International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 01 | Jan 2026 www.irjet.net p-ISSN: 2395-0072

Experimental and Analytical Study on Axial Compression Behaviour of HYSD and GFRP Reinforced Concrete Columns

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Abstract - *Reinforced concrete columns are primary load-carrying members in structural systems, and their axial compression behaviour plays a crucial role in ensuring structural safety and performance. Conventionally, reinforced concrete columns are provided with high-yield strength deformed (HYSD) steel bars as longitudinal reinforcement. However, durability issues associated with steel corrosion have led to increased interest in alternative reinforcement materials such as glass fibre reinforced polymer (GFRP) bars. In the present study, an experimental and theoretical investigation is carried out to compare the axial compression behaviour of HYSD and GFRP reinforced concrete columns. A total of four reinforced concrete column specimens were cast with identical geometric dimensions and concrete grade, differing only in the type of longitudinal reinforcement. Axial compression tests were conducted to evaluate the ultimate load-carrying capacity, axial deformation behaviour, and failure characteristics of the specimens. The experimental results were further compared with theoretical axial load capacities calculated using established design provisions. The results indicate that HYSD reinforced columns exhibit higher axial load capacity and improved ductility due to the effective contribution of steel reinforcement. In contrast, GFRP reinforced columns showed relatively lower axial strength and a brittle failure response, primarily governed by concrete crushing. The study highlights the influence of reinforcement type on axial performance and provides useful experimental data supporting the potential application of GFRP bars in compression members where durability and corrosion resistance are critical considerations.*

Keywords: **Axial compression behavior; Reinforced concrete columns; High-yield strength deformed (HYSD) steel reinforcement; Glass fiber-reinforced polymer (GFRP) reinforcement Experimental investigation; Theoretical analysis; Failure behavior.**

1. INTRODUCTION

Reinforced concrete (RC) columns are fundamental structural elements responsible for transferring loads safely from the superstructure to the foundation. The performance of columns under axial compression plays a crucial role in ensuring the overall stability and safety of reinforced concrete structures. Traditionally, high-yield strength deformed (HYSD) steel bars have been widely used as longitudinal reinforcement in RC columns due to their high strength, ductility, and well-established design provisions. However, the long-term durability of steel-reinforced concrete structures has become a growing concern, particularly in aggressive environments where corrosion significantly reduces structural capacity and service life.

Corrosion of steel reinforcement leads to cracking, spalling of concrete, reduction in cross-sectional area of reinforcement, and loss of bond between steel and concrete. These deterioration mechanisms can severely affect the axial load-carrying capacity of reinforced concrete columns and may result in premature structural failure. As a result, there has been increasing interest in exploring alternative reinforcement materials that can mitigate corrosion-related issues while maintaining adequate structural performance. Among the various alternatives, fibre reinforced polymer (FRP) bars have gained considerable attention due to their high strength-to-weight ratio, corrosion resistance, and non-magnetic properties.

Glass fibre reinforced polymer (GFRP) bars are one of the most commonly used FRP reinforcements in concrete structures because of their relatively low cost compared to other FRP types such as carbon or aramid fibres. GFRP bars exhibit high tensile strength and excellent resistance to chemical attack; however, their behaviour under compression is significantly different from that of conventional steel reinforcement. Unlike steel, GFRP bars are linear elastic until failure and lack yielding characteristics, this fundamental difference in material behavior results in a comparatively brittle response, raising important concerns regarding the suitability of GFRP bars for use in compression members such as reinforced concrete columns.

Several researchers have investigated the performance of FRP-reinforced concrete columns under axial compression. Experimental studies have shown that while FRP bars can provide confinement and improve durability, their direct contribution to axial load capacity is limited due to their low compressive strength and susceptibility to micro-buckling. Consequently, most design guidelines conservatively neglect the compressive contribution of FRP reinforcement and consider the axial capacity of FRP-reinforced columns to be primarily governed by concrete strength. This conservative

approach often results in lower predicted axial capacities for GFRP-reinforced columns compared to conventional steel-reinforced columns of identical geometry and concrete grade.

Despite these limitations, GFRP-reinforced columns offer significant advantages in terms of durability, especially in structures exposed to marine environments, chemical industries, and regions with high humidity. Therefore, a clear understanding of the axial compression behaviour, failure characteristics, and load–deformation response of GFRP-reinforced concrete columns is essential for evaluating their feasibility as alternatives to conventional steel reinforcement in specific structural applications. A direct experimental comparison between HYSD- and GFRP-reinforced columns under identical conditions offers valuable insight into their relative performance as well as their practical limitations.

In this study, the axial compression behaviour of short reinforced concrete columns (200 × 150 mm cross-section, M30 concrete grade) reinforced with HYSD steel bars and GFRP bars is investigated experimentally. A total of four column specimens were cast, comprising two HYSD-reinforced columns and two GFRP-reinforced columns, all having identical cross-sectional dimensions, concrete grade, and reinforcement detailing. The specimens were tested under concentric axial compression to examine their load-carrying capacity, axial deformation response, crack development, and failure modes. The experimental results were further compared with theoretical axial load capacities obtained using established design approaches to evaluate the accuracy and conservatism of analytical predictions.

The primary objective of this study is to present a clear comparison of the axial compression behaviour of HYSD- and GFRP-reinforced concrete columns, with particular emphasis on differences in strength, deformation characteristics, and failure mechanisms. The findings aim to provide experimental evidence to support informed decision-making regarding the use of GFRP bars in compression members, especially in applications where durability considerations are prioritised over ductility requirements.

1.1 EXPERIMENTAL PROGRAM

The experimental programmed was designed to examine and compare the axial compression behavior of reinforced concrete columns reinforced with high-yield strength deformed (HYSD) steel bars and glass fiber reinforced polymer (GFRP) bars. A total of four short reinforced concrete column specimens were cast and tested under concentric axial compression. Of these, two specimens were reinforced with HYSD steel bars, while the remaining two were reinforced with GFRP bars. All columns were designed with identical geometric dimensions, concrete grade, and reinforcement layout to ensure that the effect of reinforcement type on axial behaviour could be isolated and evaluated accurately.

All column specimens had a rectangular cross-section of **200 mm × 150 mm** and a total height of **1300 mm**. The columns were designed as short columns, and slenderness effects were neglected. The clear cover to reinforcement was maintained at **25 mm** for all specimens. The specimens were designated based on the type of longitudinal reinforcement used.

- **HYSD-1, HYSD-2**: Columns reinforced with HYSD steel bars
- **GFRP-1, GFRP-2**: Columns reinforced with GFRP bars

The concrete grade used for all specimens was **M30**, and identical reinforcement detailing was adopted to maintain consistency across specimens.

1.2 Materials Used

1.2.1 Concrete

Concrete of grade **M30** was used for casting all column specimens. Ordinary Portland cement, fine aggregates, coarse aggregates, and potable water were used in accordance with standard practice. The concrete mix was designed to achieve the target compressive strength at 28 days. Standard cube specimens were cast and tested to verify the compressive strength of concrete before testing the columns.

1.2.2 Reinforcement

- **HYSD steel bars** of **12 mm diameter** were used as longitudinal reinforcement in steel-reinforced columns.
- **GFRP bars** of **12 mm diameter** were used as longitudinal reinforcement in GFRP-reinforced columns.

Each column was reinforced with **four longitudinal bars**, placed symmetrically at the corners of the cross-section. The total area of longitudinal reinforcement was kept the same for both HYSD and GFRP reinforced columns to allow direct comparison.

Lateral reinforcement was provided in the form of **8 mm diameter ties**, spaced uniformly along the length of the column to ensure confinement and prevent premature buckling of longitudinal bars.

1.2.3 Casting and Curing

The reinforcement cages were fabricated as per the design detailing and placed inside the moulds with adequate cover spacers. Concrete was poured in layers and compacted using

mechanical vibration to eliminate air voids. After casting, the specimens were demolded after 24 hours and subsequently cured in water for 28 days to ensure adequate hydration and proper strength development.

1.2.4 Test Setup and Instrumentation

All column specimens were tested under concentric axial compression using a compression testing machine of sufficient capacity. The load was applied axially through steel bearing plates placed at the top and bottom of each specimen to ensure uniform load transfer and minimise eccentricity.

Axial deformation was measured using displacement-measuring devices positioned along the height of the column. The load was applied gradually in incremental stages, allowing the corresponding deformation response to be recorded accurately at each load level. Visual observations were carried out throughout the testing process to monitor crack initiation, crack propagation, and the overall failure behavior of the specimens.

1.2.5 Loading Procedure

The load was applied monotonically under displacement-controlled conditions until failure. At each load increment, axial deformation was recorded, and the specimen was carefully inspected for crack development. Loading was continued until a significant drop in load-carrying capacity was observed, indicating failure of the column.

1.2.6 Failure Observation

The failure modes of the specimens were documented in detail. In the HYSD-reinforced columns, failure was generally characterized by gradual concrete crushing accompanied by visible cracking and yielding of the steel reinforcement. In contrast, GFRP reinforced columns exhibited relatively sudden failure governed by concrete crushing, with limited warning prior to collapse. Crack patterns and failure characteristics were recorded for all specimens for comparison and discussion.

2. THEORETICAL ANALYSIS

The theoretical analysis of column strength was carried out based on the following assumptions:

1. The column is subjected to **pure concentric axial compression**.
2. The column behaves as a **short column**; slenderness effects are neglected.
3. Plane sections remain plane before and after loading.
4. Perfect bond exists between concrete and reinforcement.
5. Concrete crushing governs the ultimate failure of the column.

The analysis for HYSD reinforced columns was carried out using provisions of **ACI 318**, while GFRP reinforced columns were analysed based on recommendations of **ACI 440.1R**. Indian Standard provisions (**IS 456**) were referred to as a supporting framework.

2.1 Axial Capacity of HYSD Reinforced Concrete Columns

For axially loaded **tied reinforced concrete columns**, ACI 318 provides the following expression for nominal axial load capacity:

$$P_n = 0.85 f_c'(A_g - A_s) + f_y A_s$$

Where:

- P_n = nominal axial load capacity (N)
- f_c' = characteristic compressive strength of concrete (MPa)
- A_g = gross cross-sectional area of column (mm^2)
- A_s = area of longitudinal steel reinforcement (mm^2)
- f_y = yield strength of steel reinforcement (MPa)

For tied columns, the **strength reduction factor** is:

$$\phi = 0.65$$

Hence, the **design axial load capacity** is:

$$P_u = \phi P_n$$

In HYSD reinforced columns, both **concrete and steel contribute significantly** to the axial load resistance. The yielding capability of steel reinforcement provides additional strength and ductility, resulting in gradual failure behaviour under axial compression.

2.2 Axial Capacity of GFRP Reinforced Concrete Columns

Unlike steel reinforcement, GFRP bars exhibit **linear elastic behaviour until failure** and do not yield under compression. Experimental and analytical studies have shown that the compressive contribution of GFRP bars is limited due to micro-buckling and low compressive strength. Therefore, ACI 440 recommends **neglecting the compressive contribution of GFRP bars** while estimating axial load capacity.

Accordingly, the nominal axial load capacity of GFRP reinforced concrete columns is expressed as:

$$P_n = 0.85 f_c'(A_g - A_f)$$

Where:

A_f = area of longitudinal GFRP reinforcement (mm^2)

The **strength reduction factor** recommended for FRP-reinforced compression members is:

$$\phi = 0.55$$

Thus, the design axial load capacity is given by:

$$P_u = \phi P_n$$

Since the contribution of GFRP reinforcement in compression is neglected, the axial strength of GFRP reinforced columns is

Primarily governed by concrete strength.

2.3 Comparison Basis

To ensure a fair comparison, the following parameters were kept identical for both HYSD and GFRP reinforced columns:

- Column cross-section: 200 mm × 150 mm
- Concrete grade: M30
- Longitudinal reinforcement area
- Type and spacing of lateral ties
- Loading condition: concentric axial compression

The theoretical axial capacities obtained using the above expressions was compared with experimentally observed ultimate loads to evaluate the effectiveness and conservatism of the analytical models.

2.4 Significance of Theoretical Evaluation

The theoretical analysis provides a baseline for understanding the expected axial performance of reinforced concrete columns with different reinforcement types. Comparison between theoretical and experimental results helps in:

- Assessing the suitability of existing design provisions
- Understanding the influence of reinforcement type on axial capacity
- Evaluation of the adequacy and conservatism of safety margins prescribed by design codes.

3. THEORETICAL ANALYSIS Results

3.1 General

This section presents the experimental results obtained from axial compression tests on HYSD- and GFRP-reinforced concrete columns and discusses their behavior in comparison with theoretical predictions. The performance of the columns is evaluated in terms of ultimate load-carrying capacity, axial deformation response, crack development, and failure modes. The experimental findings are further compared with theoretical values calculated using relevant design provisions to assess the accuracy and conservatism of the analytical approaches.

3.2 Ultimate Axial Load Capacity

The experimental ultimate axial load for each column specimen was recorded at the point of failure, identified by a pronounced reduction in load-carrying capacity accompanied by visible concrete crushing. These experimental ultimate loads were subsequently compared with the theoretical axial capacities calculated using established analytical expressions.

Table 1. Comparison of Experimental and Theoretical Axial Compression Capacities Load

Specimen	Reinforcement Type	Theoretical Load (kN)	Experimental Load (kN)
HYSD-1	HYSD Steel	**620**	**636.7**
HYSD-2	HYSD Steel	**605**	**637.1**
GFRP-1	GFRP	**405**	**414.4**
GFRP-2	GFRP	**390**	**415**

The results indicate that HYSD-reinforced columns exhibited a higher axial load capacity than GFRP-reinforced columns with identical geometry and concrete grade. This behaviour can be attributed to the combined contribution of concrete and the yielding of steel reinforcement in HYSD columns. In contrast, the axial capacity of GFRP-reinforced columns was governed primarily by the strength of concrete, as the compressive contribution of GFRP bars is relatively limited. The theoretical predictions showed reasonable agreement with the experimental results for both reinforcement types. In the case of GFRP-reinforced columns, the theoretical values closely reflected the dominant role of concrete in resisting axial compression, indicating a generally conservative estimation of their load-carrying capacity.
The predictions were generally conservative, which is consistent with the design assumption that neglects the compressive contribution of GFRP bars.

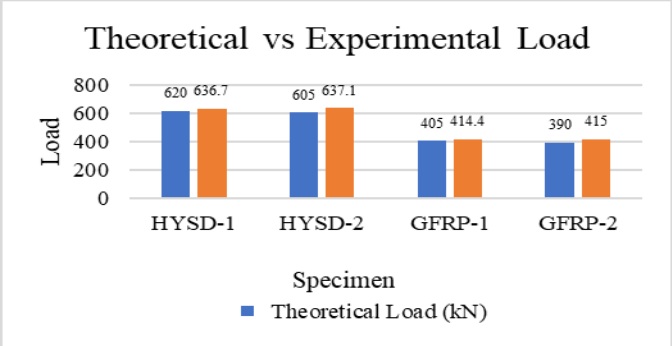

Chart -1: Theoretical vs Experimental Load

3.3 Load–Deformation Behaviour

The axial load–deformation response of the column specimens was obtained by recording axial displacement at successive load increments. The resulting load–deformation curves provide valuable insight into the stiffness

characteristics, deformation capacity, and failure behaviour of the columns.

HYSD-reinforced columns exhibited a gradual increase in axial deformation with increasing load, followed by a relatively ductile post-peak response. The presence of steel reinforcement facilitated stress redistribution after concrete cracking, leading to a more controlled and progressive failure mechanism.

In contrast, GFRP-reinforced columns demonstrated a lower deformation capacity and a steeper load–deformation response up to failure. Once the peak load was reached, failure occurred abruptly with minimal warning, indicating a brittle response. This behaviour is consistent with the linear elastic nature of GFRP bars and the absence of yielding under compressive loading.

3.4 Crack Pattern and Failure Modes

Crack initiation in all specimens was first observed at relatively higher load levels, indicating that the concrete carried the majority of the axial load during the initial stages of loading. With further increase in load, vertical and inclined cracks developed progressively along the height of the columns.

3.4.1 HYSD Reinforced Columns

HYSD-reinforced columns exhibited multiple fine cracks distributed along the surface of the specimens. Failure was characterized by progressive concrete crushing, typically occurring near the mid-height or ends of the columns, accompanied by yielding and minor buckling of the longitudinal steel bars. The failure process was gradual and provided clear visual warning prior to collapse.

3.4.2 GFRP Reinforced Columns

GFRP-reinforced columns exhibited fewer but wider cracks. Failure occurred primarily due to sudden crushing of the concrete, with little prior deformation, reflecting the brittle nature of the response of **concrete**, with minimal contribution from the GFRP bars. The absence of yielding in the GFRP reinforcement led to abrupt failure with minimal post-peak deformation.

3.5 Comparison between HYSD and GFRP Reinforced Columns

A direct comparison between HYSD- and GFRP-reinforced columns clearly highlights the influence of reinforcement type on axial compression behaviour:

• HYSD-reinforced columns demonstrated higher axial load capacity along with improved ductility.

• GFRP-reinforced columns exhibited lower strength and a predominantly brittle failure mode governed by concrete crushing.

• Theoretical predictions were generally more conservative for GFRP-reinforced columns due to the neglect of the compressive contribution of FRP bars.

• Despite the reduced axial capacity, GFRP reinforcement offers significant advantages in terms of corrosion resistance and long-term durability, making it suitable for selected applications where durability requirements outweigh strength and ductility demands.

3.6 Discussion on Design Implications

The results of this study indicate that, although GFRP bars are effective in enhancing durability, their application in compression members should be approached with caution due to the associated reduction in axial strength and ductility. HYSD reinforcement remains more suitable for columns where high axial load capacity and ductile behaviour are critical performance requirements. Nevertheless, GFRP-reinforced columns may offer advantages in environments where corrosion resistance is a primary concern and the imposed load demands are moderate.

The experimental findings also confirm the conservative nature of current theoretical design approaches for GFRP-reinforced columns, highlighting the need for further experimental investigations to refine and improve existing design provisions.

4. CONCLUSIONS

Based on the experimental investigation and theoretical analysis of short reinforced concrete columns reinforced with HYSD steel bars and GFRP bars under axial compression, the following conclusions are drawn:

1. The axial compression behaviour of reinforced concrete columns is strongly influenced by the type of longitudinal reinforcement employed. HYSD-reinforced columns demonstrated a higher axial load-carrying capacity than GFRP-reinforced columns with identical geometry and concrete grade.

2. The experimental results indicate that HYSD-reinforced columns exhibited more ductile behaviour, characterised by gradual concrete crushing and clear warning prior to failure. The yielding capacity of the steel reinforcement contributed significantly to enhanced deformation capacity and an improved post-peak response.

3. GFRP-reinforced columns exhibited comparatively lower axial strength and a brittle failure response. Failure was primarily governed by sudden concrete

crushing, with minimal contribution from the GFRP bars in resisting compressive forces.

4. The theoretical axial capacities calculated using established design provisions showed good agreement with the experimental results for both reinforcement types. The variation between experimental and theoretical values remained within acceptable limits, demonstrating the reliability of the analytical models.

5. The conservative nature of the theoretical predictions for GFRP-reinforced columns can be attributed to design assumptions that neglect the compressive contribution of GFRP bars. While this approach ensures an adequate margin of safety, it may lead to an underestimation of the actual axial capacity.

6. Although GFRP-reinforced columns exhibited lower axial capacity than HYSD-reinforced columns, the use of GFRP bars offers notable advantages in terms of corrosion resistance and long-term durability. Consequently, GFRP reinforcement may be considered for compression members in environments where durability requirements govern design and the applied load demands are moderate.

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