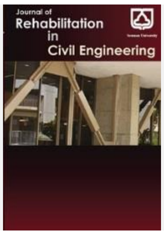

Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

An Innovative FRP Pre-Stressing Device for Retrofitting Reinforced Concrete Beams

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ARTICLE INFO

Article history:
Received: 23 November 2024
Revised: 16 December 2024
Accepted: 14 January 2025

Keywords:
Concrete beams;
Retrofitting;
FRP;
Pre-stressing;
Device.

ABSTRACT

Fiber Reinforced Polymer (FRP) composites are commonly utilized for retrofitting concrete members. While this retrofitting approach offers numerous advantages, some challenges remain. Pre-stressing the FRP is a promising strategy to optimize the proficiency of this method by enhancing the effectiveness of the composite and delaying debonding failures. However, conventional pre-stressing methods require specialized equipment and anchorage solutions. This research introduces a device explicitly designed for pre-stressing FRP composites used in retrofitting of concrete beams and slabs. Eliminating the demand for hydraulic jacks, straightforward operation, and being lightweight are among the critical advantages of the device. Furthermore, the device's dimensions and weight are adjustable to take into account various composite sizes, and desired pre-stress levels, ensuring economic and practical feasibility. This study details the design and construction of the device, followed by an evaluation of its performance in pre-stressing carbon fiber reinforced polymers (CFRP) for retrofitting reinforced concrete T-beams via experimental tests. The results showed the potential of the proposed device for utilization in retrofitting applications. Also, a finite element model of the device and the associated analysis methodology are presented.

E-ISSN: 2345-4423

How to cite this article:
Aghani, K., Afshin, H. and Abedi, K. (2026). An Innovative FRP Pre-Stressing Device for Retrofitting Reinforced Concrete Beams. Journal of Rehabilitation in Civil Engineering, 14(1) 2213 https://doi.org/10.22075/jrce.2025.36001.2213

1. Introduction

The deterioration of reinforced concrete structures presents a persistent issue. Concrete structures often experience unforeseen conditions throughout their service lifespan, not fully accounted for in the initial design. These degradations usually lead to cracking, concrete-reinforcement delamination, connection failures, and even catastrophic structural collapse. While replacement is one solution, retrofitting is generally preferred due to the complexities and costs associated with full replacement. Various retrofitting techniques exist, including concrete jacketing, steel jacketing, and retrofitting by Fiber Reinforced Polymer (FRP) composites. Each method has its own set of benefits and drawbacks. Nonetheless, FRP composite retrofitting offers distinct advantages, such as simplified application and relative cost-effectiveness, making it a compelling choice for reinforced concrete beam retrofitting. Several FRP types exist, including Carbon (CFRP), Glass (GFRP), Aramid (AFRP), and Basalt (BFRP) Fiber Reinforced Polymers, each suited to specific applications. Numerous studies confirm that FRPs significantly enhance the strength and stiffness of the concrete members [1–3].

Several methods are used for attaching FRPs to the concrete face, namely, Externally Bonded Reinforcement (EBR), Near-Surface Mounting (NSM), and Externally bonded reinforcement with grooves (EBRIG and EBROG), which generally produce positive outcomes [4,5]. However, these methods have limitations. Studies show that in CFRP-retrofitted concrete beams, only 30-40% of the CFRP's capacity is typically utilized before failure occurs, preventing full utilization of the material's strength [6–11]. Maximizing FRP utilization in concrete beams strengthening offers significant economic and technical advantages. This can be accomplished by pre-stressing the FRP. The process involves tensioning the FRP to a percentage of its ultimate tensile strength (UTS) prior to bonding. Mechanical systems (such as steel plates and bolts) anchor the FRP at both ends, maintaining the pre-stress force. This process induces initial tension allowing the FRP to reach higher strains when subjected to load, thus increasing its force contribution. The objective of pre-stressing is to ensure FRP failure precedes concrete failure at ultimate capacity, minimizing damage to the beam. However, realizing this objective presents considerable challenges.

The selection of an appropriate FRP type is critical for pre-stressing applications, as mechanical and time-dependent properties, such as Young's modulus and creep behavior, significantly influence the effectiveness of the pre-stressing process. CFRP demonstrates superior performance in this regard, exhibiting minimal creep compared to GFRP and AFRP [12]. High strength and almost elastic behavior until failure, distinguishes CFRP as the preferred choice for pre-stressing in retrofitting applications. While a wide range of CFRP pre-stressing levels are applied in experimental works, the minimum and maximum reported pre-stressing levels that improve the efficiency of the strengthening system are 20% and 50%, respectively; however, several studies showed that a high amount of pre-stressing (e.g., 50% and more) results in low ductility and immature failure [13–16]. Nonetheless, a pre-stress limit of 50% of UTS is recommended for CFRPs [17,18]. Several studies addressed the application of pre-stressed CFRP in retrofitting of RC beams. Saadatmanesh and Ehsani [19] developed a technique for applying pre-stress to the CFRP by bending a concrete beam using hydraulic jacks. The method suffers from limitations, such as, inducing compressive stresses in the concrete and achieving low levels of pre-stressing, restricting its practical applicability. Similar approach was proposed by Triantafillou et al. [20] in which the FRP is pre-stressed as demonstrated in Fig. 1, and then bonded to the concrete beam.

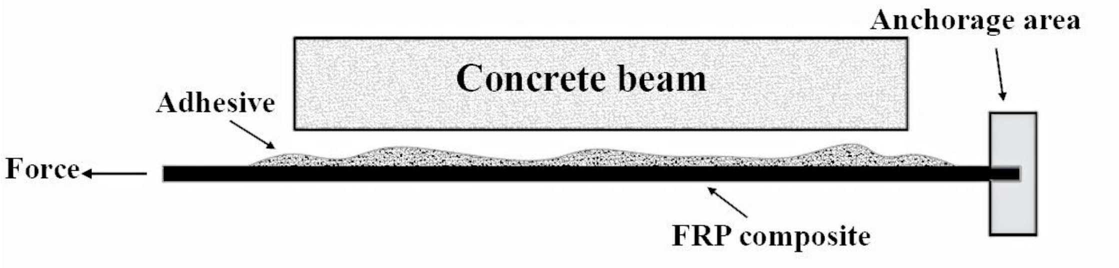


Fig. 1. FRP pre-stressing using Triantafillou et al. method [20].

Direct pre-stressing techniques utilizing hydraulic jacks were also investigated [13,14,21,22]. These methods involve positioning the FRP on the concrete beam and anchoring one end. Tension is then applied to the free end of the composite via hydraulic jacks until the desired pre-stress level is achieved, at which point the free end is also anchored. Finally, the FRP composite is bonded to the concrete beam surface with epoxy adhesive, and the hydraulic jack is released after the epoxy has cured. The anchoring system typically utilizes steel plates bolted to the beam with high-strength bolts, Fig. 2.

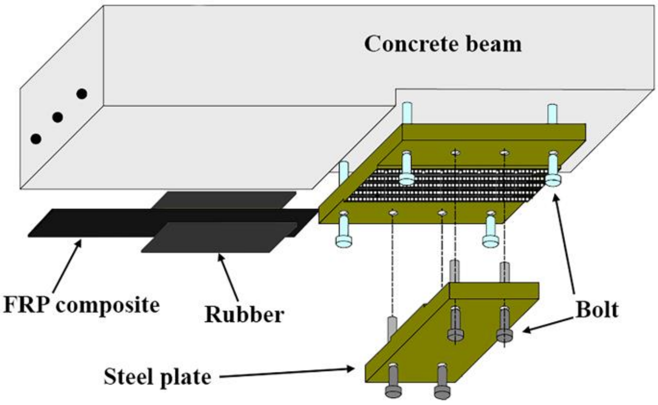


Fig. 2. Typical FRP anchorage system [13].

Generally, the direct pre-stressing methods for strengthening concrete beams with FRP composites are employed using the NSM techniques with rods or composite laminates, as shown in Fig. 3.

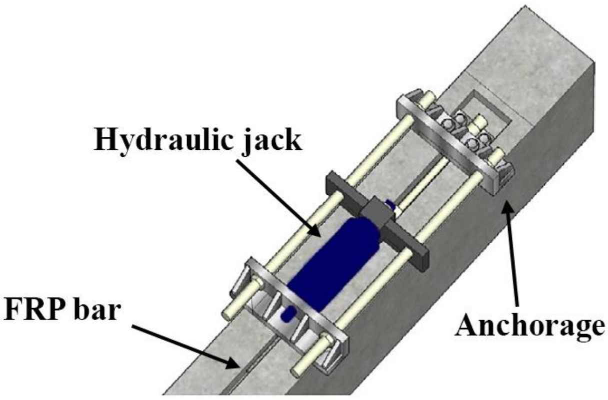


Fig. 3. Pre-stressing FRP bars.

Directly using hydraulic jacks for pre-stressing FRP composites offers a fast and convenient method. Nonetheless, this approach has several disadvantages, such as the expensive nature of hydraulic jacks, installation challenges, high costs associated with steel anchor fabrication, risk of anchor corrosion, and potential architectural constraints. Researchers have also investigated alternative pre-stressing techniques for FRP composite sheets, particularly in the EBR method. In the context of developing innovative pre-stressing devices, Rai and Mukherjee [23] employed movable wheels to implement pre-stressing on the composite. The proposed methodology employs a system of adjustable wheels to apply initial tensile forces to the FRP composite prior to its adhesion and anchorage to the concrete substrate using epoxy resin, Fig. 4. Kotynia et al. [24] introduced techniques that involve generating a vacuum system to enhance the end anchorage of the CFRP composite. A notable advancement in anchorage systems was subsequently presented by Yang et al. [25], who developed a hybrid anchoring mechanism. Their system integrates steel rods, steel strapping elements, and aluminum plates to provide robust end anchorage for pre-stressed FRP sheets, Fig. 5.

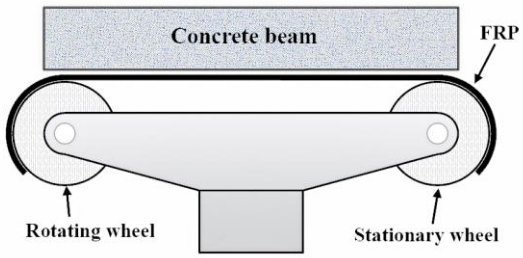


Fig. 4. Pre-stressing FRP using rotational wheels [23].

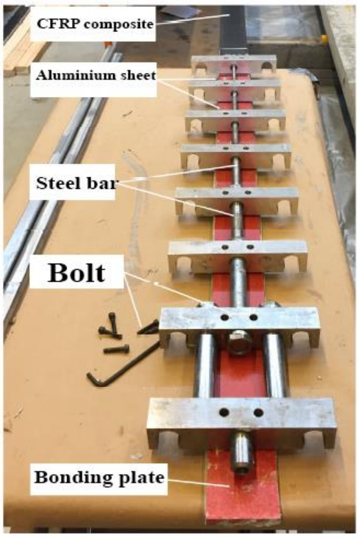


Fig. 5. Pre-stressing FRP using the method described in [25].

In addition to conventional anchorage systems involving FRP U-wraps, several anchorage systems are proposed. An anchorage system composed of anchor bolts and steel plates clamping the CFRP was proposed by Xue et al. [26]. While the system was efficient for prestressing levels lower than 50%, it demanded access to the beam's ends. You et al. [27] developed a system involving steel gripping anchors fastened to the beam by a base plated with mechanical bolts. Similar anchorage systems are proposed by Pellegrino and Modena [28] and Wang et al. [29]. A practical anchorage system encompassing two thin steel plates welded together was introduced by Piatek et al. [30]. Even though many anchorage systems are proposed and developed in the literature, their feasibility in practical cases is limited. Also, another challenge of these anchorage systems is associated with their cost.

One of the key challenges with conventional FRP pre-stressing systems is the requirement for specialized pre-stressing equipment, presenting significant practical and economical constraints in field applications. Furthermore, the level of strain rate at which the FPR is being pre-stressed has potential concerns, which can result in anchorage zone failures or compromise the bonding integrity. This research addresses these challenges by introducing a practical and effective mechanical pre-stressing system that aims to enhance the reliability and practicality of FRP retrofitting systems for strengthening and rehabilitating purposes. The concept of mechanical pre-stressing methods for FRP sheets was initially explored by Abdulhameed et al. [31] and Yu et al. [32]. These pioneer approaches utilized a bolt-nut mechanism, diverging from conventional hydraulic jack systems. While these methods offered numerous benefits, they were limited by the absence of design and computational frameworks for design and analysis.

The current research introduces a mechanical device explicitly designed for pre-stressing FRP composites for retrofitting applications. This mechanical system has several privileges namely, lightweight design, simplified manufacturing and implementation, controlled and low speeds application of pre-stressing force. This study provides a comprehensive analysis for the design and construction of the device, detailing the methodology for determining dimensions and mechanical specifications utilizing a finite element model. The efficiency of the pre-stressing system is evaluated via its application in pre-stressing CFRP sheets for strengthening reinforced concrete (RC) T-beams. This assessment demonstrates the practical implications of the proposed device in the context of structural retrofitting and rehabilitation, contributing to the advancements in concrete member's strengthening techniques using pre-stressed FRPs.

2. Description of the mechanical system

Fig. 6 shows the overall view of the proposed mechanical system for pre-stressing FRPs.

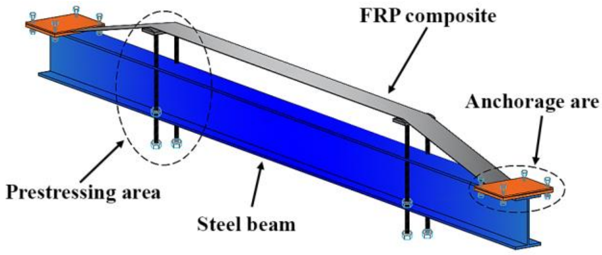


Fig. 6. The design of the innovative FRP pre-stressing system.

In the proposed system, the composite is anchored at both ends subsequently tensioned via a thread bolt-nut mechanism assembly. The fundamental principle of operation relies on maintaining a constant composite length while applying controlled elevation to generate the desired pre-stressing effect. A key characteristic that facilitates this pre-stressing methodology is the inherent material behavior of FRP composites. Since FRPs behave as almost linear elastic materials until failure, direct and predictable relation between the applied elevation and the resultant strain is established. The governing relation is expressed as follows:

$$\varepsilon_H = \frac{(L-L_H)\left[\sqrt{\frac{(L-L_H)^2}{4}+H^2}+\frac{(L_H-L)}{2}\right]}{L_H\left(\frac{L-L_H}{2}\right)+\left[\frac{(L-L_H)^2}{2}+2H^2\right]} \tag{1}$$

in which L is the composite length, L_H is the elevated composite length, H is elevation, and ε_H is strain induced in the composite. Hence, L_H is considered as retrofitting length and the total length of the system, which is characterized by transition length $\left(L_a = \frac{L-L_H}{2}\right)$, is defined by architecture limitations. For practical usages, Eq. 1 can be re-written as a percentage of the FRP's ultimate strength in the form of:

$$\frac{\sigma}{f_u}(\%) = \frac{(L-L_H)\left[\sqrt{\frac{(L-L_H)^2}{4}+H^2}+\frac{(L_H-L)}{2}\right]}{L_H\left(\frac{L-L_H}{2}\right)+\left[\frac{(L-L_H)^2}{2}+2H^2\right]}\frac{E_f}{f_u}(\%) \tag{2}$$

in which E_f and f_u are FRP's elastic modulus and tensile strength, respectively.

2.1. Anchorage area

The anchorage area comprises steel plates and high deformable rubber (HDR), to mitigate stress concentration, connected with bolts, Fig. 7.

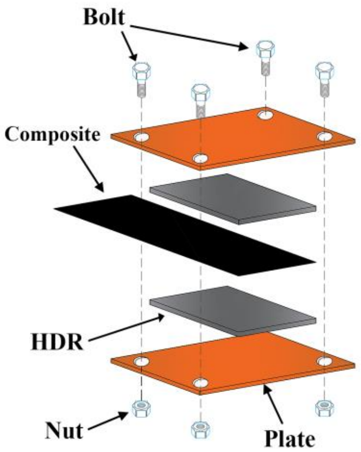


Fig. 7. The design of the anchorage area.

The dimensions of the steel plates should be adjusted to tolerate the stress resulting from pre-stressing. In this regard, Yu et al. [32] provided an equation to obtain the minimum length ($L_{Anch.}$) of the steel plate (assuming a square shape), which is expressed by:

$$L_{Anch.} \geq \sqrt{\frac{0.55 f_f A_f}{n\sigma_b}}\,(SI) \tag{3}$$

where A_f is the FRP's cross-section, f_f is the UTS of composite, σ_b is the bonding stress (taken as 2.2 MPa [32] for CFRPs), and n is the number of FRP layers. According to Yu et al. [32], Eq. 3 is adjusted such that no pre-stressing is required for the bolts. Moreover, high-strength friction bolts A325 can be used for standard practices, the diameter of which are determined by the project's requirements (will be discussed later). Since CFRPs possess the highest UTS among FRPs used for retrofitting concrete structures, calculating σ_b based on the bonding stress of CFRPs is conservative. The thickness and length of the anchorage plates were 20 mm and 200 mm, respectively.

2.2. Pre-stressing procedure

The process is initiated by rotating the thread bolts, elevating the steel straps positioned below the FRP composite. This elevation generates tension within the composite, effectively pre-stressing it since the composite's length is constant. One of the key advantages of this device is its simplicity and ease of use. The rotation of the threaded bolts is accomplished using standard hand tools, eliminating the need for specialized control equipment. This feature makes the pre-stressing process more accessible and cost-effective for a wide range of retrofitting applications. The amount of elevation and the corresponding pre-stress are calculated with Eq. 1.

3. Finite element model and design

In this section, the overall procedures and steps required for determining the dimensions of the steel beam are presented. The design considerations focus on the mechanical interaction between the pre-stressed composite and the steel beam. The careful determination of the steel beam's dimensions is essential for achieving optimal performance of the pre-stressing system while maintaining safety and reliability. The system's behavior is governed by a force equilibrium mechanism, as depicted in Fig. 8, where the tensile force generated by the pre-stressed FRP is effectively counterbalanced by the compressive force transmitted through the thread bolts to the steel beam's flange. This force transfer mechanism is fundamental to the effectiveness of our proposed pre-stressing device, as it ensures proper load distribution and structural integrity during the retrofitting process.

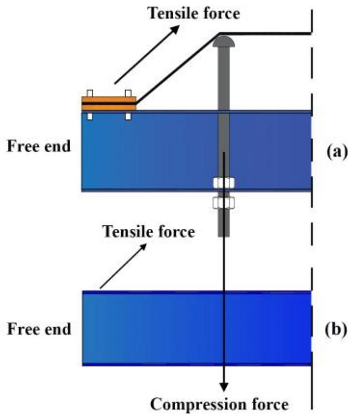


Fig. 8. Schematic view of the acting forces on the steel beam.

The analysis takes into account various parameters including the magnitude of pre-stressing force, the mechanical properties of the CFRP composite, and the structural requirements of the retrofitting application. This systematic approach ensures that the steel beam component is adequately sized to withstand the induced stresses while facilitating effective force transfer within the pre-stressing device.

The transition length L_a plays a significant role in determining the cross-sectional area of the steel beam. A reduction in L_a results in increased shear force on the web of the steel beam while decreasing the bending moment on the beam flange, and vice versa. In this context, the implementation of finite element method (FEM) proves to be effective in analyzing the pre-stressing mechanical system. While modeling most components of this pre-stressing device is relatively straightforward, modeling the thread bolts and their interaction with the steel beam presents significant challenges and increases computational costs. To address this issue, a simplified finite element model has been developed in ABAQUS utilizing the standard package (static-general solver) with default tolerances. In this model, the analysis of the pre-stressing system is divided into two distinct phases: a) Calculating the required force at the thread bolt locations to achieve the target composite elevation height; b) Removing the thread bolts and applying the calculated force at their respective locations. Fig. 9 shows the finite element model for the first phase. Assuming sufficient anchorage of the FRP composite in the anchoring area, the interaction between the steel plate and the composite is considered as full bond (*TIE interaction). Additionally, the interaction between the composite and the steel straps is assumed to be a frictionless contact. Moreover, hard contact behavior (*hard interaction) was assumed for the model to prevent the material points from penetration, concentrate on pressing eachother when contacted, and allowing for separation. This approach optimizes the computational efficiency while maintaining the accuracy required for analyzing the pre-stressing mechanism.

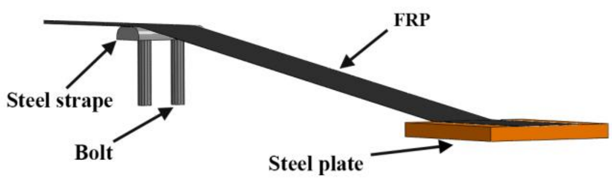


Fig. 9. Finite element model of the first part of the analysis.

Next, the displacement is transferred from the thread bolts to the steel strap and consequently to the composite material, allowing for the determination of the interaction forces in the thread bolts. By extracting the interaction forces applied both to the steel strapes and the beam, the second modeling phase can be used. The finite element model depicted in Fig. 10 is considered for modeling the second phase. In this configuration, the modeling approaches for the composite, strap, and steel anchorage plate are maintained as in the previous section. Considering the practical application in which the plates and steel beam are welded, the interaction between these components is considered as perfect bonding (Tie). As depicted in Figures (10-b) and (10-c), the bolt locations within the finite element framework were precisely modeled and the forces derived from the initial phase were applied to the steel strap.

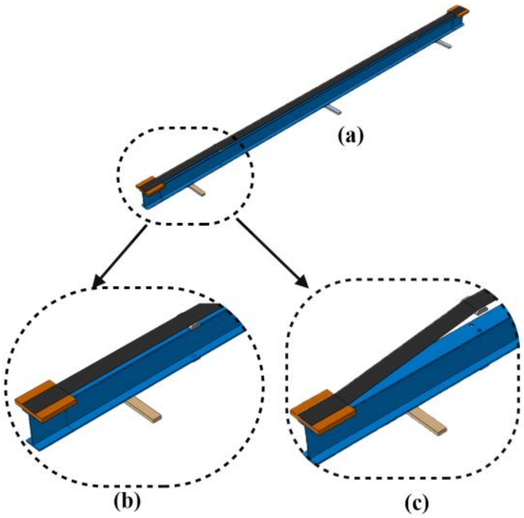


Fig. 10. Finite element model of the first part of the analysis; a) overall view; b) prior to pre-stressing; c) after pre-stressing.

A critical observation is the upward deflection experienced by the steel beam subjected to the tensile force exerted by the composite. This phenomenon introduces a minor error in the force calculations. Although the magnitude of this error is relatively small, it could potentially lead to significant design inconsistencies if left unaddressed. To mitigate this issue, an effective strategy is to limit the stress induced in the steel components to $0.6F_y$, where F_y is the yield stress of the beam's material. This approach ensures that the stress levels remain within acceptable limits, thereby reducing the risk of design errors while maintaining structural integrity during many usages. This finite element modeling approach coupled with the proposed stress limitation, provides a more accurate representation of the complex interactions between the composite material, steel straps, and anchorage system.

4. Manufacturing the FRP pre-stressing system

4.1. Problem statement

The experimental investigation was conducted on two RC T-beams with a length of 3 m and a depth of 30 cm, Fig. 11. The primary objective of this study was to enhance the flexural capacity of the beams via strengthening with pre-stressed CFRP sheets.

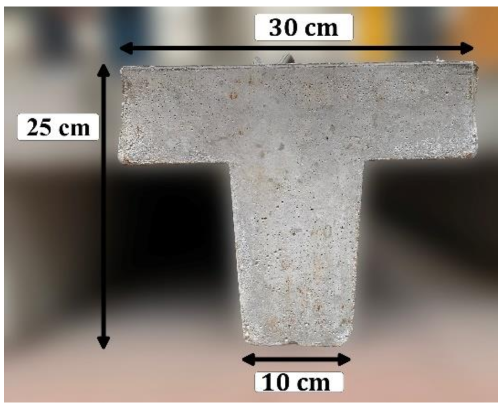


Fig. 11. Cross-section of the concrete beam.

The strengthening system consisted of a unidirectional CFRP sheet with a thickness of 0.165 mm, a width of 100 mm, and length of 3000 mm (extending along the entire length of the beam). The CFRP sheets were pre-stressed by 35% of UTS. The reason for choosing such a pre-stressing level is to consider the practical aspects with regards to the recommendations provided in the literature [14–16,33], considering ductility as well as maximizing the efficiency of the system. The mechanical properties of the utilized CFRP sheet material are presented in Table 1. Two Standard uniaxial tensile tests with the provision provided by ASTM D3039 [34] were used for evaluation of the elastic modulus, rupture strain and tensile strength of the CFRPs.

Table 1. Mechanical properties of CFRP composite.

Tensile strength	Elastic modulus	Rupture strain
3400 MPa	211 GPa	1.8%

4.2. Preliminary considerations

Based on the considerations outlined in this study, the minimum anchorage length ($L_{Anch.}$) is determined as 139 mm. For this research, a square plate with dimensions of 200 mm is assumed. Additionally, a transfer length of 80 cm for each end of the beam and high-strength, thread bolts (used in pre-stressing area) with a diameter of 20 mm is considered. By inverting Eq. 1 and solving for H, the resulted elevation required to achieve a 35% pre-stressing level in the CFRP is 145 mm.

4.3. Finite element modeling

The objective of this section is to obtain the cross-section of the device's steel beam, assuming an IPE section and ST37 steel material. The steel were modeled as elastoplastic material with the yield stress of 235 MPa. The CFRP is modeled as unidirectional material having a linear orthotropic behavior with the mechanical properties given in Table 1. Since failure was not expected during the pre-stressing procedure, no failure criterion was considered for the CFRP. Solid, full integration, hexahedral (C3D8) elements were utilized for modeling the steel beam, steel anchorage plates, and CFRP. Additionally, the steel straps and thread (high-strength) bolts were modeled using tetrahedral Solid (C3D4) elements. After a detailed mesh sensitivity analysis, the minimum and maximum seed size of 3 mm and 5 mm were considered for all elements, respectively. A trial-and-error technique was employed and ultimately an IPE20 section was selected. Fig. 12 shows the components of the finite element model.

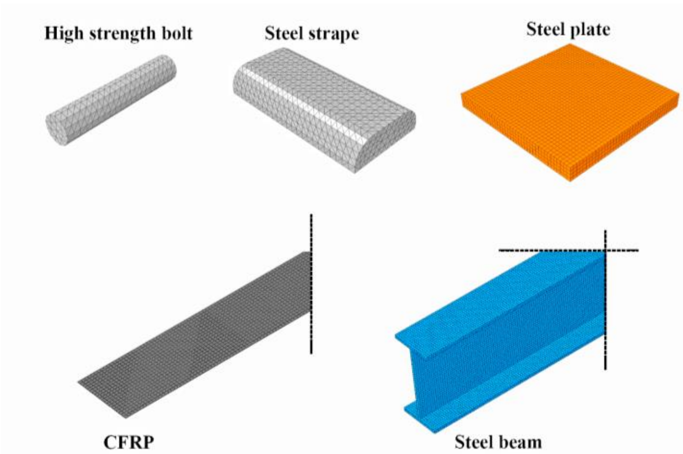


Fig. 12. Meshing of the parts of the finite element model.

Fig. 13 and Fig. 14 depict the elevation induced in the CFRP by the device (145 mm according to Eq. 1) and the corresponding stress, respectively. The amount of stress indued in the CFRP should be about 1200 MPa (refer to section 4.1,), which is consistent with the finite element analysis (FEA) results.

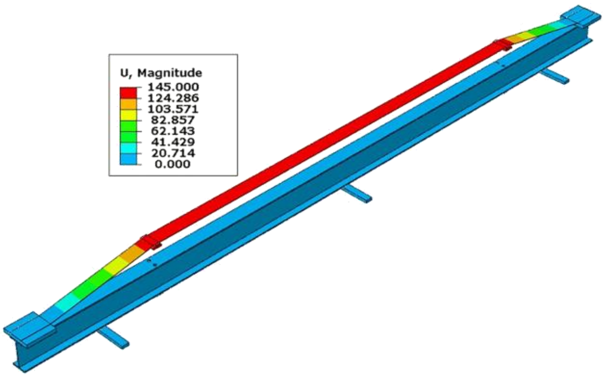


Fig. 13. Elevation induced in the CFRP for pre-stressing (units is mm).

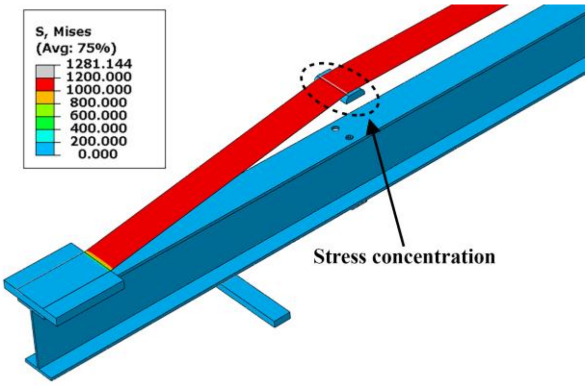


Fig. 14. Induced stress in composite (units is MPa).

Furthermore, the finite element model revealed the locations of stress concentration in the composite and steel beams (refer to Fig. 15), which must be taken into account during the device's manufacturing process. It should be noted that the FEA results yield the maximum stress concentration of 95 MPa around the bolts' hole, which is below $0.6F_y \approx 140$MPa. Also, FEA results pointed out the maximum upward displacement of the steel beam as 3.451 mm, Fig. 16, which can be neglected judging by the length of the steal beam and the stress induced in the material.

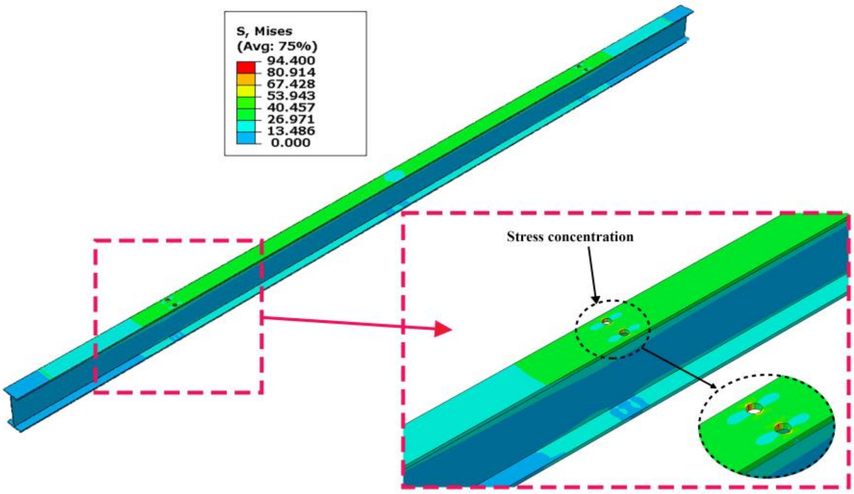


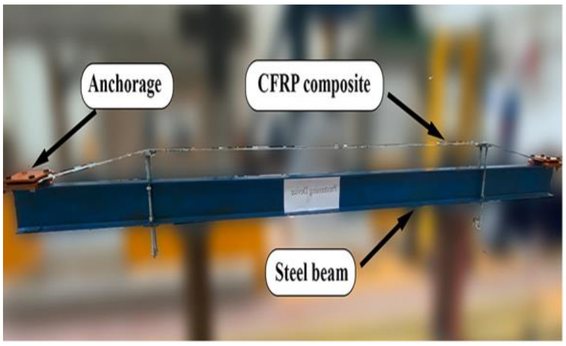
Fig. 15. Stress concentration in the steel beam (units is MPa).

Fig. 16. Upward displacement of the steel beam during the CFRP pre-stressing procedure (units is mm).

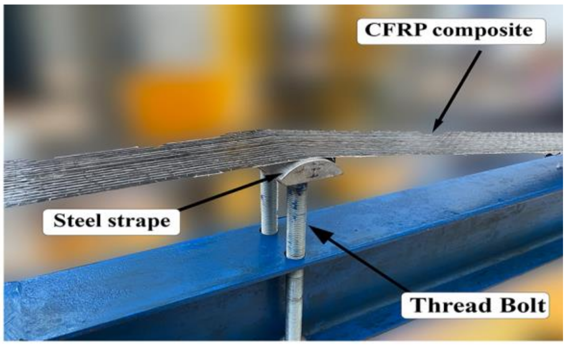
To alleviate stress concentration in the composite when applying pre-stressing, it is vital to make the steel straps rounded and polished. Moreover, the stress concentrations observed in the steel beam are attributed to the positioning of the threaded bolts. This issue can be resolved in practice by using bearing nuts. Additionally, the region surrounding the threaded bolts can be reinforced with a steel plate if required.

4.4. Device manufacturing

Fig. 17 shows the overall view of the manufactured mechanical system for pre-stressing the CFRP for the problem described in Sections 4.1 and 4.2.



(a)



(b)

Fig. 17. CFRP pre-stressing system; a) overall view; b) view of the pre-stressing area.

The device weighed approximately 120 kg, which can be easily transported. The anchorage areas consist of two steel plates, measuring 10 mm for the upper plate and 20 mm for the lower plate, connected by four high-strength bolts A325 (nominal diameter of 16 mm), Fig. 18. Moreover, no pre-stressing is applied to the bolts. To minimize stress concentration in the CFRP at anchorage zones, high deformable rubbers (anti-wear) with dimensions of 200×100×10 mm were utilized.

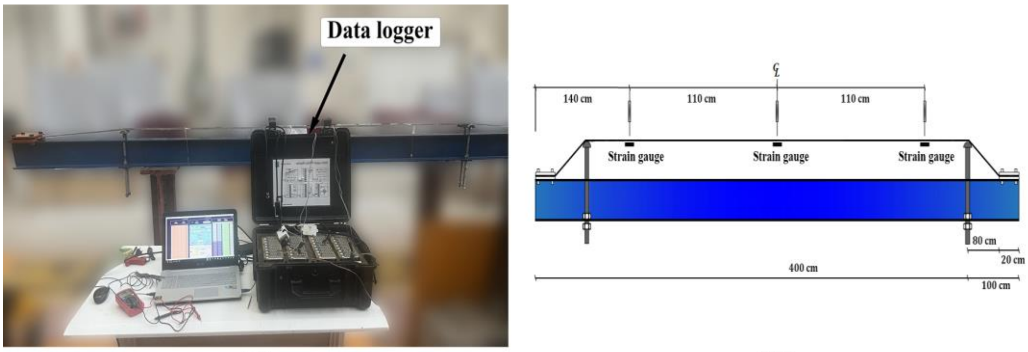
Figure 18. Details of the anchorage area.

5. Results

In this section, the results for inducing pre-stress in the CFRPs and strengthening of reinforced concrete T-beams with the pre-stressed CFRPs are presented.

5.1 Pre-stressing results for the CFRPs

In order to monitor the level of pre-stressing applied to the composites during the elevation process, three strain gauges were positioned along the composite, as shown in Fig. 19. Moreover, two LVDTs with an opening length of 200 mm and ±1 μm precision were utilized to measure the elevation.



(a) (b)

Fig. 19. Measuring the induced strain in the CFRP; a) data logging equipment; b) the location of the strain gauges.

A comparison of the results derived from the pre-stressing of the CFRPs (average readings from the three strain gauges) alongside the FEA is provided in Fig. 20. The stress induced in the composites was calculated using:

$$\frac{\sigma}{f_u}(\%) = \frac{\sum \varepsilon_{gauge}}{3}\frac{E_f}{f_u}(\%) \tag{4}$$

in which ε_{gauge} is the strain recorded by the gauges. The strain gauges had a length of 5 mm with the resistance of 120 Ω, which were attached directly to the CFRPs.

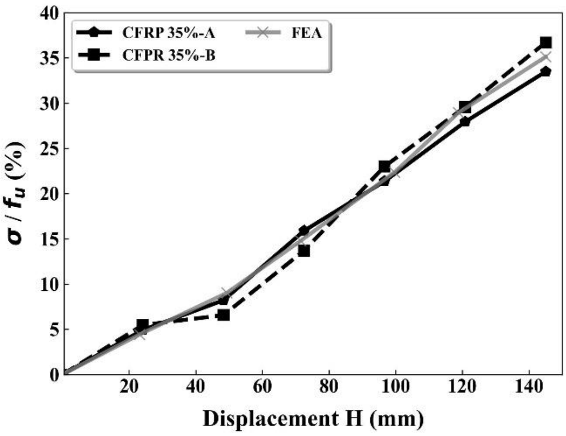


Fig. 20. Experimental and numerical results for pre-stressing the CFRP.

It can be seen that the mechanical system effectively pre-stressed the CFRP by an average of 33%. Also, the FEA results are consistent with the experimental data, pointing out the accuracy of the finite element model and design.

5.2. Strengthening concrete T-beam with pre-stressed CFRPs

An experimental program was conducted to investigate the efficiency of the FRP pre-stressing system for retrofitting RC beams. The study involved subjecting six reinforced concrete T-beams to four-point bending tests with a loading span of 2760 mm, Fig. 21.

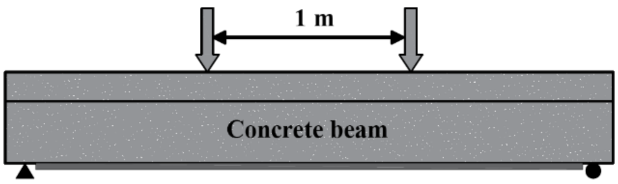


Fig. 21. Four-point testing of the strengthened beams.

Among the test specimens, two T-beams served as control specimens, while the remaining four beams were strengthened with externally bonded CFRP sheets applied to the flexural tension region. To evaluate the influence of the pre-stressing force on the structural performance, two of the CFRP-strengthened T-beams were strengthened by non-pre-stressed CFRPs, Table 2.

Table 2. Strengthening procedure and labeling the T-beams.

Label	Properties
CB	Two control T-beams
RB	Two control T-beams strengthened with CFRPs, non-prestressed
P35RB	Two control T-beams strengthened with CFRPs, prestressed by 35% of UTS

The end anchorage of CFRPs consisted of U-shaped composite with a width of 150 mm, as shown in Fig. 22. Moreover, the pre-stress losses for the CFRPs were recorded for four weeks from the beginning of the pre-stressing procedure until the initiation of flexural tests, Table 3. It is evident that the total pre-stress losses for all of the CFRPs were below 10%, pointing out that the pre-stressing process was successful. Fig. 23 shows the load versus mid-span deflection for the control and strengthened T-beams.

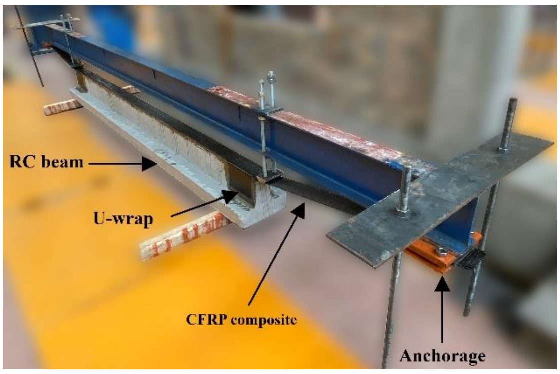


Fig. 22. Retrofitted beam using the pre-stressed CFRP.

Table 3. Measured stresses (in percentage of UTS) and prestress losses until testing.

Specimen ID	Initial stress	stress at week one	stress at week two	stress at week three	stress at week four	Before static test	Total prestress loss (%)
CFRP 35%-A	33.4	32.8	32.1	31.6	31.4	31.3	6.2
CFRP 35%-B	36.6	35.9	34.8	34.5	34.3	34.1	6.8

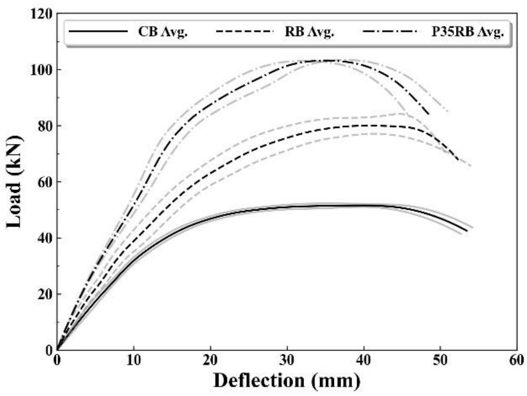


Fig. 23. Load- mid span deflection diagrams for the beams.

The control beams had an average load-bearing capacity of 51 kN and a deflection of 55 mm. In contrast, the beams strengthened with CFRP had an average maximum capacity and maximum deflection of 80 kN and 51 mm, respectively. These values for the beams strengthened with pre-stressed CFRP are 102 kN and

49 mm, respectively. It can be seen that strengthening T-beams by CFRPs without applying pre-stressing resulted in an increase in bearing capacity by 56% on average. Additionally, applying pre-stressing to the CFRPs further increased the load-bearing capacity by 27% compared to the non-pre-stressed state. Furthermore, the failure modes of the strengthened beams are shown in Fig. 24. For the control beams, cracks with 80˚~90˚ angle was observed at the flexural region. This cracking pattern continued failure. On the other hand, the failure mode of the RB beams was a concrete cover rupture. A similar concrete cracking pattern was observed for the P35RB beams at first; however, the ultimate failure mode was CFRP rupture.

6. Discussion

6.1. Effects of L_a and L_H

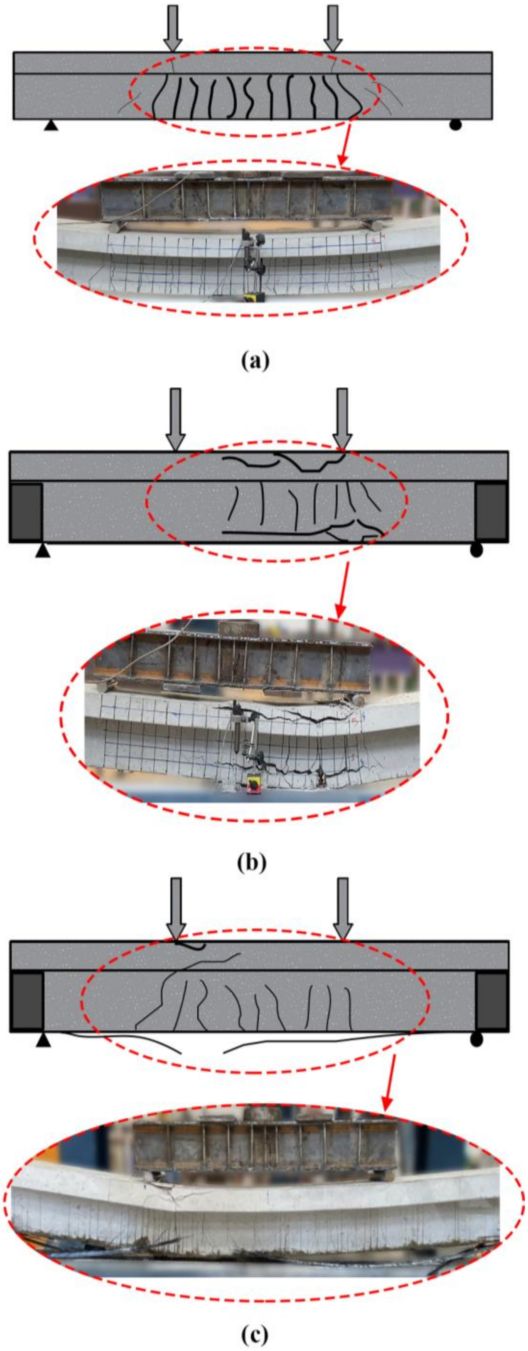


Fig. 24. Schematic view of the cracking pattern and failure modes of the beams; a) CB; b) RB; c) P35RB.

The influence of the geometric parameters L_a and L_H on the pre-stressing level of is investigated. It is evident that reducing the L_a while maintaining L_H constant leads to increased force transferred to the composite, subsequently elevating pre-stressing levels. Conversely, increasing L_a diminishes stress concentrations, while architectural limitations might be imposed. The impact of L_a on pre-stressing levels in the CFRPs, assuming a retrofitted length of 5 m, is demonstrated in Fig. 25.

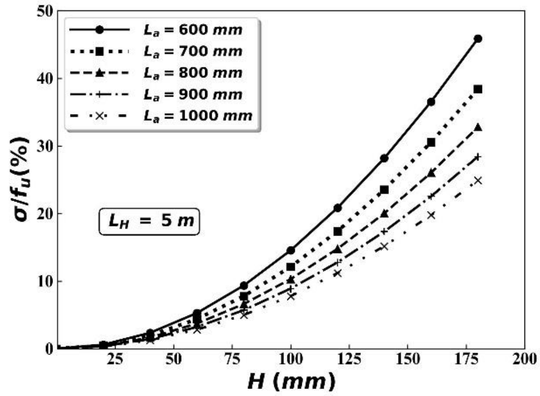


Fig. 25. The effect of L_a on the amount of FRP pre-stressing.

The impact of L_H on pre-stressing levels, assuming $L_a = 0.15L_H$, is depicted in Fig. 26. It is evident that as L_H increases, pre-stressing amount in the composite decreases. However, this can be offset by adjusting L_a and managing stress concentration at the bending points.

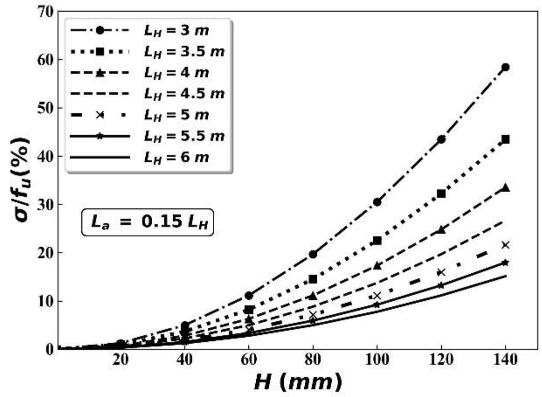


Fig. 26. The effect of L_H on the amount of FRP pre-stressing.

6.2. Steel beam's section

In this study, an IPE steel section was used to manufacture the pre-stressing system. The IPE section was chosen as it provided the requisite stiffness and strength to effectively pre-stress the CFRPs. Typically, the selection of the beam type and cross-section is based upon the specific requirements of the project. For scenarios requiring higher resistance, girder profiles with stiffeners can be employed. The design framework presented in section 3 is not dependent on the shape of the section, but rather on the force interaction generated by the coupling forces. Thus, various sections could be utilized.

6.3. General usage

CFRP pre-stressing is commonly applied in retrofitting concrete slabs and beams. Thus, the retrofitting method must be applicable for usages at elevated altitudes. In practice, the mechanical system presented in this study can be utilized as shown in Fig. 27, which is a key benefit. This method involves attaching the device to the concrete member with steel straps and the FRP is bonded to the member. Once the adhesive has sufficiently cured, the device can be detached from the retrofitted member and repurposed for other applications. This reusability feature enhances the practicality and cost-effectiveness of the proposed CFRP pre-stressing system, making it an attractive solution for strengthening existing RC members.

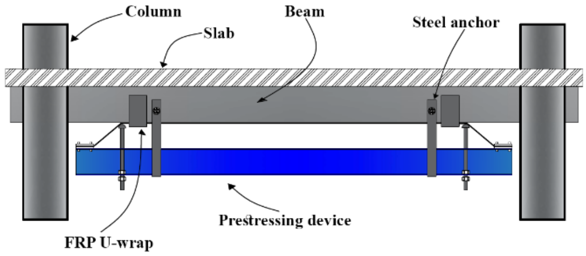


Fig. 27. Application of the FRP pre-stressing system in practice.

7. Conclusion

This investigation presents the development and experimental validation of a mechanical system designed for pre-stressing FRPs in concrete member retrofitting applications. In this regard, a comprehensive finite element model was proposed to design and analyze the device. Subsequently, the manufactured device was employed to pre-stress CFRP sheets, which were then utilized for strengthening concrete T-beams. The effectiveness of the proposed device was evaluated through four-point bending tests on retrofitted reinforced concrete (RC) T-beams. Experimental results demonstrate the device's efficiency in applying pre-stressing forces to CFRPs. Notably, RC T-beams strengthened with pre-stressed CFRPs exhibited substantial increase in load-bearing capacity compared to their counterparts strengthened with non-prestressed CFRPs.

The device's dimensional parameters and weight are optimized based on specific project requirements, including the composite's nominal strength and desired pre-stressing level, rendering it both practically and economically feasible. The proposed system offers several advantages, particularly eliminating hydraulic jack requirements and operational simplicity. Similar to other FRP pre-stressing techniques, certain limitations persist regarding the force transfer zones, which may present architectural constraints. Nevertheless, the developed device demonstrates the potential for practical implementation in retrofitting applications.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Authors contribution statement

Kian Aghani: Investigation; Data curation; Formal analysis; Software; Writing – original draft

Hassan Afshin: Methodology; Project administration; Supervision; Writing – review & editing.

Karim Abedi: Conceptualization; Project administration; Supervision; Writing – review & editing.

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