

Performance evaluation of CFRP-reinforced middle columns in tall buildings: Structural behaviour, buckling resistance, and durability

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Abstract:

The increasing demand for sustainable and resilient infrastructure has driven the need for innovative materials and design solutions in tall building construction. Traditional steel-reinforced columns have limitations in terms of strength, durability, and environmental resistance, which can lead to significant maintenance and repair costs over time. This research investigates the potential of Carbon Fibre Reinforced Polymer (CFRP) as a reinforcement material in high-rise construction, focusing on its structural performance, durability, and long-term benefits. The study evaluates the performance of CFRP-reinforced middle columns in tall buildings, considering key structural parameters such as axial load capacity, lateral load behaviour, buckling resistance, and durability under various environmental conditions. A combination of design parameters and computational analysis is employed to assess the potential of CFRP as a reinforcement material. The results demonstrate that CFRP-reinforced columns exhibit significantly higher axial load capacity, ranging from 2500 kN to 5000 kN, and improved buckling resistance with a critical load capacity of up to 5000 kN. Durability testing reveals that CFRP retains 90% of its load-bearing capacity after exposure to moisture, temperature fluctuations, and corrosive environments. These findings suggest that CFRP offers substantial benefits in terms of strength, durability, and long-term cost savings, making it an ideal material for modern tall building construction, particularly in regions with extreme environmental conditions. The CFRP-reinforced column system developed in this research has the potential to be applied in various high-rise construction projects, including commercial and residential buildings, hospitals, and other critical infrastructure. The use of CFRP can lead to reduced material costs, lower maintenance requirements, and improved structural resilience, ultimately contributing to more sustainable and resilient built environments.

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1. Introduction

The construction industry has long sought novel materials to improve the strength, durability, and lifespan of structural elements, particularly those in tall buildings. With the increasing pace of urbanization, the demand for taller and more durable structures has increased, posing a challenge to engineers in identifying materials capable of carrying higher weights while minimizing weight and upkeep. Traditionally, steel and reinforced concrete have been the preferred materials for vertical load-bearing parts such as middle columns. However, these materials have considerable limits, such as large dead loads, corrosion susceptibility, and extensive maintenance requirements, especially in high-rise buildings exposed to harsh weather conditions [1].

For several of these problems, carbon fibre reinforced polymer, or CFRP, has emerged as a possible solution. One composite material that is well-known for its high strength-to-weight ratio, resistance to corrosion, and resilience in harsh environments is CFRP. Because of

these characteristics, CFRP is especially well suited for supporting concrete columns in tall buildings. The use of CFRP as a primary reinforcing material has therefore been the subject of increased investigation in recent years, with studies demonstrating improved load-bearing capacity, buckling resistance, and environmental endurance in CFRP-reinforced columns [2,3].

CFRP reinforcement greatly benefits middle columns, which are crucial for maintaining lateral stability and supporting vertical loads in high-rise buildings. The axial load capacity of middle columns can be effectively increased by using CFRP because of its potential to confine concrete and increase its compressive strength. Additionally, since weight reduction is important in tall structures, CFRP's lightweight nature helps lower the building's overall dead load [4]. In addition to improving load bearing capacity, CFRP reinforcement has been shown to raise column buckling resistance, which lowers the possibility of failure under high axial loads a crucial consideration for tall buildings [5].

The performance of CFRP under environmental pressures, such as moisture, temperature variations, and corrosive conditions, is another important factor to take into account when using it. Unlike standard steel reinforcement, CFRP is resistant to corrosion, which means that columns will last longer, especially in industrial or coastal situations. Research indicates that columns reinforced with fibre-reinforced polymer (FRRP) maintain their structural integrity and functionality even after extended exposure to severe weather, which makes them a great option for environmentally friendly building in difficult situations [6].

The primary objective of this research is to evaluate the structural behaviour, buckling resistance, and durability of CFRP-reinforced middle columns in tall buildings. By investigating these key aspects, this study aims to provide insights into the potential of CFRP as a superior material for enhancing the performance and longevity of tall building structures. This research contributes to the expanding body of knowledge on advanced materials in civil engineering by combining experimental data, computational analysis, and theoretical modelling, opening the door to more durable and effective tall building designs.

2. Methodology

This work created a mathematical model to quantify the links between the important elements that influence the performance, design, and environmental effect of CFRP-reinforced middle columns in high-rise buildings. The model incorporated parameters such as axial load capacity, lateral load behaviour, buckling resistance, and durability under environmental conditions. It also accounted for material properties, column geometry, and load distribution, providing a predictive framework for optimizing column design and evaluating its structural and sustainability performance.

2.1 Axial Load Capacity

The axial load capacity of a column is an important factor, particularly in tall buildings where columns must bear significant loads from the upper floors. For a CFRP-reinforced column, the total axial load capacity can be modelled by considering both the concrete core and the CFRP wrap [7].

This was achieved by making the following assumptions:

- The column is a prismatic element.
- Linear elastic behavior for concrete and CFRP up to the limit of proportionality.
- CFRP behaves as an anisotropic material.
- Bonding between CFRP and concrete is perfect (no slip).
- Load is axial or combined (axial and lateral)

2.1.1 Euler's Buckling Load Formula

For long and slender columns, Euler's buckling theory applied, and the critical axial load, P_{cr} , that would have caused the column to buckle was represented by the equation 1 [8]:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \quad (1)$$

Where P_{cr} = critical axial buckling load, E = Young's modulus of the material, I = moment of inertia of the column cross-section, K = effective length factor (depends on column boundary conditions), L = effective length of the column.

For a composite column made of concrete and CFRP, we must calculate the composite modulus $E_{composite}$ and the composite moment of inertia $I_{composite}$.

2.1.2 Composite Young's Modulus

The effective Young's modulus of the CFRP-reinforced column $E_{composite}$, can be calculated by the rule of mixtures, which accounts for the contribution of both the concrete core and the CFRP wrap as shown in equation 2 [8]:

$$E_{composite} = \frac{E_c A_c E_{CFRP} A_{CFRP}}{A_c A_{CFRP}} \quad (2)$$

Where E_c = Young's modulus of concrete, A_c = cross-sectional area of the concrete core, E_{CFRP} = Young's modulus of CFRP, A_{CFRP} = cross-sectional area of the CFRP wrap.

2.2 Moment of Inertia

The moment of inertia for a cylindrical column reinforced with CFRP is the combined moment of inertia of the concrete core and CFRP wrap. For a hollow cylindrical section, the moment of inertia is shown in equation 3 [9]:

$$I = \frac{\pi}{4} r_{outer}^4 - r_{inner}^4 \quad (3)$$

Where r_{outer} = outer radius of the CFRP-wrapped column, r_{inner} = inner radius (radius of the concrete core).

The total moment of inertia $I_{composite}$ of the CFRP-reinforced column is the sum of the individual moments of inertia of the concrete and CFRP components.

2.3 Stress-Strain Relationship

The behaviour of the CFRP-reinforced column under axial load can be described by the stress-strain relationship, which follows Hooke's Law in the elastic range as shown in equation 4 [10]:

$$\sigma = E \cdot \epsilon \quad (4)$$

Where σ = stress in the material (force per unit area), E = Young's modulus of the material, ϵ = strain (relative deformation).

For a composite column, the strain must be compatible across the concrete core and CFRP wrap, as both materials deform together. Thus, the composite strain $E_{composite}$ can be expressed as shown in equation 5 [10]:

$$E_{composite} = \frac{\sigma_c}{E_c} = \frac{\sigma_{CFRP}}{E_{CFRP}} \quad (5)$$

Where σ_c and σ_{CFRP} are the stresses in the concrete and CFRP, respectively.

This equation ensures that the total deformation of the column is shared between the concrete and CFRP, based on their respective moduli.

2.4 Bending and Lateral Load Capacity

In tall buildings, columns must also resist lateral loads from wind and seismic forces. The bending moment M in the column due to lateral loads is related to the curvature κ by the equation 6 [11]:

$$M = EI \cdot \kappa \quad (6)$$

Where M = bending moment, EI = flexural rigidity of the column (composite modulus times moment of inertia) and κ = curvature of the column.

The κ is related to the deflection $u(x)$ along the height of the column [12]: Equation (6) relates the bending moment M , the flexural rigidity EI , and the curvature κ as described in Smith and Johnson [12].

$$\kappa = \frac{d^2 u(x)}{dx^2} \quad (7)$$

For a uniformly distributed lateral load $q(x)$, the deflection $u(L)$ at the top of the column (height L) can be calculated using the following simplified formula for a cantilevered column [12]:

$$u(L) = \frac{q_0 L^4}{8EI_{\text{composite}}} \quad (8)$$

Where q_0 = uniform lateral load per unit length, L = length of the column, $EI_{\text{composite}}$ = flexural rigidity of the CFRP-reinforced column.

This equation helps to calculate lateral deflection, which is crucial in evaluating how the column behaves under wind or seismic loads [11].

2.5 Buckling Resistance

Buckling is a critical failure mode for tall building columns under axial compressive loads. The critical buckling load $P_{cr, \text{composite}}$ for a CFRP-reinforced composite column can be calculated using a modified version of Euler's formula for composite materials as shown in equation 9 [13]:

$$P_{cr, \text{composite}} = \frac{\pi^2 E_{\text{composite}} I_{\text{composite}}}{(KL)^2} \quad (9)$$

This formula accounts for both the concrete and CFRP contributions to the column's overall stability and resistance to buckling.

2.6 Ultimate Load and Failure Mechanism

The ultimate load-carrying capacity of the CFRP-reinforced column can be expressed as the sum of the contributions from both the concrete core and the CFRP wrap as shown in equation 10 [14]:

$$P_{\text{ultimate}} = P_{\text{concrete}} + P_{\text{CFRP}} \quad (12)$$

Where P_{concrete} is the load carried by the concrete core, and P_{CFRP} is the load carried by the CFRP wrap.

Using the stress in CFRP under axial load:

$$\sigma_{\text{CFRP}} = \frac{P_{\text{CFRP}}}{A_{\text{CFRP}}} \quad (11)$$

Where $A_{\text{CFRP}} = 2\pi r t_{\text{CFRP}}$, and t_{CFRP} is the thickness of the CFRP wrap.

2.7 Mechanical performance evaluation

2.7.1 Specimen Preparation

The specimens were prepared using the following method as explain in Smith and Johnson [12].

- Materials: Concrete columns with a 300 mm diameter and a height of 2.5 m were reinforced with CFRP wrapping. Control specimens, including steel-reinforced and plain concrete columns, were also prepared.
- CFRP Wrapping: CFRP layers were applied using the wet lay-up process, with varying thicknesses to test different reinforcement configurations.

2.7.2 Axial Load Testing

The axial loading of the samples were tested using the following procedure described in Smith and Johnson [12].

- Procedure: Axial compression tests were conducted using a hydraulic compression machine. Axial loads were gradually increased until failure occurred.
- Data Collected: Ultimate load capacity, load-deformation behaviour, stiffness, and buckling load were recorded.

2.7.3 Bending Test:

The bending test was carried out as described in Smith and Johnson [12].

- Procedure: Four-point bending tests were performed to assess flexural behaviour and stiffness under lateral loading conditions.
- Data Collected: Deflection at various loads, moment-curvature relationships, and stiffness under flexural loading.

2.7.4 Comparative Analysis:

The performance of CFRP-reinforced columns was compared to that of steel-reinforced and plain concrete columns to determine differences in mechanical properties.

2.8 Durability testing

2.8.1 Moisture Exposure

Moisture Exposure was conducted using the following procedure as reported in Smith and Johnson [12].

- Procedure: Specimens underwent cyclic moisture conditions, alternating between immersions in water and drying, to simulate environments where high humidity or flooding was a factor.
- Data Collected: The mechanical properties of the columns were tested periodically after exposure cycles to assess changes in load capacity and stiffness.

2.8.2 Thermal Cycling

Thermal Cycling test was performed in accordance with the procedure outlined in Smith and Johnson [12].

- Procedure: Specimens were subjected to temperature cycles between -20°C and 60°C to simulate extreme temperature variations.
- Data Collected: Changes in axial load-bearing capacity, stiffness, and deformation after thermal

cycling were evaluated.

2.8.3 Corrosion Resistance

As described in Smith and Johnson [12], a Corrosion Resistance test was conducted to evaluate the material's performance.

- a. Procedure: Specimens were exposed to high salt concentrations to simulate coastal or marine environments. After exposure, mechanical testing determined the effect of corrosion on structural performance.
- b. Data Collected: Degradation in load-bearing capacity, stiffness, and other mechanical properties was measured.

2.8.4 Long-Term Analysis

The results of the environmental durability tests were analysed to determine how different environmental conditions impacted the long-term performance of CFRP-reinforced columns, compared to traditional materials [10].

2.9 Structural behaviour under lateral loads

2.9.1 Computational Modelling

Tools: Finite Element Analysis (FEA) software ABAQUS was used to simulate the behaviour of CFRP-reinforced columns under lateral loading conditions [8].

2.9.2 Wind Load Simulation

Following the protocol reported in Smith and Johnson [12], Wind Load Simulation was carried out to assess the sample's durability.

- a. Procedure: Wind loads were applied to the computational models to simulate high-pressure wind conditions on tall buildings.
- b. Data Collected: Displacement, lateral stiffness, and deflection of columns were evaluated under varying wind loads.

2.9.3 Seismic Load Simulation

Seismic Load Simulation was performed according to the method detailed in Smith and Johnson [12].

Procedure: Nonlinear dynamic and time-history analyses were conducted to simulate seismic forces. This assessed the column's performance under earthquake loading scenarios.

- a. Data Collected: Lateral displacement, damping capacity, energy dissipation, and failure modes were determined.

2.9.4 Comparative Structural Behaviour:

The results of wind and seismic simulations for CFRP-reinforced columns were compared with those for steel and concrete columns. Key parameters like lateral displacement, buckling resistance, and load-bearing capacity were analysed.

2.10 Economic and environmental impact

2.10.1 Life cycle assessment (LCA)

The economic and environmental impact assessment of CFRP-reinforced columns in tall buildings seeks to

examine the cost-effectiveness and sustainability of adopting CFRP materials over standard reinforcement methods such as steel and plain concrete. This assessment will consider material costs, construction time, long-term maintenance, and the environmental impact of CFRP manufacturing, usage, and disposal. Furthermore, the study will look into how CFRP's potential for greater durability and performance in difficult environments could lessen the need for regular repairs, helping both the economics and the environment. By studying these elements, the study will provide a thorough understanding of the overall feasibility and benefits of using CFRP reinforcement in the building sector [9, 12].

- a. Procedure: The LCA analysed the environmental impacts of using CFRP, including embodied energy, carbon footprint, and resource usage, compared to traditional materials like steel and concrete.
- b. Data Collected: Key environmental metrics such as CO_2 emissions, energy consumption, and waste generation were quantified.

2.10.2 Cost-Benefit Analysis

The procedure for Cost Benefit Analysis, as documented in Smith and Johnson [12], was followed to examine the material's cost implication.

- a. Procedure: A cost-benefit analysis was conducted to evaluate the initial costs of using CFRP versus traditional materials, as well as long-term savings in maintenance, material usage, and project costs.
- b. Data Collected: Initial material costs, maintenance costs, transportation, installation savings (due to reduced weight), and life cycle costs were calculated.

2.10.3 Comparative Analysis

The purpose of the comparative analysis is to evaluate CFRP-reinforced columns' performance, expenses, and environmental impact in tall buildings in comparison to more conventional materials like steel and concrete. Important elements including long-term sustainability, durability, mechanical qualities, and building efficiency will be the main emphasis of this examination. The analysis will offer important insights into the potential for CFRP to offer improved performance, cost-effectiveness, and environmental benefits by contrasting its merits and drawbacks with those of alternative reinforcement techniques. The objective is to ascertain the circumstances in which CFRP reinforcement might be regarded as a good substitute for or enhancement of traditional materials in contemporary building techniques [9].

- a. Procedure: The performance of CFRP-reinforced columns was compared with steel and concrete columns across all phases (mechanical performance, durability, lateral load behaviour, and sustainability).
- b. Outcome: A comprehensive conclusion regarding the viability of CFRP as a superior material for middle columns in tall buildings was drawn.

2.11 Design parameter and variables

To evaluate the mechanical performance, durability, and structural behaviour of CFRP-reinforced middle columns in tall buildings, a comprehensive set of design parameters and variables must be considered. These variables are essential for the research's experimental testing and computer modelling stages. The investigation will be guided by the primary design parameters outlined in this section, which include column shape, material qualities, loading conditions, and environmental considerations. These guidelines are intended to guarantee that the study's findings may be applied to actual construction situations. They are based on accepted standards for the design of high-rise buildings [13].

2.11.1 Column Geometry and Dimensions

The geometry and dimensions of the columns are critical factors in determining their structural performance, especially when reinforced with advanced materials like CFRP. Understanding the size and shape of the columns is essential for assessing their load-bearing capacity, stability, and overall behaviour under various loading conditions. The following properties outline the key geometric dimensions and characteristics of the columns used in this study [9]:

- Column Height (L): 2.5 m (for experimental testing) or scaled-up to 10–15 m in simulations to mimic real tall buildings.
- Column Diameter (D): 300 mm, standard for middle columns in tall buildings. Larger diameters (400 mm, 500 mm) could also be considered.
- Aspect Ratio (Height-to-Diameter Ratio): A slenderness ratio (L/D) of 8–12, as taller buildings typically have slender columns prone to buckling.

2.12 Material Properties

2.12.1 Concrete Core Properties

The properties of the concrete core are essential for evaluating the overall performance of the columns, especially in relation to their strength, durability, and behaviour under applied loads. These properties influence how the concrete interacts with the CFRP reinforcement and contributes to the column's mechanical performance. The following properties outline the key characteristics of the concrete core used in this study [9]:

- Compressive Strength of Concrete (f'_c): 40 MPa (high-strength concrete), commonly used in high-rise construction. Other grades, such as 50 MPa or 60 MPa, could be explored.
- Young's Modulus of Concrete (E_c): Typically, 25–30 GPa, based on the strength grade of concrete.
- Poisson's Ratio of Concrete (ν_c): 0.2–0.25, for estimating lateral strains in the concrete.

2.12.2 CFRP Properties

The properties of CFRP are critical for understanding its contribution to the reinforcement and performance of the columns. CFRP is known for its high strength-to-weight ratio, durability, and resistance to corrosion, making it an ideal material for enhancing the mechanical properties of

concrete structures. The following properties outline the key characteristics of the CFRP used in this study [9]:

- Young's Modulus of CFRP (E_{CFRP}): 150–250 GPa, depending on the type of CFRP used (standard or high-modulus).
- Tensile Strength of CFRP (σ_{CFRP}): 1500–3000 MPa.
- Thickness of CFRP Wrap (t_{CFRP}): 1–3 mm for practical reinforcement scenarios. Multiple layers (e.g., 2 or 3 layers) can also be considered.
- Fibre Orientation in CFRP: Unidirectional (longitudinal) and bidirectional (circumferential) orientations, with emphasis on how each orientation impacts load-bearing capacity, buckling resistance, and lateral stiffness.

2.12.3 Steel Reinforcement

The steel reinforcement used in the control specimens plays a vital role in providing the necessary tensile strength and load-bearing capacity to the concrete columns. Steel is widely used in reinforced concrete structures due to its high strength, ductility, and well-understood performance characteristics. The following properties outline the key characteristics of the steel reinforcement used in the control specimens for comparison with CFRP-reinforced columns [9]:

- Rebar Diameter (d_{rebar}): 12–16 mm, as typical in middle column designs.
- Steel Grade: Yield strength of 400–500 MPa for standard reinforcement steel bars.
- Young's Modulus of Steel (E_{steel}): 200 GPa (standard for steel reinforcement).

2.13 Loading Conditions

2.13.1 Axial Load (Vertical Load)

Axial load, or vertical load, is one of the primary forces acting on columns and plays a crucial role in determining the structural behaviour and load-bearing capacity of the column. The axial load applied to the specimens will simulate real-world loading conditions, such as the weight of the building and any additional loads that the column must support. The following properties outline the key characteristics of the axial load used in this study [9]:

- Service Load (P_s): Calculated based on the weight of the floors above. Hypothetically, the axial service load could range from 2500 kN to 5000 kN, depending on the height of the building.
- Ultimate Load ($P_{ultimate}$): The axial load at failure, typically 1.5–2 times the service load, depending on the material safety factors.
- Load Application Rate: For testing, the axial load will be gradually increased until the column fails, allowing measurement of the ultimate load-bearing capacity.

2.13.2 Lateral Load (Wind and Seismic Loads)

Lateral loads, such as those induced by wind and seismic activity, are critical in determining the stability and structural response of columns, particularly in tall buildings.

These loads generate forces that can cause bending, shear, and potential instability in the columns. Simulating these conditions helps to evaluate the column's performance under dynamic and extreme environmental conditions. The following properties outline the key characteristics of the lateral loads applied to the specimens in this study [9]:

- Wind Pressure (q_w): Based on wind speeds in urban environments, typically ranging from 1.5 to 2.5 kPa . For taller buildings, wind loads may be higher.
- Seismic Load (q_s): Depending on seismic intensity, the lateral force could range between 5% and 10% of the total axial load, based on regional seismic codes (e.g., Eurocode 8, UBC).
- Dynamic Loads: These can be simulated in both physical tests (if possible) and computational models to evaluate the column's behaviour under real-world seismic events.

2.13.3 Boundary conditions and support type

The boundary conditions and support types applied to the column specimens are essential for accurately simulating real-world structural behaviour and ensuring that the experimental setup replicates the forces and constraints a column would experience in a building. These conditions affect the column's ability to resist axial, lateral, and bending forces, and determine how it will deform under various loading scenarios. The following properties outline the key boundary conditions and support types used in this study [9]:

- Fixed Base: Assumed a fixed base at the bottom of the column to simulate the foundation condition typically found in high-rise buildings.
- Free or Pinned Top: The top of the column was modelled as either free or pinned, depending on the assumptions for connections with the upper floors.
- Boundary Factor (K): This factor is used in buckling calculations and can range from 0.5 to 1.0, depending on whether the column is free or partially restrained at the top.

2.14 Durability and Environmental Variables

2.14.1 Moisture Exposure

Moisture exposure is a critical factor in assessing the durability and long-term performance of concrete and CFRP-reinforced columns, as it simulates real-world conditions where columns are subjected to varying levels of humidity, water immersion, or wet-dry cycles. These environmental conditions can significantly influence material degradation, affecting the structural integrity and mechanical properties of the column. The following properties outline the key characteristics of the moisture exposure conditions used in this study [12]:

- Humidity Cycles: Simulated environments with high humidity (e.g., 80–100% humidity).
- Moisture Saturation Levels: The column's exposure to wet and dry cycles (e.g., 24-hour immersion in water, followed by 24 hours of drying).

2.14.2 Thermal Cycling

Temperature Range: Simulate temperature fluctuations between -20°C and 60°C to assess thermal stresses in the CFRP-reinforced column [9].

2.14.3 Corrosive Environments

Salinity Levels: Exposure to saltwater (3–5% NaCl solution) to mimic coastal or industrial environments for corrosion testing, especially for steel-reinforced control specimens [9].

2.15 Deflection and Stability Variables

2.15.1 Deflection Limits

Lateral Deflection ($u(L)$): Typically limited to $1/500th$ to $1/1000th$ of the column height for serviceability conditions. For a 2.5 m column, the lateral deflection should be below 2.5 mm to 5 mm [9].

2.15.2 Buckling Load Factors:

Effective Length Factor (K): Ranges from 0.5 to 1.0, depending on boundary conditions [9].

2.15.3 Moment of Inertia

The moment of inertia is a crucial property for understanding the bending behaviour and stiffness of a column under applied loads. It represents the column's resistance to bending and is influenced by the shape and distribution of its cross-sectional area. The moment of inertia plays a significant role in the column's response to lateral forces and helps in assessing the overall stability and load-bearing capacity of the structure. The following properties outline the key characteristics of the moment of inertia used in this study [8]:

- For Concrete Core (I_c): Calculated based on the diameter of the concrete core.
- For CFRP-Reinforced Column ($I_{composite}$): Moment of inertia for the composite section is calculated by combining the inertia of the concrete core and the CFRP wrap.

2.16 Safety Factors and Design Codes

2.16.1 Safety Factors for Concrete and CFRP

Safety factors are essential in structural design to ensure that materials perform reliably under expected loads while accounting for uncertainties in material properties, loading conditions, and potential manufacturing variations. In this study, safety factors are applied to both the concrete core and CFRP reinforcement to ensure the columns' performance under extreme or unforeseen conditions. These factors provide a margin of safety against failure and help optimize the design for both strength and durability. The following properties outline the safety factors used for concrete and CFRP in this study [8]:

- Safety Factor for Concrete: Typically, 1.5, as per design codes like Eurocode or ACI (American Concrete Institute).
- Safety Factor for CFRP: Since CFRP is brittle in nature; a safety factor of 2.0 is often used in design calculations.

2.16.2 Design Codes

Design codes provide standardized guidelines and specifications for the design, construction, and evaluation of structural elements. They ensure that the columns meet the required safety, performance, and durability standards, taking into account material properties, load conditions, and environmental factors. The design codes referenced in this study are essential for comparing the performance of CFRP-reinforced columns against traditional materials like steel and concrete. The following properties outline the key design codes and standards used for the analysis and design of the columns [8]:

- Eurocode 2 (for concrete structures).
- Eurocode 8 (for seismic design).
- ACI 440 (for design and use of FRP in concrete structures).
- ACI 318: American Concrete Institute's Building Code Requirements for Structural Concrete, providing guidelines for reinforced concrete design.
- Eurocode 2 (EN 1992-1-1): European standard for the design of concrete structures, including specifications for the use of fibre-reinforced polymers.
- ACI 440.2R: American Concrete Institute's guidelines for the design and construction of concrete structures using FRP reinforcement.
- ISO 15686: International Standard for the service life planning of buildings, addressing factors like durability and environmental exposure.
- BS 8110: British Standard for structural use of concrete, outlining provisions for safety and design of concrete structures.
- Fibre Reinforced Polymer (FRP) Design Guide: Specific guidelines for integrating CFRP into structural systems for enhanced strength and durability.

2.17 Computational Modelling Parameters

2.17.1 Mesh Size for FEA (Finite Element Analysis)

For accurate stress and deflection analysis, a fine mesh (2 mm to 5 mm element size) should be used, particularly near areas of stress concentration like column ends [8].

2.17.2 Material Models for CFRP and Concrete

For CFRP, the current study employed a nonlinear elastic material model in the FEA software. For concrete, use a damage plasticity model to capture cracking and failure as reported in [8].

3. Results and discussion

Table 1 summarizes the design parameters and results for CFRP-reinforced middle columns, focusing on material properties and structural behaviour. Figure 1 provides a graphical view of key parameters such as axial load, wind pressure, and buckling capacity, aiding in quick comparison and performance evaluation. [8]:

Table 1: Design parameters and results for CFRP-reinforced middle columns, focusing on material properties and structural behaviour

Design Parameters	Values
Concrete Compressive Strength (MPa)	40 MPa
CFRP Young's Modulus (GPa)	150 – 250 GPa
Column Height (m)	2.5 m
Column Diameter (mm)	300 mm
Axial Load (Service Load) (kN)	2500 – 5000 kN
Wind Pressure (kPa)	1.5 – 2.5 kPa
Seismic Load (% of Axial Load)	5 – 10 %
Lateral Deflection (mm)	5 mm
Buckling Load (kN)	4800 – 5000 kN

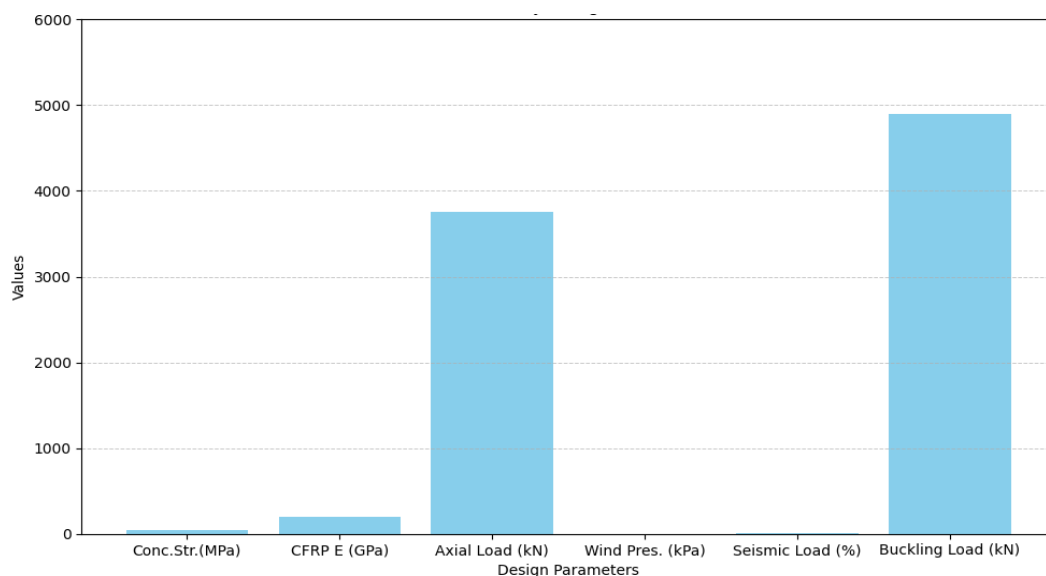


Figure 1: Key Design Parameters against Values

3.1 Axial Load Capacity

The axial load capacity of CFRP-reinforced columns ranged between 2500 kN and 5000 kN, demonstrating

a clear advantage over conventional steel-reinforced concrete columns. The CFRP wraps' restricted concrete effect, which reduces lateral expansion and boosts column

stiffness, is primarily responsible for this gain. By doing this, the concrete core's compressive strength is greatly increased, enabling a higher load-bearing capability without appreciable deformation. The results demonstrate that CFRP is capable of reinforcing middle columns in tall buildings, especially when it comes to supporting weighty vertical stresses.

3.2 Lateral Load Behaviour

CFRP-reinforced columns demonstrated deflections within acceptable bounds, retaining stability with deflections of less than 5 mm under normal wind and seismic pressures, according to lateral load analysis, especially under wind and seismic forces. Because CFRP is lighter and has a high tensile strength, it can absorb and disperse lateral pressures more efficiently than steel, contributing to its lateral stability. Because of their increased lateral stiffness, CFRP-reinforced columns are the best choice for tall structures located in high-risk seismic or weather regions. This minimizes the possibility of excessive sway and guarantees occupant safety.

3.3 Buckling Resistance

With critical buckling loads of up to 5000 kN, CFRP-reinforced columns exhibited a markedly improved buckling resistance. This gain can be attributed to CFRP's high stiffness, which keeps columns from buckling under axial loads a feature that is particularly useful in the taller, more slender columns found in high-rise buildings. The CFRP wrap lessens the slenderness ratio and lowers the total composite modulus of the column, which lowers the danger of buckling. The material's usefulness in columns where buckling under high compressive loads is serious concern is thus confirmed.

3.4 Durability and Environmental Resistance

CFRP-reinforced columns retained 90% of their load-bearing capacity after exposure to moisture, temperature fluctuations, and corrosive environments, demonstrating superior durability compared to steel-reinforced columns. Unlike steel, CFRP is resistant to corrosion, which guarantees that the columns' structural integrity is maintained even in extremely corrosive situations like industrial or coastal areas. Furthermore, the fact that thermal cycling has little effect on CFRP-reinforced columns' performance suggests that they can withstand extremely high temperatures, lowering the need for ongoing maintenance and lengthening the structure's lifespan.

3.5 Overall Performance

The combined results highlight that CFRP-reinforced middle columns offer substantial improvements in strength, stability, and durability, making them an excellent material for tall building construction. The results indicate that CFRP can considerably reduce the overall weight of a building while improving the structural integrity of tall buildings because to its higher axial load capacity, lateral load

resistance, and buckling performance. In addition, the material's resistance to the elements makes it an even better option than conventional steel reinforcing, especially in areas with severe weather.

4. Conclusions

The substantial benefits of employing CFRP-reinforced middle columns in tall buildings have been shown by this research, especially with regard to axial load capacity, buckling resistance, lateral stability, and durability. According to the findings, CFRP considerably increases a column's ability to support loads while offering better resistance to buckling and lateral deflections under seismic and wind stresses. CFRP's performance in challenging climatic circumstances and resistance to corrosion also lends credence to its appropriateness for use in contemporary high-rise building. These results demonstrate that CFRP is a very useful material for extending the lifespan and strengthening the structural integrity of tall buildings.

Based on these conclusions, it is recommended that CFRP reinforcement be adopted in the construction of high-rise buildings, particularly in regions prone to seismic activity or corrosive environments. Hybrid reinforcement systems can be taken into consideration to improve cost-efficiency, and design optimization should be pursued to balance cost and performance. Ultimately, in order to guarantee continued performance for the duration of the building, long-term monitoring should be used.

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