

Original Article

# Experimental Study on the Load Response of GFRP-Reinforced RC Short Columns under Concentric and Eccentric Loading Conditions

Guruprasad T N<sup>1,2</sup>, Suresh Babu K S<sup>2</sup>, M H Prashanth<sup>1</sup>

<sup>1</sup>Department of Civil Engineering, National Institute of Technology, Karnataka, Surathkal, Mangalore, India.

<sup>2</sup>Department of Civil Engineering, Sri Siddhartha Institute of Technology, SSAHE, Tumkur, Karnataka, India.

<sup>1</sup>Corresponding Author : [gurutn008@gmail.com](mailto:gurutn008@gmail.com)

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**Abstract** - The present study is on the structural performance of Reinforced Concrete (RC) short columns with Glass-Fibre Reinforcement Polymer (GFRP) bar reinforcement to evaluate their practicality as an alternative to the conventional steel reinforcement as a sustainable solution. GFRP reinforcement offers higher resistance to corrosion in hostile environments and a smaller carbon footprint compared to steel manufacturing. Twenty specimens of RC short columns with cross-sectional dimensions of 150 x 150 mm and a height of 1050 mm (slenderness ratio = 7) were prepared and tested in this work. The reinforcements were reinforced using GFRP and mild steel bars, and the axial concentric loading and an axial eccentric loading with eccentricities of 25 mm and 50 mm were performed to investigate the effect of the reinforcement percentage on the load-carrying capacity and the behavior of deformation. The findings indicated that the axial load-carrying capacity was almost 12 percent greater with GFRP-reinforced columns under concentric loading compared to steel-reinforced ones. Eccentric loading of GFRP reinforcement increased ductility and resistance to compressive stresses, which added to a better structural resistance. The results have shown that GFRP bars could be a valuable alternative to the steel reinforcement of RC short columns with both sufficient strength and improved durability and sustainability. This study enhances the experimental research findings on GFRP reinforcement use in RC applications and solidifies the necessity of additional large-scale research under different loading patterns.

**Keywords** - GFRP bars, Loading conditions, Load-deformation behaviour, Short columns, Structural performance.

## 1. Introduction

In construction industry today, Fiber-based Reinforcement Polymer (FRP) bars have become an environmentally friendly substitute of steel reinforcement in the general concrete structures, and especially where greater corrosion resistance is needed [1]. Glass Fiber-based Reinforced Polymer (GFRP) bars are one of the many types of FRP, where electromagnetic transparency allows them to be used in any type of structures that are found to act in the presence of electromagnetic fields or even companies that are situated near such areas. GFRP bars have both good mechanical and physical properties; hence, they are not only corrosion resistant, but also resistant to shear and flexural stresses, making them a possible alternative to conventional steel reinforcement. Metallic reinforcement corrosion has been a mainstream and crucial durability issue in elements that have reinforced concrete, particularly in hostile marine and coastal severe environments. Although many prevention measures have been applied to avert corrosion through protection by cathodic method and cathodic coating, or the use of additional cementitious materials, they are, in most cases, expensive, and their effectiveness is doubted in the long run. An even more novel and enduring resilience solution is to remove one of the factors of the

corrosion process, that is, steel, oxygen, or water. This is achieved through the replacement of steel reinforcement with FRP materials [2]. As such, a considerable amount of research has been focused on the behavior of GFRP bars in any structural member, such as beams, slabs, and bridge decks [3, 4] respectively. These investigations consistently highlight the suitability of GFRP reinforcement when structures are exposed to corrosive environments, primarily in marine conditions, or for specialised applications whose electromagnetic sensitivity must be considered [5]. Although GFRP bars are increasingly employed in structural elements subjected to flexure [6], their application in compression members, such as Reinforced Concrete (RC) columns, remains limited. Several researchers have argued that substituting steel with GFRP in compression members may be ineffective [7]. Current design codes, such as IS 456 [8], provide no specific guidelines and procedures for the practice of GFRP reinforcement experiencing compression, and Fib Bulletin 40 [9] reports that the influence of GFRP bars on the compressive load-carrying capacity of concrete columns is significantly less than that of conventional steel reinforcement, leading to their exclusion from design recommendations. Experimental studies have also raised concerns regarding the compressive performance of GFRP



reinforcement. Large-scale column tests under concentric compression loading [5] demonstrated that GFRP-reinforced columns are more prone to instability due to the lower stiffness and compressive strength in GFRP bars compared with their tensile capacity. Similarly, [10] stated that GFRP bars reinforced concrete columns carried loads, contributing approximately 10% of the total column capacity, compared to 12% for steel reinforcement. This is a signifier of the necessity of sufficient confinement of the GFRP in the utilization of the GFRP in columns. However, there are other studies that indicate that GFRP bars can give an effective compression reinforcement under certain conditions. Indicatively, [11] observed that slender columns that are reinforced using GFRP bars were strong, and longitudinal bars used along with spirals provided a viable reinforcement system [12]. Additional tests, as reported by [13, 14], proved that FRP-reinforced columns were capable of sustaining significant compressive strains, with GFRP and CFRP bars withstanding 0.007 mm/mm and 0.004 mm/mm strains, respectively. The same findings were reported by [15, 16], who found that in appropriately confined RC columns, GFRP bars can sustain significant compressive strains. Based on the literature reviewed, it is clear that there has been a divisive opinion on the behavior of GFRP bars in compression members, including columns. There are major doubts about their compressive strength, modulus of elasticity, and susceptibility to early buckling or crushing as longitudinal reinforcement.

In addition, there are no standardized methods of testing GFRP bars that would help accurately assess the material and mechanical characteristics of the latter, which, in turn, has led to the absence of unanimity to define their structural integrity. In order to overcome these shortcomings, more studies need to be made to explore the physical, mechanical, and safety aspects of GFRP reinforcement in concrete columns. Notably, design considerations when doing concentric loading do not have to be concentrated on concentric loading only, but should also extend to the eccentric patterns of loading that are more realistic of real-world structures. Although good results are anticipated, the existing design codes and guidelines do not give much consideration to the possibilities of the GFRP bars replacing the compression members, thus creating a setback in an attempt to accept them as an alternative to the conventional steel reinforcement. Moreover, the manufacturers are yet to develop a standardized testing procedure, hence, disparity in material property data.

Based on these gaps, the current research undertakes an exploration of the behavior of GFRP bars as longitudinal reinforcement in RC short columns subjected to axial concentric and eccentric loading. The experimental program was carried out on square columns keeping 7 a slenderness ratio, and GFRP bars reinforced, and compared to conventional steel reinforced ones. The results are expected to improve the current knowledge on the load-taking capacity and performance of the GFRP-reinforced concrete columns, thus leading to the formation of design provisions and the increased utilization of GFRP as a sustainable reinforcement material.

## 2. Experimental Details

The experimental program aimed to investigate the response of short columns made of Reinforced Concrete (RC) using the GFRP bars as reinforcement compared to the traditional steel bars as the longitudinal reinforcement [15]. Each specimen was tested in axial loading by loading the specimen on a loading frame with a capacity of 2000 kN applied at a rate of 2 kN/s, which was controlled. Testing the columns under both concentric and eccentric loading conditions will help to test the structural performance of the columns under a realistic situation. In order to ease the process of systematic assessment, the procedure of the experiment is introduced in successive steps. First, the details of the test specimens and material properties are provided, followed by the fabrication of reinforcement cages and the casting of concrete using appropriate shuttering [12]. Along with the loading arrangement for concentric and eccentric conditions, the instrumentation and testing setup are then described. At last, the testing procedure, observations, and data acquisition methods are outlined. The obtained results from these tests are later discussed and compared parametrically to highlight the influence of the type of reinforcement and behaviour of the column under different loading conditions.

### 2.1. Test Specimens

Twenty Reinforced Concrete (RC) short column specimens were cast and tested. Each column had a right-angled cross-section with dimensions 150 mm X 150 mm, a height of 1050 mm, with a slenderness ratio of 7. Three longitudinal reinforcement ratios, described as the ratio of reinforcement area to column cross-sectional area, were considered: 1.4% (R1), 2.0% (R2), and 3.6% (R3). Of the twenty specimens, twelve were tested for compressive concentric loading, whereas eight were tested for compressive eccentric loading. For concentric loading, six specimens had GFRP reinforcement bars, and six had conventional steel bars [17]. For eccentric loading, four specimens were tested with GFRP reinforcement and four with steel reinforcement [18]. The application of eccentric loadings was at offsets of 25 mm and 50 mm, respectively, from the centroid of the column section. The specimen identification followed the notation "X\_Y\_Z," where X denotes the concrete type, Y the reinforcement type (G = GFRP, S = steel), and Z the loading condition (C = concentric, E = eccentric). For eccentric loading, the eccentricity is also indicated. For example, "C\_G\_C" represents a cement concrete specimen with GFRP bars as reinforcement, which is subjected to concentric compressive loading, while "C\_G\_E-25" denotes a cement concrete specimen with GFRP reinforcement tested under eccentric loading with an eccentricity of 25 mm [19]. Table 1 summarizes the specimen details.

### 2.2. Specimen Properties

The specimens were cast using a site-mixed M30 grade cement concrete designed in accordance with IS 456. The mix was prepared with coarse aggregates consisting of a maximum size of 12.5 mm, retained on a 10 mm sieve. The average compressive strength obtained from three standard

cubes of size 150 mm X 150 mm X 150 mm, which were tested after curing for 28 days, was 36.9 MPa. A compressive test was also conducted to confirm the mix design strength. Reinforcement for the specimens consisted of either conventional steel bars or GFRP bars having nominal diameters of 10 mm, 12 mm, and 16 mm. The steel bars' mechanical properties, like moduli of elasticity, strength at both yield and ultimate tensile conditions, were determined in accordance with IS 1786. Similarly, tensile tests were performed on the GFRP bars to evaluate their strength and stiffness characteristics. The comparative representation of the tensile behaviour of steel and GFRP bars is provided in Figure 1. The mechanical properties of the reinforcement bars were evaluated by subjecting them to concentric tensile and compressive loading. While standardised procedures exist for testing the tensile properties of steel rebars, no equivalent standards are currently available for GFRP bars, either in tension or compression. Consequently, although tensile tests on both steel and GFRP bars were carried out, the compressive properties of GFRP reinforcement remain less clearly defined in the literature. Previous studies have highlighted the variability in the reported compressive behavior of GFRP bars. For example, Luca reported that the modulus of elasticity and the compression strength of the GFRP bars decreased by approximately 20% and 45%, respectively, compared to their tensile values [5]. In comparison with Khan [20], the observed results indicate higher tensile strength and modulus of elasticity than those obtained from compression tests. Further, Mallick [21] highlighted such variations in the lamina of structure with GFRP, which may result in compressive performance that is minimal, equal to, or in some cases greater than tensile performance. These contradictions suggest that there are no common testing norms for GFRP bars, and there are additional requirements for experimental studies. The present investigation addresses this gap by designing an experimental setup to evaluate the behaviour of GFRP reinforcement in RC short columns under both concentric and eccentric loading conditions.

### 2.3. Skeleton and Shuttering Fabrication

Using wooden shuttering moulds, the formwork for the specimens was prepared, with internal dimensions of 150 mm × 150 mm in cross-sectional area and a height of 1050 mm. The moulds were carefully inspected to prevent leakage of slurry, and both ends were secured to ensure proper alignment during casting and subsequent testing. Reinforcement cages were assembled with longitudinal reinforcement, either steel or GFRP. A cage 1000 mm in length was designed, maintaining a uniform 25 mm clear cover at both the top and bottom ends, as shown in Figure 2(a). Transverse reinforcement consisted of ten mild steel ties, placed with uniform spacing and adequate cover on all sides of the concrete surface. For instrumentation, four strain gauges were installed—two on longitudinal bars and two on transverse bars—to monitor strain development during testing. Particular care was taken during concreting and vibration to avoid damage to the strain gauges, and lead wires were positioned outside the column before setting. The columns were cast with M30 grade concrete and left undisturbed until the initial set was achieved, after which water immersion curing was carried out for 28 days. As the slenderness ratio was maintained at 7, all specimens were designed as short columns governed by crushing, and the effects of buckling were neglected.

### 2.4. Test Setup and Instrumentation

The experimental setup employed pin-supported end conditions, as illustrated in Figure 3. This arrangement allowed axial loading of the columns without rotational restraints. For concentric loading, the loading axis coincided with the centroidal axis of the column. For eccentric loading, the pin supports at both ends were adjusted to introduce the required eccentricities of 25 mm and 50 mm. For the transmission of a uniform load, the columns were positioned between two geometrically similar hexagonal steel end caps, each with a thickness of 30 mm and a side dimension of 200 mm.

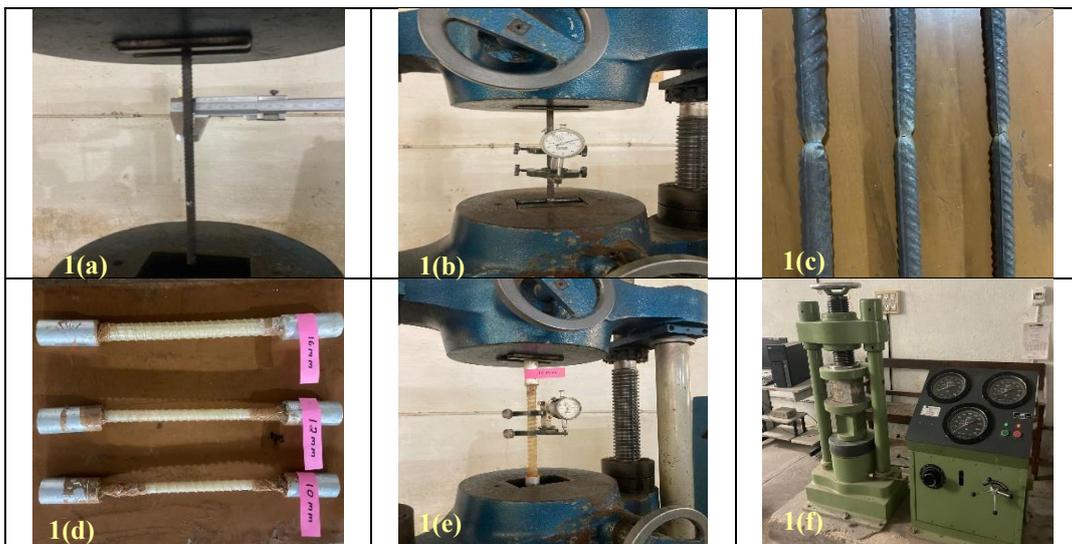


Fig. 1(a) Actual measurements of specimens checked, (b) Tensile test conducted on steel bars, (c) Tested steel specimens, (d) GFRP bars with aluminum casing are designed to ensure from crushing while gripping, (e) Tensile test conducted on GFRP bars, and (f) Design mix cube tested for compression.

Table 1. Test specimens

SL. No	Bar Type	Specimen	Area Ratio	Loading	
				Concentric	Eccentric
1	GFRP	C_G_C	R1	C	-
2	GFRP	C_G_C	R1	C	-
3	GFRP	C_G_C	R2	C	-
4	GFRP	C_G_C	R2	C	-
5	GFRP	C_G_C	R3	C	-
6	GFRP	C_G_C	R3	C	-
7	Steel	C_S_C	R1	C	-
8	Steel	C_S_C	R1	C	-
9	Steel	C_S_C	R2	C	-
10	Steel	C_S_C	R2	C	-
11	Steel	C_S_C	R3	C	-
12	Steel	C_S_C	R3	C	-
13	GFRP	C_G_E-25	R2	-	E
14	GFRP	C_G_E-25	R2	-	E
15	GFRP	C_G_E-50	R2	-	E
16	GFRP	C_G_E-50	R2	-	E
17	Steel	C_S_E-25	R2	-	E
18	Steel	C_S_E-25	R2	-	E
19	Steel	C_S_E-50	R2	-	E
20	Steel	C_S_E-50	R2	-	E

Table 2. Specimen properties (Tensile)

Bar type	Nominal diameter of bar (mm)	Actual diameter of bar (mm)	Yield strength (MPa)	Max Tensile Strength (MPa)	Modulus of elasticity (GPa)	Max elongation (%)
GFRP	10	9.95	-	983.45	52.76	3.21
GFRP	12	11.92	-	936.43	51.65	3.02
GFRP	16	15.89	-	929.82	51.42	2.98
Steel	10	10.09	474.34	559.87	201.03	-
Steel	12	12.11	511.76	669.31	199.98	-
Steel	16	16.10	486.43	621.89	201.54	-

Table 2 provides a summary of the nominal reinforcement diameters and the corresponding material properties adopted for the test specimens.

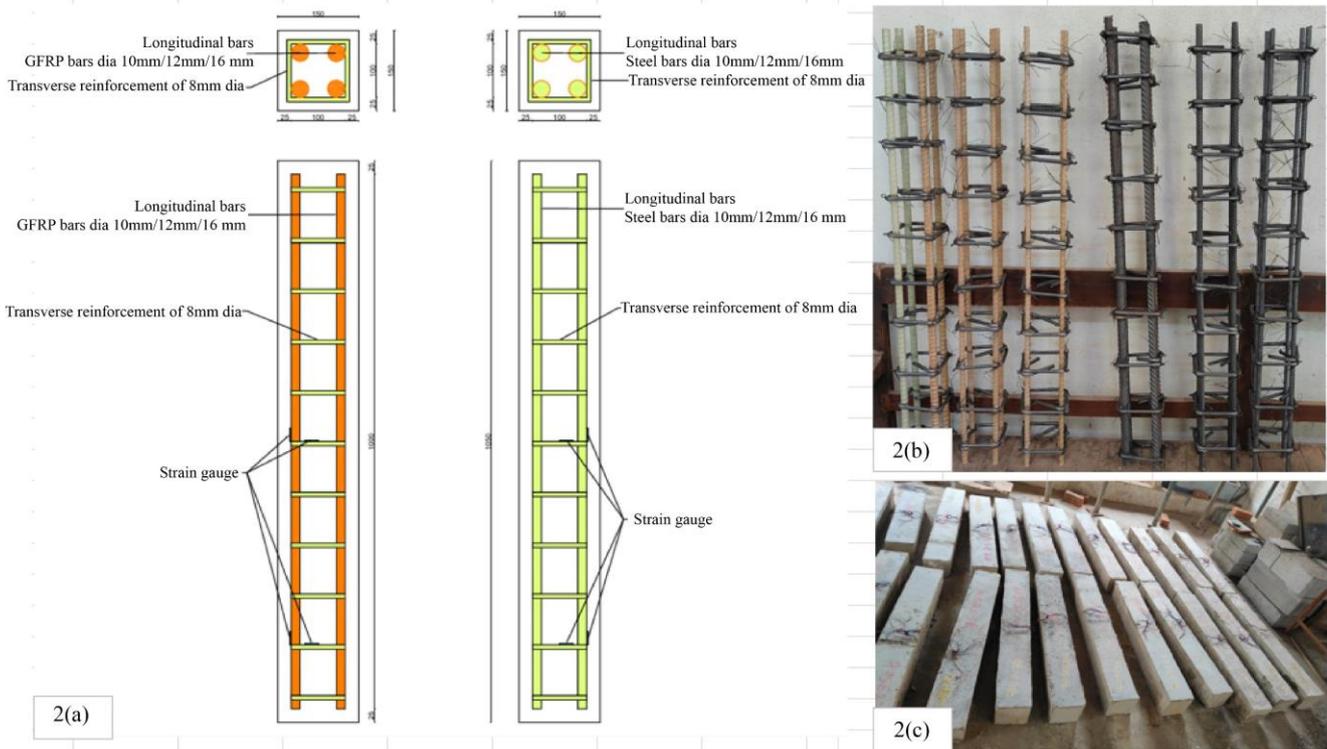


Fig. 2 (a) Schematic drawing of the fabricated reinforcement members, (b) Actual fabrication of reinforcement, and (c) Specimens after curing, arranged for testing.

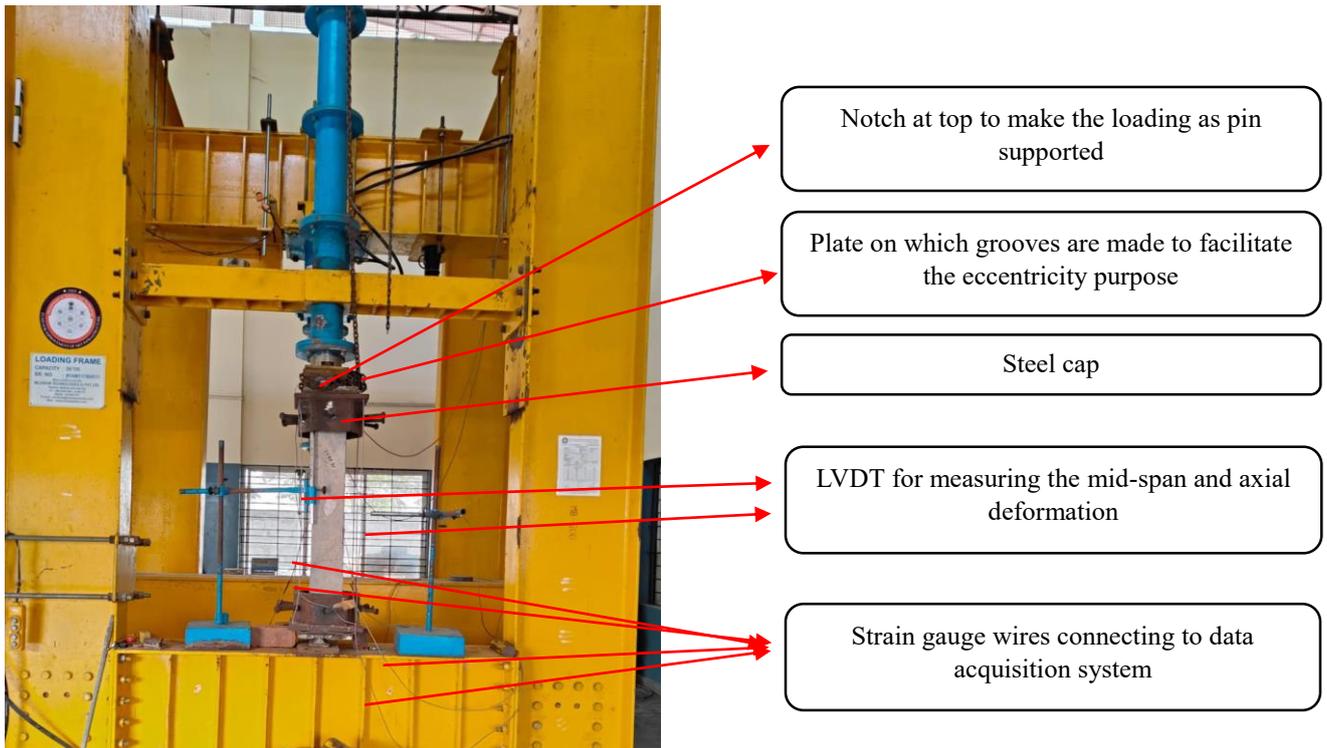


Fig. 3 Testing setup of the specimen subjected to eccentric loading

To the top and bottom surfaces, additional plates of the same thickness were also affixed to ensure proper alignment and effective application of load. These plates had grooves to accommodate notches for the pin supports, enabling precise alignment. Concentric loading was achieved when the notch was positioned at the centre of the groove, whereas offsetting the notch by 25 mm or 50 mm produced eccentric

loading. Experimental Instruments were provided to monitor both strain and displacement during testing. The reinforcements were affixed with four strain gauges, two on longitudinal bars and two on transverse ties. Displacement measurements were recorded through the application of two LVDTs: one positioned to record vertical displacement and the other to monitor horizontal displacement. All strain and

displacement readings were recorded by a computerised data acquisition system connected to the loading frame, which receives the data at intervals of 0.1 seconds, and the loading rate was 2 kN/s, which was applied until the failure of the test specimen.

### 3. Results and Discussion

The experimental results obtained from the tested specimens, presented in Table 3, include the ultimate compressive load, stresses developed in the reinforcement, crushing strains at peak load, and maximum deformation of the reinforcement [22]. The failure patterns of the columns under both concentric and eccentric loading conditions are also summarised, which resembles the literature [23]. For GFRP bars reinforced specimens, the ultimate compressive load was consistently lower compared to their steel-reinforced counterparts, confirming the relatively lower compressive stiffness of GFRP reinforcement. The experimental results showed that columns reinforced with GFRP bars exhibited notably higher crushing strain values when compared to steel-reinforced columns. This behaviour indicates that members with GFRP reinforcement possess a greater tendency to undergo deformation before the final failure. Thereby highlighting under compressive loading

their superior deformability characteristics. This observation is consistent with the findings of [24, 25], which reported a reduced compressive modulus but increased deformability of GFRP reinforcement. In the case of eccentric loading, at the ultimate load, lateral strains increased significantly, in particular with the specimens reinforced with GFRP bars. The mid-span deformation was observed to be considerably larger than in concentric loading; the same trend was followed with the behaviour of compression members under eccentricity.

To corroborate this effect more accurately, an additional LVDT and strain gauge were placed at the mid-span, confirming higher lateral displacements for GFRP specimens compared to the steel bars. Between the two reinforcement types, a change in failure modes occurred. Also, Steel-reinforced columns exhibited typical crushing of concrete with slight yielding of the bar, while GFRP-reinforced columns exhibited earlier instability and splitting of the cover concrete near peak load. These results showcase the sensitivity of GFRP-reinforced columns to eccentric loading and suggest that adequate confinement is necessary for their effective application [26].

Table 3. Review of results

SL No.	Specimen	Ratio	Reading @ Ultimate Load						Reading @ crushing	
			Ultimate Load (KN)	Stress (KN/mm <sup>2</sup> )	Axial deformation (mm)	Longitudinal Strain	Lateral strain	Mid span Deformation (mm)	Longitudinal Strain	Lateral strain
1	C_G_C	R1	613.5	27.267	6.32	0.108	-	-	0.099	-
2	C_G_C	R2	635.9	28.699	5.49	0.093	-	-	1.055	-
3	C_G_C	R3	746.4	33.173	5.82	0.087	-	-	1.224	-
4	C_S_C	R1	607.7	27.009	5.39	0.262	-	-	0.569	-
5	C_S_C	R2	625.1	27.782	6.11	0.237	-	-	0.653	-
6	C_S_C	R3	665.2	29.564	6.70	0.213	-	-	0.705	-
7	C_G_E-25	R2	412.3	18.239	5.58	0.120	0.052	4.76	0.128	0.057
8	C_S_E-25	R2	400.2	17.795	4.39	0.155	0.118	2.89	0.161	0.122
9	C_G_E-50	R2	254.8	11.324	2.33	0.149	0.231	5.22	0.154	0.246
10	C_S_E-50	R2	168.2	7.475	4.09	0.253	0.323	4.53	0.264	0.345

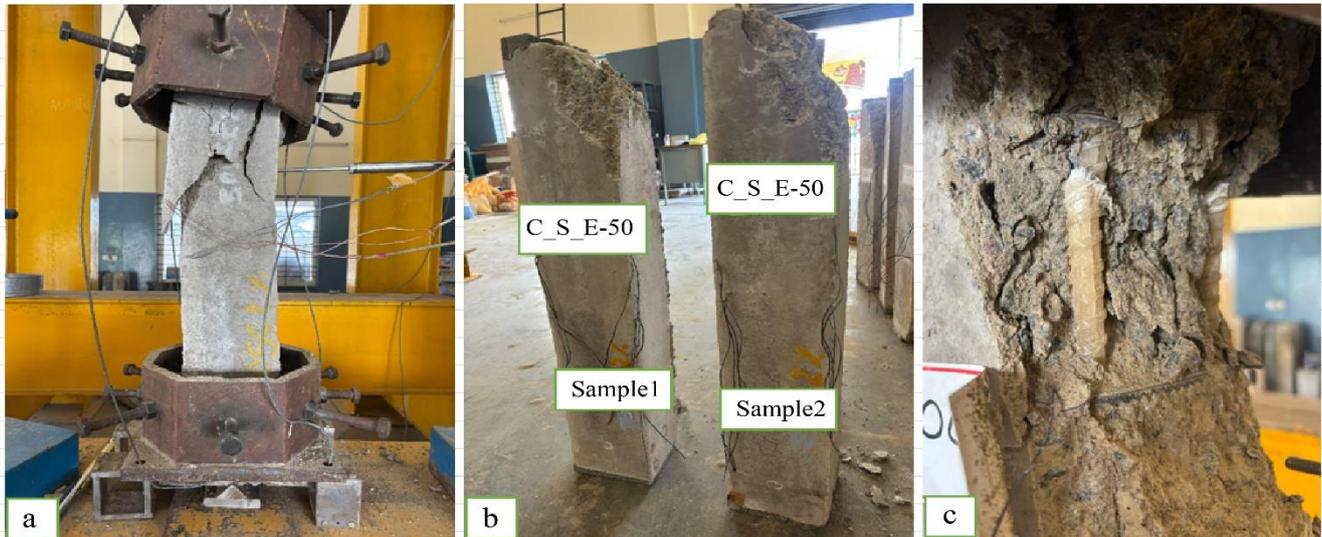


Fig. 4 Failure patterns, (a) The concentrically loaded column failed in crushing, (b) Eccentrically loaded columns failed on the sides diagonally, exposing the reinforcement, and (c) GFRP bars got disrupted subsequently, and spalling in concrete was observed when the column was loaded eccentrically.

### 3.1. Failure Patterns

The experimental observations revealed distinct failure patterns for specimens subjected to concentric and eccentric loading. In both cases, the predominant modes of failure were concrete crushing and spalling of the surface, particularly with cover concrete. For columns reinforced with GFRP bars, no signs of rupture or crushing of the reinforcement were observed before reaching the ultimate compressive load under concentric loading [27]. Throughout the entire loading cycle, the GFRP reinforcement remained intact, with failure governed primarily by concrete crushing. In contrast, specimens subjected to eccentric loading exhibited more severe damage. Along with concrete crushing and spalling, localised ruptures of the GFRP reinforcement were observed.

Load, particularly in columns with higher eccentricity [28]. This implies that eccentric loading produces two additional effects of bending and instability, which make GFRP bars more susceptible to rupture compared to concentric loading scenarios. The nature of failure mechanisms of the columns in test (shown in Figure 4) gives us some understanding of how the columns respond structurally under applied loading that causes spalling of the cover concrete and the local rupture of the GFRP bars that can be seen in the eccentrically loaded structures. As a precautionary measure, loading was discontinued just after peak load was attained, and the columns already indicated crushing damage.

### 3.2. Performance of Reinforced GFRP Bars under ConCentric Loading

The final load-carrying capacities of short columns with GFRP and conventional steel bars under concentric loading were summarised in Table 3, which helped draw a direct comparison of the structural performance of this material. Regarding specimens with GFRP reinforcement, the average ultimate loads of reinforcement ratios R1, R2, and

R3 were 613 kN, 635kN, and 746kN, respectively. In comparison, the corresponding steel-reinforced columns achieved 607 kN, 625 kN, and 665 kN, as illustrated in Figure 5. Columns reinforced with GFRP bars consistently exhibited marginally higher load-bearing capacities than those with steel reinforcement. The observed enhancement was approximately 1.0% for R1, 1.7% for R2, and more pronounced at 12.2% for R3.

This indicates that with an increasing reinforcement ratio, as the loading conditions intensify, the participation of GFRP reinforcement in resisting axial forces becomes increasingly pronounced, thereby contributing more substantially to the overall load-carrying capacity of the column [29]. The superior performance of GFRP-reinforced columns is primarily associated with the high tensile strength-to-weight ratio of GFRP bars, along with their capability to undergo substantial strain before the onset of failure. Moreover, the results suggest that under concentric loading, the potential limitations of GFRP in compression (e.g., reduced modulus compared to steel) do not critically undermine the axial load capacity of short columns, particularly when higher reinforcement ratios are employed.

### 3.3. Performance of Reinforced GFRP Bars under Eccentric Loading

The experimental results for eccentric loading are summarized in Table 3. For columns subjected to an eccentricity of 25 mm, the peak axial load recorded was 412 kN for GFRP-reinforced specimens and 400 kN for steel-reinforced specimens, representing a 3% increase in capacity for GFRP reinforcement. At a larger eccentricity of 50 mm, the ultimate loads were 254 kN for GFRP and 168 kN for steel, indicating a significant 51% increase in load-bearing capacity for the GFRP-reinforced columns. The corresponding load–deformation responses are shown in Figure 6(a) and 6(b). With increasing eccentricity, a reduction in axial deformation was observed for both types of reinforcement. It was shown in the experimental findings

that there was a significant decrease in the axial deformation of the GFRP-reinforced columns with increasing load eccentricity of the columns between 25 mm and 50 mm, and the magnitude of the change was found to be approximately 58. This observation shows that the deformation capacity of such columns is very sensitive to changes in loading eccentricity, and it shows the role played in eccentric loading conditions on the structural response of such columns, but the decrease was only around 7% in steel-reinforced columns.

The results here confirm the fact that the higher the degree of eccentricity, the lower the peak axial load is with both types of reinforcements. It is important to note that the higher eccentricities in which GFRP reinforcement performs better imply that such bars will be able to maintain the more stress-generating bends without the associated reduction in their axial capacity, as is the case with steel [30]. This improved performance with eccentric loading highlights the possible relevance of GFRP reinforcement under structural performance, where the combination of both axial and bending loads occurs.

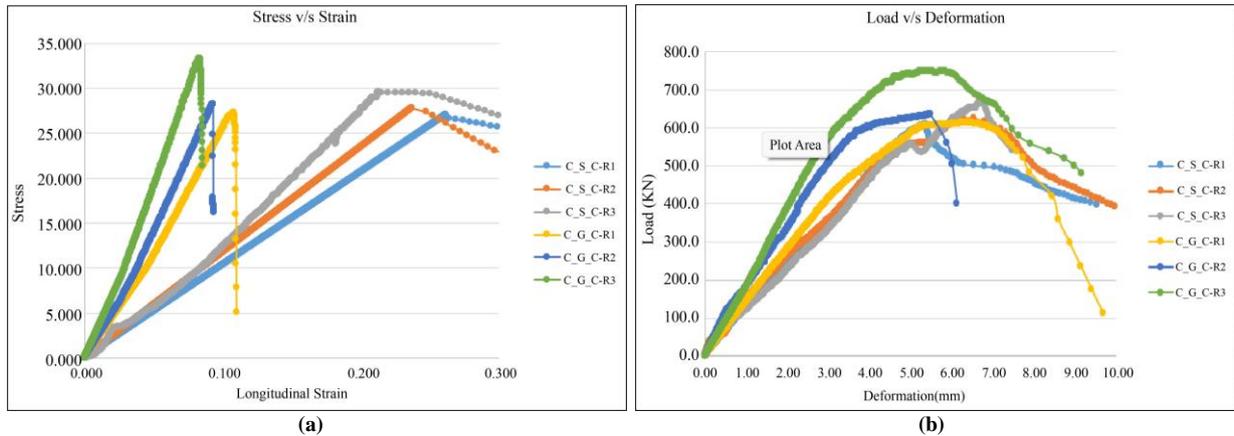
**3.4. Strain and Deformation Behavior**

The displacement in the middle of the span of the tested columns showed an evident dependence on the degree of eccentricity. The increase in eccentricity, 25 50 mm, and the

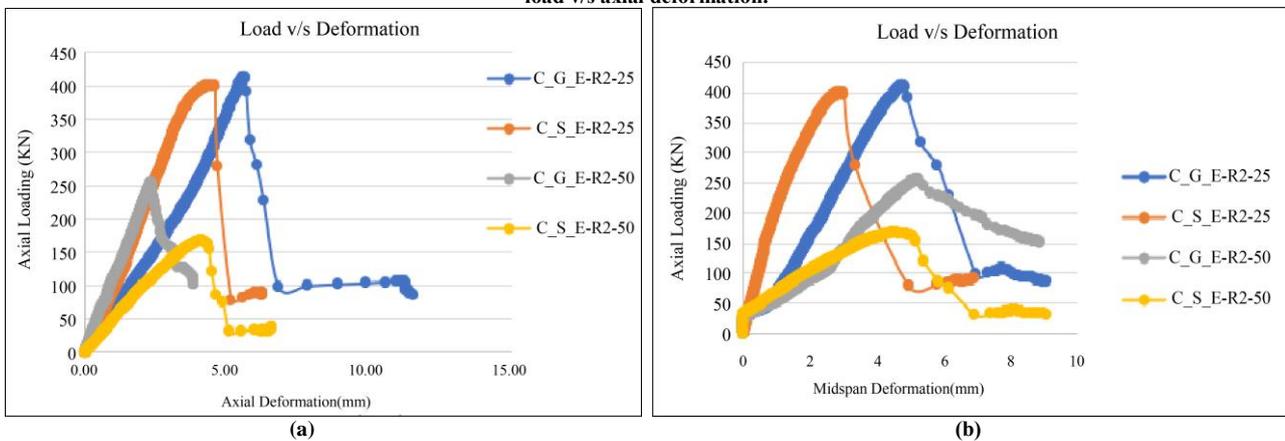
mid-span movement also rose, a fact that is indicative of a positive proportional relationship existing between the eccentricity and deformation. This behaviour emphasizes the strong effect of the bending moments on deflections of the columns under asymmetric loading. No topical evidences of crushing and buckling of the GFRP reinforcement were found during the peak loading stage. Nevertheless, local discontinuities of certain bars of GFRP were observed in post-peak behaviour and were generally associated with the spalling of the concrete in the compression zone.

This suggests that failure initiation was governed primarily by the concrete rather than by premature rupture of the GFRP reinforcement. In terms of lateral deformation, a marked difference was observed between GFRP and steel reinforcement. For GFRP-reinforced columns, lateral deformation increased by approximately 22% as the eccentricity rose from 25 mm to 50 mm.

In contrast, steel-reinforced columns exhibited a much larger increase of 56% for the same change in eccentricity. This contrast suggests that GFRP reinforcement facilitates better control of lateral deformations under eccentric loading, which is beneficial for maintaining serviceability and limiting crack propagation in compression members [31].



**Fig. 5 Behaviour of reinforcement bars under concentric loading conditions, (a) Plot of stress v/s longitudinal strain, and (b) Plot of concentric load v/s axial deformation.**



**Fig. 6 (a) Graphical representation of Axial loading and axial deformation for eccentricities of 25mm and 50mm, and (b) Graphical representation of Axial loading and mid-span deformation for eccentricities of 25mm and 50mm.**

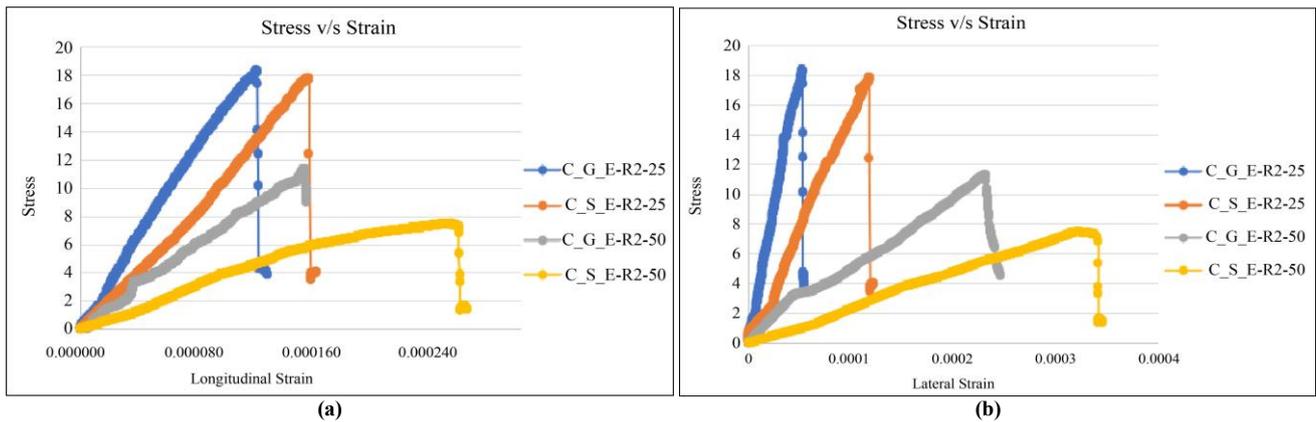


Fig. 7 (a) Graphical representation of stress and longitudinal strain for eccentricities of 25mm and 50mm, and (b) Graphical representation of stress and lateral strain for eccentricities of 25mm and 50mm.

At the time of application of ultimate load, both longitudinal and lateral strains were found to increase with the increment in eccentricity from 25 mm to 50 mm. For GFRP-reinforced columns, the longitudinal strain at ultimate load increased by approximately 24%, while for steel-reinforced columns, the corresponding increase was significantly higher at 63%. This illustrates that steel-reinforced specimens were more sensitive to variations in eccentricity, whereas GFRP-reinforced columns showed relatively controlled development of strain. In terms of lateral strains, GFRP bars exhibited a much more pronounced increase compared to their steel counterparts. This observation implies that although the GFRP reinforcement is capable of maintaining compressive loading tendencies without being crushed early, it can have increased strain lateralisation, especially at larger eccentricities [32]. The variations accompanying the types of reinforcements point to dissimilar responses of stress-strain in GFRP bars, which are dependent on the anisotropic composition and laminate action of the bars. Figure 7(a) and Figure 7(b) show the longitudinal and lateral strain variation under eccentricity, and clear indications of the difference in the strain response under eccentricity as shown by GFRP- and steel-reinforced columns.

#### 4. Conclusion

The current experimental program investigates the comparative behaviour of short reinforced concrete columns with Glass Fibre-Reinforced Polymer (GFRP) bars and conventional steel reinforcement under concentric and eccentric loading conditions. Twenty specimens were tested, which were identical to those with GFRP and steel reinforcement. Three reinforcement ratios (R1, R2, and R3) were adopted for concentric loading, while eccentricities of 25 and 50mm were considered for both reinforcement types. The following conclusions can be drawn:

- The elastic modulus of GFRP bars was determined, and the linear portion of the stress-strain curve indicates their suitability for further structural applications.
- Under compressive loading, no premature rupture of GFRP bars was observed. Failures initiated with the spalling of concrete, followed by the disruption of GFRP bars at advanced stages.

- The failure of the concrete matrix was primarily governed by the ultimate compressive load, with minimal direct effect on the GFRP reinforcement.
- For both GFRP- and steel-reinforced specimens, the increase in longitudinal and lateral strains from peak load to crushing load was limited to less than 7% indicating comparable behaviour of strain near ultimate failure.
- The ultimate load-carrying capacity was higher in the R3 GFRP specimens compared to R1 and R2, and in several cases, this exceeded the performance of counterparts of steel-reinforced specimens. This highlights the potential of higher reinforcement ratios with GFRP, though to validate performance across a wider range of parameters. Additional studies are required.
- The results of this investigation establish that under compressive loading, GFRP bars provide adequate resistance in short concrete columns, highlighting their suitability as an alternative to steel reinforcement in structures exposed to corrosive and aggressive environmental conditions.

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#### Credit Authorship Contribution Statement

Guruprasad T N: Investigation, Data curation, Validation, Formal analysis, Methodology, Visualisation, Writing - original draft, Writing - review & editing.

Suresh Babu K S: Investigation, Data curation, Visualization, Writing - original draft

M H Prashanth: Conceptualisation, Idea, validation & writing, review, editing, and supervision.

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