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Article

Carbon fiber reinforcement design based on biomechanics to improve the bearing capacity of concrete structure

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Abstract: In concrete constructions, carbon fiber-reinforced polymer (CFRP) bars had considered as an alternative to traditional steel reinforcement for enhancing the capability of loading in reinforced concrete (RC) components. Whereas the advantages of CFRP are well-known, its potential applications have been confined by concerns, such as lesser ductility, decreased strength of bonds under continuous loads, and elastic response. This research investigates the performance of 7 slender beams of concrete that are reinforced with CFRP beams with maximum loads to calculate the bearing capacity using biomechanical concepts to improve reinforcement design. CFRP reinforcement can improve the concrete constructions of load capacity, as demonstrated by findings of the applying biomechanical design concepts. Special emphasis is placed on the bond behavior at the CFRP bars' anchorage lengths (600 mm), with biomechanical design concepts involving local confinement at these anchorage regions (90%) shown to impact cracking behavior and enhance overall bearing capacity. Results from experiments on CFRP-reinforced beams compared to other reinforced beams are examined. The research examines key performance indicators, such as load capacity (180 kN), and stiffness (25 kN/mm), as well as bond strength at anchorage (18 MPa), failure mechanisms with reducing failure, and crack propagation (0.2 mm/min). Experimental findings demonstrated that the CFRP beams are more efficient in the bearing capacity of concrete structure performance.

Keywords: bearing capacity; crack propagation; reinforced concrete (RC); biomechanical design concepts; concrete structure

1. Introduction

The usage of concrete has been improved by the advancements in industrial technologies. The bearing capacity of concrete structures is being increased by the improvement and utilization of more inexpensive, low-strength concrete mixes. A novel high-strength, high-modulus material with over 95% carbon content and carbon fiber (CF) has become a crucial component in the military, civic, and security industries [1]. Considering its superior compressive qualities and inexpensive cost, concrete is frequently utilized in the construction of construction works, including roads, buildings, and bridges. High chloride corrosion resistance is features of fiber-reinforced polymer (FRP) bars are a type of the nonmetallic reinforcement [2]. The capacity of reinforced concrete (RC) beam bridges is increased through region extension approaches, CFRP, steel stick enhancement, and external pre-stressed procedures, resulting in substantial advantages for both shear and flexural reinforcement [3]. The production of cement contributes to the world's carbon dioxide emissions. By integrating these high-performance materials and making use of their beneficial properties, such as durability, high breaking capacity, and high compressible strength of the concrete, smooth and thin-walled structures can be created by Hammerl and Kromoser [4]. Construction works, along with the products, components, and building structures from which they are constructed, must satisfy several particular requirements provided by modern construction. The layouts of cities are transforming with more growth and expanded structures along with buildings rising, and the lack of physically investigated areas makes engineering and physical environments more complex. Buildings and other structures have to be constructed in difficult engineering and physical environments, including in packed urban areas [5]. It is essential to comprehend how the reinforced concrete components perform under high-rate loadings throughout both the design and retrofitting phases to prevent the catastrophic outcomes of potential impact events. To increase the effect generated by reinforced concrete members, researchers have searched to use newly developed materials and methods, like FRP, steel fiber-reinforced concrete, and high-performance concrete [6]. The RC components need to be able to sustain the shear in this complex stress-strain condition. Since there is an extensive range of strength in the breaking designs, a large amount of money has been utilized for materials. Dependencies that accurately determine the RC bearing capability framework on the stress that has to be strengthened need to be established [7]. Shield tunnels are man-made structures composed of concrete portions, bolts, and closed gaskets that are impacted by local engineering works, especially for shallowly buried assignments. The tunnel’s overall rigidity against deformation was significantly diminished as an effect of severe structural damage, which included broken concrete components, visible bolts, and extensive water leaking [8]. The experimental performance of RC frameworks augmented with CFRP showed a good correlation with the analytical load-deflection bends and finite element computations, indicating a significant strength potential for improvement. It needs to be highlighted that the research investigations are conducted to determine how constant forces influence the elements of RC beams [9]. To resist a variety of environmental conditions on the duration of the estimated operating duration, the RC buildings are constructed. Throughout time, individual errors can cause severe damage caused by elements like shifting usage patterns, defects in structural design, poor maintenance, and changes in the environment. These environmental elements have the potential to cause corrosion in steel reinforcement, deterioration of concrete, and consequently a loss in structural integrity [10]. The utilization of CFRP bars as an alternative to conventional steel reinforcement in concrete structures is the primary objective, which focuses on designing reinforcement using biomechanical concepts. Identifying the bearing capacity and researching biomechanical design options for RC structures are the specific tasks involved in evaluating the thin material reinforcement in CFRP beams performed in continuous loads.

Writing framework: Relevant articles are provided in Phase 2. The research methodologies with CFRP in the ability of bearing structures in biomechanics are explored in Phase 3. Results are demonstrated in Phase 4. Conclusions are provided in Phase 5.

2. Relevant articles

The concrete strength's effect on seismic resistance of concentric RC fields surrounded by CFRP and basalt was investigated by Huang et al. [11]. Based on the evaluation outcomes, all of the fields showed indications of flexural failure in detention. The constrained fields' toughness, flexibility, and capacity to release energy were all effectively improved. The capacities of bearing with CFRP-RC buildings, numerical simulation assessment was used by Song et al. [12] to assess the seven CFRP strengthen the building materials arch constructions by employing 5 different strong systems. It resulted in an analysis of the concrete and CFRP interfacial bonding performance under various strengthening techniques and identification of the RC arch model static damage mode. The results indicated that applying CFRP to the surface could result in the development of a concrete arch's linear segmental rigidity, breaking loads, and maximum weight. Alternatives to employed steel reinforcement have been searched for concrete remains in control of the construction field. Maidi et al. [13] investigated that CFRP could be used as an alternative in rigid frames with a concentration on the ways it could affect the flexibility of the sections and the overall structural stability against seismic occurrences. Considering the material's cracking, it demonstrated that using CFRP in concrete to create flexible bending components was possible. Through addressing assumptions, the financing created new opportunities for CFRP, use in structural applications where resilience and flexibility were essential. The CFRP and engineered cementitious composite (ECC) were used by Liu et al. [14] to reinforce the RC frames. The analytical prediction techniques were used to validate the experimental findings concerning reinforced RC beams' flexibility. The experimental findings demonstrated that with the beam reinforced with CFRP, there could be a quick separation between the CFRP plate and the concrete could be effectively prevented by using CFRP and ECC in combination. CF-containing self-compacting cement reduced its lateral strength to investigate and promote the application of CF for its mechanical properties and embodied carbon enhancements as determined by Khan et al. [15]. By reducing the blockage ratio, CF was the primary advantage that strengthened the concrete as a clustering structure. A model based on the outcomes of in-depth testing was created using response surface methodology (RSM). The final model equations for calculating the impact of adding CF to concrete were presented after the model was refined by Turkowski [16]. According to the load level and degree of strengthening, externally bonded reinforcement CFRP (EBR CFRP) was used to reinforce fire-resistant RC beams. The outcomes of thorough experimental testing on concrete beams reinforced with EBR CFRP strengthening for fire resistance under varied load situations and with and without fire protection. The test specimens without or with CFRP strengthening were shown to achieve similar fire resistance in instances where it was not necessary to carry the weight in the occurrence of a random fire. The compressive strength and construction performance of basalt fiber-RC (BFRC) with different fiber lengths and fiber volume concentrations were carefully examined by Wang et al. [17] using axial load. Depending on whether the finite element analysis (FEA) approach and the suggested prediction technique match the experimental data, it could be able to predict the BRFC compact columns' final bearing capacity in practical implementation. Selected sections of load tests in flexed components with transversal polymer reinforcement that have inclined cracks and differ in stress durations and lateral reinforcing options could be performed by Polskoy et al. [18]. After tests on the experimental beams, the RC's characteristics showed early vertical fractures. Near surface mounted CFRP (NSM-CFRPs) were used by Al-Zu'bi et al. [19] to strengthen the RC beams in the stretch. It was investigated both experimentally and analytically. The CFRP breakage failure circumstances were less probable attributed to the NSM approach. Using the guidelines, test results were compared to theoretical forecasts, and the results indicated consistency. Polyurethane cement's design was modified by Ding et al. [20] to repair concrete quickly in the anchorage region of gaps while considering the drawbacks of conventional repair solutions, including the tendency for breakage and extended maintenance periods. The CF grid enhanced the ability of polymers in concrete to bend, as resulted by Al-Zu'bi et al. [21]. A detailed analysis was conducted on the acceleration of RC beams reinforced with NSM-CFRPs compounds. In all compositions, the findings showed consistency between the analytical and experimental outcomes and the average protection factor, k values were 0.80 and 0.73, with associated standard deviations of 0.195 and 0.125. High-performance, self-compacting FRC's load capacity was essential to the effectiveness of load capability. Furtak and Ostrowski [22] investigated factors that affect the stress-strain properties of concrete that were constrained by laminated CFRP. The findings demonstrated that high performance augmented with CFRP's load-bearing capacity was significantly impacted by the concrete surface design. The effect of steel fiber length on a RC column's ability to support loads using a reinforcement layer was highlighted by Vavruš [23]. The length of the fiber has less impact on the compressive strength of FRC than on its tensile and flexural tensile strengths. The tensile strength of fiber concrete was 50%–100% more than that of regular concrete. Several hygro-thermal elements could interact to cause instances like water seepage and tunnel disintegration in shield regions of subway tunnels. In a hygro-thermal atmosphere, the effects of CFRP-strengthened shield parts' slip-on-bending strength were examined by Gu and Nie [24]. The shield segments were damaged at the outside pressure using a mixture of temperature (20 ℃, 25 ℃, 30 ℃, and 40 ℃) and moisture (0%, 5%, and 10%). To test a CFRP-reinforced concrete arch, an experimental protocol was developed. The primary goal of Alhawamdeh and Alqam [25], was to evaluate the effectiveness of CFRP and thin RC columns tested with eccentric loads. Twelve short reinforced concrete columns measuring 150 mm by 150 mm by 900 mm were used in an experimental investigation. There were six control specimens and six CFRP-rehabilitated specimens. The subject columns had variances of 15 mm, 30 mm, and 45 mm. The findings increased the eccentricity from 15 mm to 45 mm resulting in an increased load-carrying capacity of 22.5% to 37.2%.

3. Research methodology

The experimental setup and instruments utilized for the process, biomechanical design consideration, and testing procedures for the CF reinforcement design based on biomechanics for enhancing the capability of bearing in concrete structures are examined more comprehensively. The processes and features are given in **Table 1**.

Table 1. Comparison of CFRP and GFRP features.

Process	Features
Experimental Setup	Concrete Beams
	CFRP bar
Biomechanical Design Consideration	Anchorage Lengths
	Confinement at Anchorage
Test Procedures	Load Increments
	Deflection Measurement
	Cracking and Failure Mechanisms

3.1. Experimental setup

The seven slender concrete beams are presented in the experimental configuration and each beam is sized precisely to duplicate common structural components used in building. The CFRP bars have been used to reinforce these beams by the use of more standard bars. The CFRP bars have been employed and selected to satisfy the stiffness and load-bearing capacity design specifications. The beams are tested to the sequence of gradually increasing static loads to approximate real stress conditions. Depending on the design of the beam, these loads are delivered uniformly to estimate the way that the CFRP beams for the beams in static loading conditions, concerning the capacity of load bearing, deflection, and failure processes. The concrete beams, CFRP bars, and loading conditions are as follows.

Concrete beams: They support a wall or floor's weight and transfer into different structural components. **Figure 1** depicts the structure of a common concrete beam structure. Beams can be used to expand a ceiling's span and/or load capacity. Seven thin concrete beams each with accurate measurements to replicate common structural components in the building have been selected for testing. The CFRP bars serve as the main reinforcement material for the beams. A structural member with a high shear span-to-depth or span-to-height ratio is a thin concrete beam. It is frequently employed to shift vertical weights from the surface components to columns in parking structures. Concrete constructions can be strengthened with CFRP bars, which are composite materials, composed of CF and polymer.

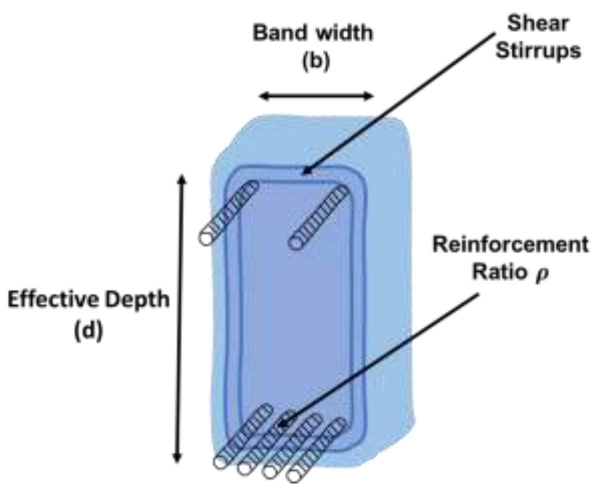

Figure 1. Reinforced concrete beam structural design.

CFRP bars: In the beams, traditional steel reinforcements have been changed with the CFRP bars. These bars have been thoroughly selected to provide the stiffness and load-bearing capacity design criteria. CFRP bars provide a high strength-to-weight ratio, are robust, and are lightweight. It can tolerate higher pressures without breaking than concrete or steel, which are resistant to weathering and corrosion. To prevent corrosion, CFRP bars are utilized compared to steel reinforcing. To maximize the tensile strength, it can be used as the pre-stressing tendons. The CFRP's illustrations are displayed in **Figure 2**.

Figure 2. Basic structure of CFRP reinforcement.

There are four types of FRP CFRP, Glass FRP (GFRP), Aramid FRP (AFRP), and Basalt FRP (BFRP). The GFRP and CFRP are the most effective polymers employed for building constructions. This research utilizes the CFRP with biomechanics and it is more efficient than the GFRP in terms of bearing capacity. To duplicate actual stress conditions, the beams are exposed to the sequence of increasing static loads. Depending on the beam's design, these loads are uniform to test the CFRP reinforcement's ability to resist the stress. The external forces or loads that are applied to a material or system are known as loading conditions, and they can involve bulk carriers like alternative hold loading, block hold loading, and homogenous hold loading along with materials like stress, compression, bending, shear, and torque.

3.2. Biomechanical design concepts

The CFRP utilizing the biomechanical design concepts increases the carrying capacity of concrete structures by improving the bond strength, stress distribution, and crack resistance. The anchorage length design is a crucial factor that affects the bonds of strength associated with the CFRP bars and the adjacent concrete. To provide efficient load transfer and avoid inappropriate failure, biomechanical techniques are utilized to optimize the essential portion. It focused on the anchorage lengths, as the bond efficiency is influenced by the length of CFRP bars implemented in the concrete. Stress transfer is enhanced by longer anchoring lengths, whereas shorter lengths can lead to early breakdown. Biomechanical optimization techniques including external wrapping or reinforcement at the anchoring regions are used in the confinement at anchorage. These approaches strengthen the concrete's bond with CFRP bars by increasing compressive strength, which improves the performance of the structure. Better tension distribution and reduced crack propagation are the advantages of confinement techniques, which increase the load capacity and enhance the behavior in static loads. The biomechanical design concepts include anchorage lengths and confinement at anchorage.

Anchorage lengths: The length of reinforcement bars established into concrete at an angle to securely transmit the load between the concrete and CFRP bars is known as the anchorage length. CFRP rod anchorage damage leads frequently to anchoring failure and premature breakage. Equation (1) depicts the anchorage length.

$$Anchorage\ length = \frac{q_v}{\pi c \tau_v} \quad (1)$$

The maximum tensile load of reinforcement is denoted by q_v, the diameter by c, and the bond strength by τ_v. Increasing the length of the anchorage is typically used to prevent anchoring failure, making the anchorage significantly larger than the normal one. The primary cause of premature fracture is the significant local fiber bends in CFRP rods within the anchorage. A representation of the anchorage length structure is examined in **Figure 3**.

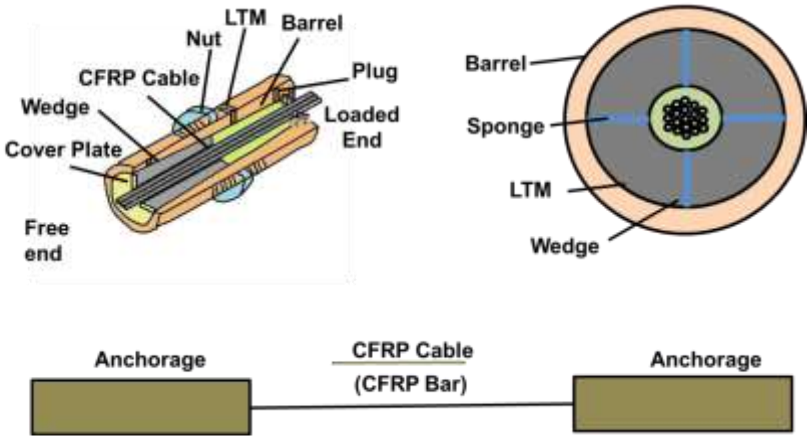

Figure 3. CFRP anchorage lengths structural design.

Note: LTM refers to the load-transfer medium.

Pre-tightening force, copper channel thickness and stiffness, anchoring length, roughness of each contact surface, and the type of CFRP tendon are the main factors affecting mechanical anchorage performance. To effectively transfer the strain from the CFRP connection or hangers to the bridge's structure, the majority of observed bridges with these components use bond-type anchorages. There was an uneven distribution of bond stresses brought on by the tensile pressures applied to the anchor rod. The load level and the bonded length have no bearing on the characteristic bond strength. The tendon's surface conditions and the grout's strength are connected. In the anchoring, the main factor influencing the bond stress distribution is the anchor rod length. The shorter the anchor dowel length, the distribution is more uniform. A longer anchor rod results in a less consistent distribution of stress.

Confinement at anchorage: Internal confinement of an anchorage node through transverse reinforcement is known as confinement at anchorage. This procedure differs from the exterior transverse pressure that prevents cracks from opening by applying pressure to the outer surface of the concrete. The anchorage confinement structure is represented in **Figure 4**. Concrete beams can be strengthened and the load capacity and flexibility increased by covering them with CFRP at the anchorage.

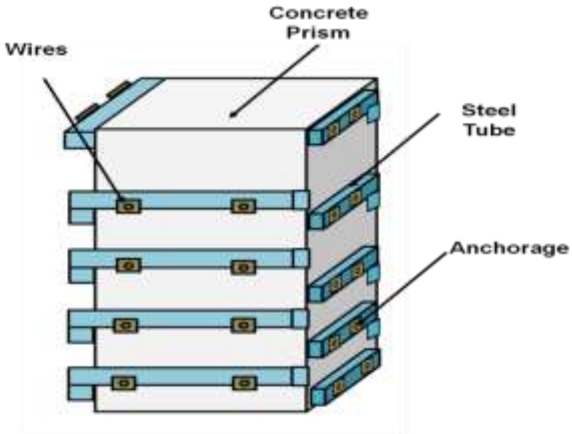

Figure 4. Reinforcement anchorage and confinement structure.

The pre-tightening force gradually lessens its impact on the confinement effectiveness as the force increases. To provide a confinement effect, post-tensioned anchoring zones require circumferential reinforcing and sufficient strength to resist significant raising pressures from pre-stress. Using high-strength concrete, which combines the confinement effect with high strength, could improve the anchorage zone's performance. The growth of cracks with slopes could not be stopped by the positioning of supports on a single side of the beam with greater separation. The weaker portion of the beam developed several positioned cracks compared to the well-confined region. The weaker side of the beam experienced the failure, inclined cracks have been observed in the well-confined portion.

3.3. Test procedures

To evaluate the beam's behavior under various stress levels and finally ascertain its maximum load capacity for failure, the testing process involves applying static loads in incremental steps. With the use of displacement sensors or dial gauges, deflection is monitored at advantageous positions along with the beam to provide information about the stiffness and reactivity of the beam to applied stresses. The main sign of possible failure or fracture is established with enhanced deflection. During the loading process cracks are observed visually and through the use of sensors, with an emphasis on the area of failure along with the beginning and spread of cracks. The effects of biomechanical design modifications on cracking behavior are specifically examined for CFRP bar anchorage locations. Failure mechanisms such as bond failure, concrete crushing, or CFRP bar fracture have been investigated, and the degree to which biomechanical design improves the structural integrity and load-bearing capacity of the beam. Loading procedures include load increments, deflection measurement, and cracking and failure mechanisms.

Load increments: An increase in a body's total strain energy is referred to as a load increment. Determining poro-elastic constants, cross-section analysis and FEA represent its applications. Static loads are applied incrementally and gradually. To determine the behavior of the beam at various stress levels, every load increase is thoroughly tracked. It is possible to evaluate the beam's effectiveness to its highest load capacity without failure. **Figure 5** determined the load increment process and static load components. CFRP can be used to enhance the concrete arches' ultimate load, cracking load, and linear segmental stiffness. Strengthening the arch's exterior and interior surfaces could significantly increase its ultimate bearing capacity. The load capacity of RC constructions can be increased by CFRP sheets, and the thickness of CFRP enhances the weight-carrying capacity of beams. The strip U-wrap structure is ideal for shear strengthening, whereas the extended U-wrap system is optimal for flexural strength.

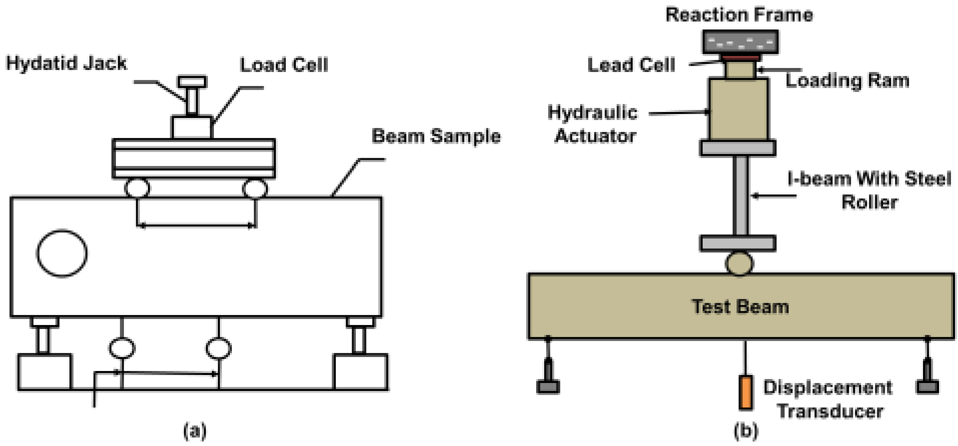

Figure 5. Analysis of load application and force distribution **(a)** load increment process and **(b)** static components in structural analysis.

To assess the way the RC beams reinforced performed under service and ultimate loads with repeating loads and half-cyclic incremental bending moments. The evaluation was based on fracture width and deflection in the specified load range. The evaluation depended on a maximum load and the way of failure within the ultimate load range. Continuous loading affects the final capacity of the RC beams due to creating small cracks in the concrete, which gradually reduce, particularly in the bonding locations of the CFRP adhesive-concrete interface. CFRP-reinforced RC structures frequently break down under recurring loads, resulting in bond stresses that are less than the maximum stress with static loads. During cyclic stresses, CFRP plates and conventional steel can cause cracks in concrete flexural members.

Deflection measurement: The dial gauges or displacement sensors, deflection at particular points in the beam is continuously measured was employed for the function of bearing capacity performance. When assessing the stiffness of the beam and reaction to applied loads, the data is essential. A major indication of approaching breakdown or the beginning of cracking is increased deflection. The beams and slabs were tested to determine the applied load, the middle deflection, strains in the concrete's severe compression particles, strains in the supports, strains in the concrete at the reinforcement surface, and crack depths in the constant region. The deflection measurement and displacement sensor are shown in **Figure 6**.

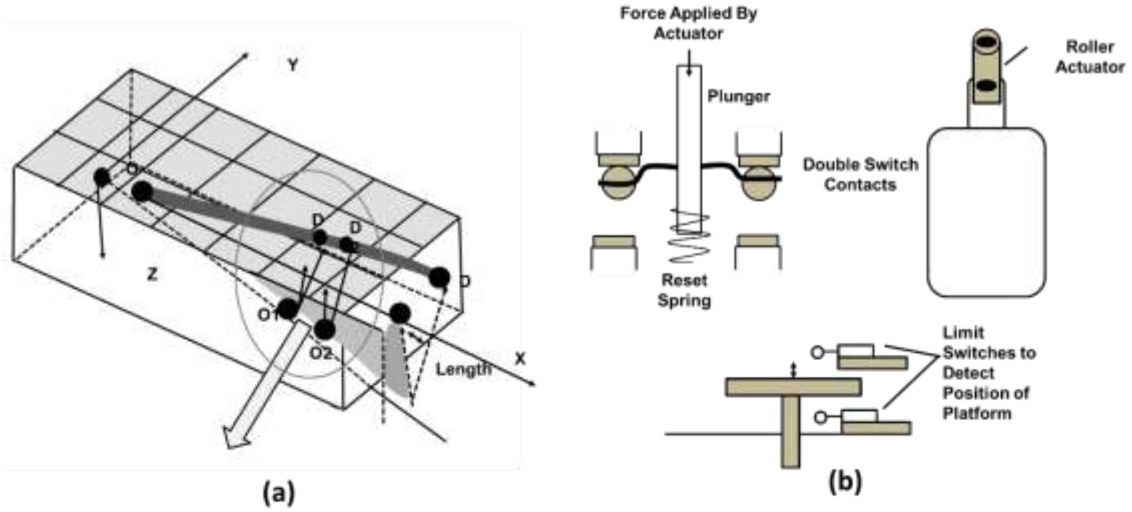

Figure 6. Deflection measurement and sensor application **(a)** dial gauge setup for deflection measurement; **(b)** strain gauges on concrete and reinforcement surfaces.

The test procedure intended to find the way CFRP-RC components performed when bending to failure. It comprises the process of failure, ultimate capacity, deflection, crack pattern, and behavior at cracking. Several approaches for predicting the deflection of concrete components reinforced with CFRP bars were found to ignore the factor. The deflections and strains of CFRP-RC components are often higher than those of GFRP-RC components. The CFRP reinforcements' unique bond characteristics and low stiffness of elasticity are defined by the properties. Industrial manufacturing uses sensors to maintain updates on defects in mechanical process manufacturing, like misalignments that occur during CFRP layering. Procedures that reduce the amplitude and position uncertainty caused by diffraction contribute to identifying the center of the received signals through the sensor.

Cracking and failure mechanisms: To maintain the attention on crack during loading, it employed the sensors. Its focus has been placed on failure, crack initiation, and crack propagation. It is useful in determining the way CFRP bars influence structural integrity when alterations are made to the biomechanical design. The failure modes such as bond failure, concrete crushing, and CFRP bar fracture are identified to provide reinforcement effectiveness. The CFRP can crack and fail related to a variety of reasons, such as matrix yielding (it causes the fibers to bend and micro-buckle, creating kink bars), matrix fractures (beginning at the 90° plies' kink-band edges), Near the tip of kink-bands, de-lamination (which occurs between 0° and 90° plies) Moisture absorption results in fiber/matrix de-bonding and resin matrix pores/voids in the composite, fiber kinking occurs under compressive load, and fiber fracture shows the thickness direction of laminates. The mechanism of polymer failures is presented in **Figure 7**.

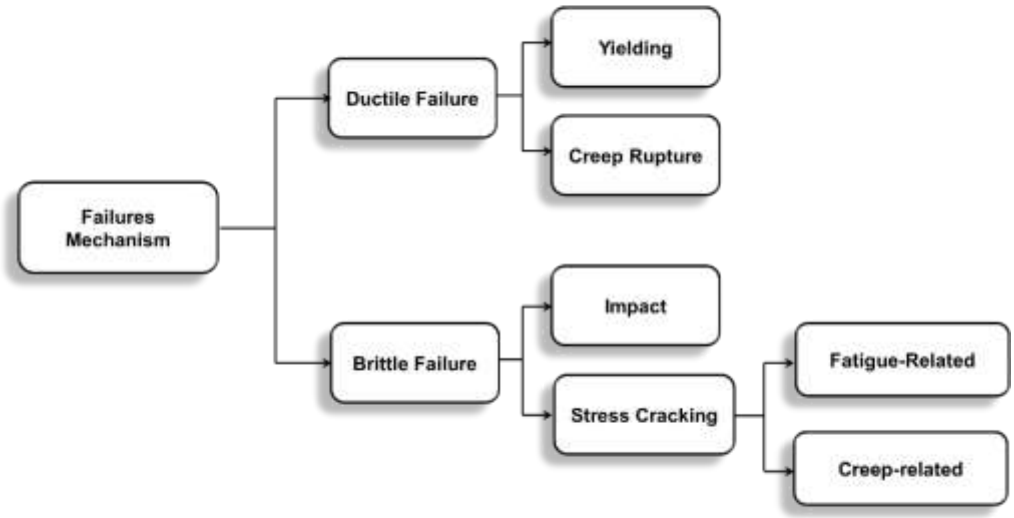

Figure 7. Failure mechanisms affecting the bearing capacity of CFRP-reinforced structures.

There are two types of failures such as ductile failure and brittle failure. A material experiences ductile failure when it has been exposed to tensile forces that exceed its yield strength. Before breaking, ductile materials such as certain metals and low-carbon steels can bend and utilize strength. Material deformation and failure under stress are linked to ductile failure, yielding, and creep failure. A material can continuously deform when its elastic limit is exceeded, resulting in a ductile failure mode. Visible deformation, like bending or stretching, could indicate the result of yielding failure, a breakdown that occurs when materials are repeatedly exposed to high temperatures and stresses along with deforming them in the estimated yield point. For re-heaters and superheaters functioning under design circumstances, creep failures are anticipated and variations from the parameters can result in unnecessary failures.

When a material cracks with minimal or no plastic deformation before the fracture, it is considered to have brittle failure. Brittle materials include glass, cast iron, concrete, and other materials. A material could suffer brittle fracture, a form of failure when it is under stress, and fractures suddenly and quickly. This crack requires a greater amount of tension to begin and to spread. When brittle fracture is distinguished from ductile fracture by the feature, the stress needed to start the crack reduction than the stress needed for it to widen. All beam specimens's experienced random flexural cracks on the pressure edge within the continuous stress area. The cracks in several beam started near the region's edges. The tested High-Strength Concrete (HSC) beams reinforcing bars reached stress fracture anterior to face-and-side real covers tensile cracking around the attached bars. Splitting tensile cracks on both sides of attached bars were caused by extra refractions that were applied to the beam failed after.

4. Performance evaluation

This phase examines the evaluation criteria of CFRP performance with matrices like anchorage lengths and confinement at anchorage. The comparison among the CFRP-reinforced beams and GFRP-reinforced beams with the performance indicators such as load capacity, stiffness, crack propagation rate, bond strength at anchorage, and failure mechanism.

4.1. Evaluation criteria

An evaluation criterion of CFRP reinforced mechanism with the biomechanical design concepts is determined in **Table 2**. Components such as anchorage lengths and confinement at anchorage are employed for the evaluation.

Table 2. Optimizing anchorage length and confinement.

Components	CFRP reinforced mechanism
Anchorage Lengths	600 mm
Confinement at Anchorage	90%

The anchorage length identified the specimen's failure mode when the concrete and reinforcement bond strength remained constant. The critical length of anchorage is the crucial distance between the reinforcement's tensile failure and extraction failure. The de-bonding of CFRP plates and sheets from concrete constitutes a frequent factor that beams to fail too quickly. Concrete beams can be strengthened and their load capacity and ductility increased by confining them with CFRP at anchorage.

4.2. Comparison phase

The CFRP and GFRP are compared with various performance indicators such as load capacity, stiffness, crack propagation rate, bond strength at anchorage, and failure mechanism. **Table 3** shows CFRP and GFRP comparison functions for improving the bearing capability of concrete structures.

Table 3. Comparison of CFRP and GFRP reinforced beams.

Performance Indicators	CFRP	GFRP
Load Capacity (kN)	180	140
Stiffness (kN/mm)	25	18
Crack Propagation Rate (mm/min)	0.2	0.5
Bond Strength at Anchorage (MPa)	18	14
Failure Mechanism	Reduce Failure	Early Debonding

Load capacity: It indicates the load at which a bearing can function in many rotations without breaking. To find the bearing's static load-carrying capability, use the following Equation (2).

$$Load\ Capcity = (Q_0/E_0) \times D \tag{2}$$

The static load applied to the bearing is represented by Q_0. An appropriate load factor is determined as E_0 and D determines the fundamental loading dimension rates in the bearing performance.

Stiffness: The resistance of a bearing component to deformation when a load or force is applied is known as bearing stiffness. **Figure 8** explores the load capacity and stiffness.

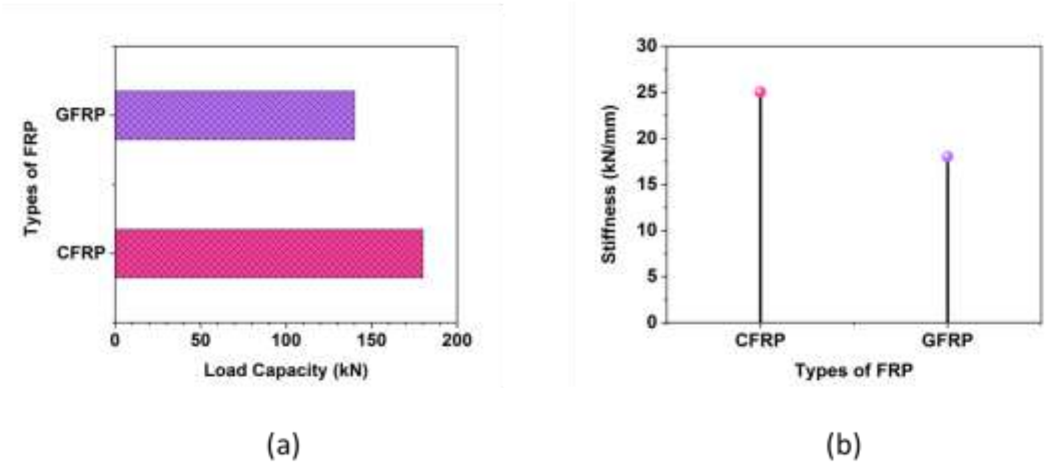

Figure 8. FRP comparison, **(a)** load capacity; **(b)** stiffness.

The load capacity of CFRP was 180 kN and GFRP was 140 kN. The stiffness provided by GFRP was 18 kN/mm and CFRP provided 25 kN/mm. This performance shows that the utilization of CFRP is improved more than the GFRP in improving the capacity of bearing for concrete structures.

Crack propagation rate: On the basis of fracturing mechanics, the stress crack propagation rate for constant frequency loads is frequently determined in Equation (3).

$$Crack\ Propagation\ Rate = D_x \Delta L^n \quad (3)$$

The material constants are D_x and n used together with the stress crack propagation rate and the stress intensity component range ΔL.

Bond strength at anchorage: The connection strength between bars and material is determined from the measurement of tensile strength by the concrete structure design standard, avoiding the influence of the bar type, stainless bar dimensions, anchorage measurement, and covering thickness. Equation (4) shows the basic bond strength evaluation. **Figure 9** represents the comparison of both types of FRP (**Figure 9a**) crack propagation rate and (**Figure 9b**) bond strength at anchorage.

$$\tau_{max} = \frac{q_{max}}{R.k_c} \quad (4)$$

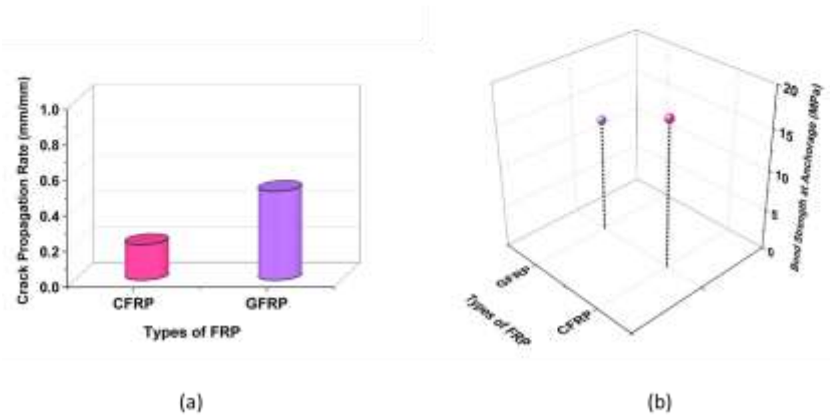

Figure 9. Comparison of (**a**) crack propagation rate; and (**b**) bond strength at anchorage.

The performance of the CFRP (0.2 mm/min) and GFRP (0.5 mm/min) in the crack propagation was demonstrated. Anchorage bond strength of GFRP (14 MPa) and CFRP (18 MPa) is presented and it showed that the CFRP performance in bearing capacity was more significant compared to the GFRP-reinforced beams.

Failure mechanism: The composites' thickness direction, fiber fracture, and breakdown are observed. Depending on compressive load, the fiber kinking failure pattern was observed.

4.3. Discussion

This research enhances the bearing capacity of CFRP-reinforced concrete beams through biomechanical design concepts focusing on bond behavior and anchorage reinforcement by Huang et al. [11]. The investigation focuses on composite plywood reinforced with carbon fiber, limiting its generalizability to other materials and structures due to its emphasis on three-point bending by Song et al. [12]. The analyzed and reveals that current design specifications for BFRP-SWSSC beams are inconsistent in predicting deflection, necessitating further refinement for more accurate serviceability predictions by Maidi et al. [13]. The research highlights limitations, including the need for a reduced stirrup ratio for optimal reinforcement effects and challenges in ensuring consistent bonding and durability in real-world applications. CFRP in structural reinforcement, including high tensile strength, lightweight properties, and excellent resistance to corrosion and fatigue. It significantly enhances the load-bearing capacity, stiffness, and durability of structures while minimizing crack propagation. CFRP is also versatile and easy to apply, making it ideal for strengthening and retrofitting concrete structures in various conditions. The proposed CFRP design is overcome by enhancing bond strength and anchorage through biomechanical optimization, improving load-bearing capacity and crack resistance. It ensures consistent performance and resolves deflection prediction inconsistencies in current design standards.

5. Conclusion

To increase the capability of loads in RC components, the application of CFRP beams in concrete structures was suggested as an alternate possibility for conventional steel reinforcement. Considering the well-established advantages of CFRP, its applications have been limited by difficulties such as its poorer flexibility, decreased durability of bonds with repeated loads, and elastic response. The ability of bearing in seven slender RC beams with CFRP was investigated using biomechanical principles to optimize reinforcement design as the bearing loads increased. Biomechanical design solutions that involved anchorage confinement (90%) and the anchorage lengths (600 mm) of CFRP bars have been demonstrated to influence cracking behavior and improve overall bearing capacity. It examined important performance metrics like bond strength at anchorage (18 MPa), failure processes that provided the failure reduction, crack propagation (0.2 mm/min), load capacity (180 kN), and stiffness (25 kN/mm). Special emphasis was given to the bond behavior at these anchorage lengths.

Limitations and future scope

The limitations presented in this assessment include the utilization of minimum beams and static loading that could not reliably reflect the dynamic loads presented in the actual instances. The effectiveness of CFRP reinforcement in dynamic, seismic, and environmental circumstances could be investigated in further investigations. The creation of more economical, environmentally friendly materials and effective CFRP repair approaches could expand the utilization of the material in building.

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