.4897598.
[3] Burningham C, Pantelides C, Reaveley L (2014) Repair of Prestressed Concrete Beams with Damaged Steel Tendons Using Post-Tensioned Carbon Fibre- Reinforced Polymer Rods. ACI Structural Journal 111.
[4] Du XL, Wang ZH, Liu JB (2010) Flexural Capacity of Concrete Beams Prestressed with Carbon Fibre Reinforced Polymer (CFRP) Tendons. Advanced Materials Research 168–170:1353–1362.
[5] Edan AS, Abdulsahib WS (2024) The impact of using prestressed CFRP bars on the development of flexural strength. Open Engineering 14.
[6] El-Hacha R, Gaafar M (2011) Flexural strengthening of reinforced concrete beams using prestressed, near-surface-mounted CFRP bars. PCI Journal 56:134–151.
[7] Elgholmy L, Shaaban H, Salim H, et al (2024) Prestressed CFRP Plates and Tendon Strengthening of Steel–Concrete Composite Beams. Journal of Composites Science 8:301.
[8] Katou T, Hayashida N (1993) Testing and Applications of Prestressed Concrete Beams with CFRP Tendons. In: Fibre-Reinforced-Plastic (FRP) Reinforcement for Concrete Structures. Elsevier by, pp 249–265.
[9] Pham TM, Hao H, Le TD (2020) Flexural Performance of Precast Segmental Concrete Beams Prestressed with CFRP Tendons. springer Singapore, pp 655–665.
[10] Qiang X, Jiang X, Chen L (2023) Experimental and theoretical study on flexural behaviour of steel–concrete composite beams strengthened by CFRP plates with unbonded retrofit systems. Composite Structures 309:116763.
[11] Wu T, Sun Y, Liu X, Cao Y (2021) Comparative study of the flexural behaviour of steel fibre-reinforced lightweight aggregate concrete beams reinforced and prestressed with CFRP tendons. Engineering Structures 233:111901.
[12] Joe Robert Paul G. Lucena et al (2024) Strength, Serviceability, and Anchorage of Fibre-Reinforced Polymer and Carbon Fibre Composite Prestressing Tendon. IOP Conf. Series: Earth and Environmental Science **1326** (2024) 012047.
[13] Zhang et al. (2024) Entire mechanical analysis of prestressed CFRP strengthened RC beams under different prestressed introduced methods. Advances in Bridge Engineering (2024) 5:13.
[14] Sha, X.; Davidson, J.S. (2023) Verification of Composite Beam Theory with Finite Element Model for Pretensioned Concrete Members with Prestressing FRP Tendons. Materials 2023, 16, 6376.

[15] E.E. Etman et al. (2023) Flexural behaviour of concrete beams reinforced with steel-FRP composite bars. Structures 50 (2023) 1147–1163.

[16] Marwah S. Abduljabbar & Wael S. Abdulsahib (2023) Flexural Performance of Concrete Beams Reinforced with Hybrid FRP-Steel Bars: A mini review. Engineering and Technology Journal 41 (05) (2023).

[17] F. El Meski and M. Harajli (2014) Evaluation of the Flexural Response of CFRP-Strengthened Unbonded Post-Tensioned Members. J. Compos. Constr., 2015, 19(3): 04014052.

[18] E.M.A. Abbas et al. (2022) Flexural behaviour of UHPC beam reinforced with steel-FRP composite bars. Case Studies in Construction Materials 16 (2022) e01110.

[19] Tianlai et al. (2016) Experimental and Theoretical Investigation of Bending in Concrete Beams Strengthened with External Prestressing CFRP Tendons. The Open Construction and Building Technology Journal, 2016, 10, 492-510.

[20] F. El Meski and M. Harajli (2014) Flexural Capacity of Fibre-Reinforced Polymer Strengthened Unbonded Post-Tensioned Members. ACI Structural Journal/March-April 2014.

[21] F. El Meski and M. Harajli (2013) Flexural Behaviour of Unbonded Post-Tensioned Concrete Members Strengthened Using External FRP Composites. J. Compos. Constr. 2013.17:197-207.

[22] Askari D, Maghsoudi A (2014) Ultimate Tendon Stress in CFRP Strengthened Unbounded HSC Post-Tensioned Continuous I-Beams. Journal of Rehabilitation in Civil Engineering 2:35–45.