Behaviour of axially and eccentrically loaded short columns reinforced with GFRP bars

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Abstract. The corrosion of steel reinforcing bars is a predominant factor in limiting the life expectancy of Reinforced Cement Concrete (RCC) structures. Corrosion resistant Fibre Reinforced Polymer (FRP) bars can be an effective alternative to steel bars in this context. Recent investigations reported the flexural behaviour of RCC beams reinforced with Glass Fibre Reinforced Polymer (GFRP) bars. This study is meant to investigate the suitability of Sand Coated GFRP reinforcement bars in short square columns which when loaded axially and loaded with a minimum eccentricity. Standard tests to assess mechanical properties of GFRP bars and pullout test to quantify the bond strength between the bars and concrete were conducted. GFRP reinforced column specimens with a cross-sectional dimension of 100mm X 100mm and of length 1000mm were cast and tested under axial and eccentric loading. The assessed load carrying capacity was compared with that of conventional steel reinforced columns of the same size. The yield load and ultimate load at failure withstood by the steel reinforced columns were considerably more than that of GFRP reinforced columns. The energy absorption capacity of GFRP reinforced columns was also poor compared to steel reinforced columns. Both the columns exhibited nearly the same ductile behaviour. Hence GFRP reinforcements are not recommendable for compression members.

1. Introduction

Columns are structural members subjected to compressive forces, which will transmit the load from the slabs and beams to the lower level. Hence, these columns are the most critical elements in the structure [1]. Corrosion of steel bars is one of the threats to the strength and serviceability of Reinforced Cement Concrete (RCC) columns. The gradual process of corrosion will weaken the columns and the problem will become severe when it is exposed to aggressive environments. The difficulty in repairing these degraded elements raises the demand for a noncorrosive material as reinforcements. Fiber Reinforced Polymer (FRP) composites are popular for strength and corrosion resistance. Both cost and durability benefits can be achieved by properly employing these composites in the field of infrastructural development. Its high strength and stiffness to weight ratios, tractable thermal expansion, damping properties and electromagnetic neutrality are the additional benefits [2-4]. These benefits can bring in improved safety and life cycle with a possible reduction in production, equipment and maintenance costs. FRPs are composites made of polymer matrices reinforced with fibers. The fibers may be glass, carbon, aramid or basalt and the polymer may be epoxy, vinyl ester, phenol formaldehyde etc. [5]. Glass Fibre Reinforced Polymer (GFRP) is selected for this study. Investigators recently studied the possibilities of using GFRP bars in flexural members as longitudinal

and shear reinforcements. Studies are less on the behaviour of GFRP bars in compression members. Micro-buckling of fibers is expected to occur in the bars when it is compressed and it becomes deficient to withstand compressive loads further. This is because of the non-homogeneous and anisotropic nature of the GFRP matrix. Hence the use of GFRP bars is less recommendable. American Concrete Institute (ACI) through their standard code [6] demands for further studies on the behaviour of GFRP reinforced compression members [1].

1.1 Previous Studies
Previous researchers confirmed the poor performance of GFRP reinforcements under compression. The reported compressive strength of GFRP reinforcement bars was as low as 55% of its tensile strength [7]. The tests conducted on small scale square columns of size $200 \times 200 \times 650$mm with grid type FRP reinforcement reported a conservative axial load carrying capacity ignoring the part of FRP bars [8]. The study of compression behaviour of rectangular columns of size $450 \times 250 \times 1200$mm with GFRP longitudinal reinforcement reported a reduction of 13% in the load carrying capacity compared to the conventional steel reinforced columns irrespective of the type of lateral ties (Steel or GFRP). An investigation done on square columns reported the improvement in the ductile behaviour of the column with increasing the reinforcement ratio [9].

1.2 Objectives of the study
The study is aimed to
  • Provide a clear idea of the mechanical properties of GFRP reinforcement bars.
  • Illustrate the behaviour of Sand Coated GFRP reinforced short columns under axial loading and loading with minimum eccentricity.
  • Frame equations to predict the load carrying capacity of the columns and to validate the same.

2. Experimental Investigation
2.1 Specifications of Materials
In this research, a concrete mix of grade M30 with the characteristic compressive strength of 30 N/mm^2 was used. The proportion of the constituents was designed to conform to Indian standards [10,11] and obtained a ratio of 1:1.16:2 with water to cement ratio 0.50.

Ordinary Portland Cement (OPC) of grade 53 with specific gravity 3.15 was used in the mix. The fine aggregate passing through a 4.75 mm sieve and retained on 150-micron sieve having a specific gravity of 2.68 was used. The grading zone of fine aggregate was zone II as per Indian standard specification [12]. The maximum size of coarse aggregate used for this investigation is limited to 12.5 mm to avoid the chances of honeycombing in the specimen. The specific gravity of the coarse aggregate was determined based on Indian standards [12] and it was 2.78.

Potable water was used which was free from acids, oil, alkalis and other organic impurities. Fe500 grade High Yield Strength Deformed (HYSD) bars were used for steel reinforced columns. 12 mm diameter bars were used as longitudinal reinforcement. The lateral ties were about 8 mm diameter steel bars of the same grade for both steel and GFRP reinforced columns. 12 mm diameter HYSD bars were used for the column head reinforcements for both types of columns.

Table 1. Mechanical properties of steel and GFRP

Property	Steel bar	GFRP bar
Tensile Strength (in MPa)	549	965
Yield Strength (in MPa)	500	-
Compressive strength (in MPa)	520	320
Tensile Modulus of Elasticity (in GPa)	210	41
Specific gravity	7.9	1.7

Sand Coated type GFRP rebars were used. The GFRP reinforcements are shown in Figure 1. The diameter of GFRP bar used in this study was 12 mm (including the thickness of sand coating). Table 1 gives the properties of steel and GFRP bars used in this study.

Figure 1. Sand Coated GFRP Rebar.

2.2 Details of test specimens

Totally four numbers of column specimens were cast and tested. Out of four specimens, two were reinforced with GFRP rebars and the remaining two were reinforced with steel rebars. The specimens were tested under both axial and eccentric loading. The columns were designed as short columns with a cross-sectional dimension of 100 mm x 100 mm. The length of the column is 1000 mm. All were provided with end corbels of cross-sectional dimension 200 mm x 100 mm to avoid direct crushing failure [13]. The depth of end corbels (column head) was 100 mm. The control columns were reinforced with four 12 mm diameter HYSD steel bars as longitudinal reinforcement. It was provided with steel lateral ties of 8mm diameter with a spacing of 100 mm from centre to centre at its mid height. The spacing was reduced to 50mm from centre to centre at the supports. 12mm diameter HYSD steel bars were used for column head reinforcement.

For GFRP reinforced columns the longitudinal bars were of 12mm diameter Sand Coated GFRP rebars and the lateral ties were of 8mm diameter HYSD steel bars. 12mm diameter HYSD steel bars were used for column head reinforcement. The dimensions and reinforcement detailing of the column specimen are shown in Figure 2. Figure 3 shows a typical reinforcement arrangement. The details of cast specimens are shown in Table 2.
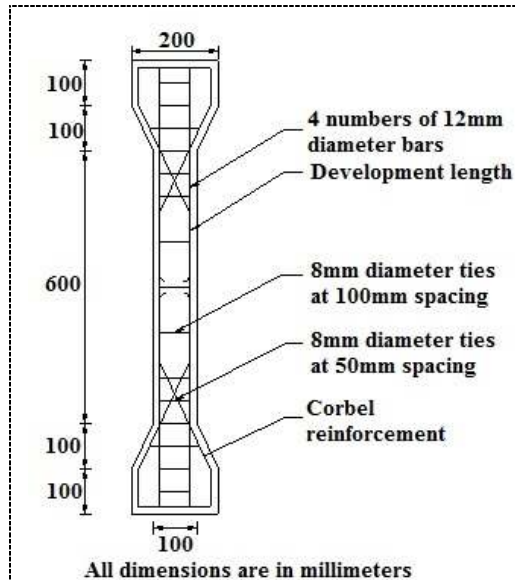
Figure 2. Dimensions and detailing of the column specimen.	**Figure 3.** Typical reinforcement arrangement for the column

Table 2. Details of cast specimens

Column designation	Reinforcement type	Type of loading
CRSA	Steel	Axial loading
GRSA	GFRP	
CRSU	Steel	Eccentric loading
GRSU	GFRP	

2.3 Experimental setup and Instrumentation
The column specimens were tested in a loading frame of 2000kN capacity. The axial load was applied using a hydraulic jack of 1000 kN capacity. The load applied to the specimen was measured using an electronic load cell of 1000 kN capacity, which is connected to the data acquisition system. Axial load was transmitted to the column through the steel plate and ball setup to provide hinged end condition. Figure 4 shows the specimen with support condition. The column specimens CRSA and GRSA were tested under axial compression. The specimens were placed in such a way that the line of action of the axial load coincides with the axis of the column. The verticality of the column specimens was checked using a plumb bob and a spirit level to avoid unexpected eccentricity in loading. A mechanical strain gauge, which is demountable, having a gauge length of 200mm and least count of 0.002 mm was used to measure the axial deformation at the mid-height of the specimen. Two numbers of Linear Variable Differential Transformer (LVDT) were used to measure the mid-height lateral deflections (if any) of the short column specimens. The strain is measured in four faces at the middle of the column.

The specimens CRSU and GRSU were loaded by applying compression on a point with an eccentricity of 0.05D from the axis, where D is the lateral dimension of the column. This was performed for accounting the behaviour of column specimens under loading with accidental eccentricity. The specimens were so placed that the axis of loading passes through the eccentric point. Throughout the test setup, care was taken to ensure that the load was applied with permissible eccentricity. The plumb bob was used to check the verticality of columns.
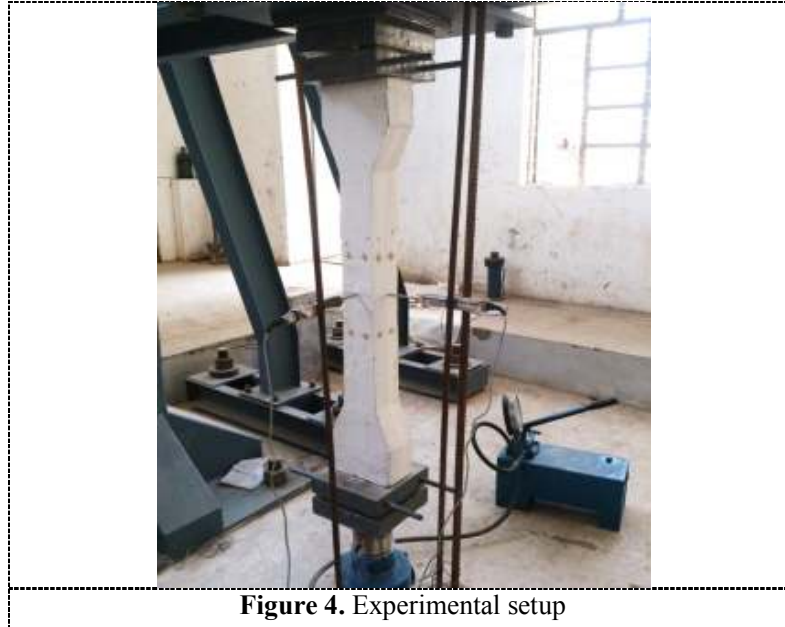
Figure 4. Experimental setup

Initially, an axial load of 5 kN was applied to hold the specimen in its position and then the instruments were normalized and initial readings were observed. Lateral deflections were measured at mid height using Linear Variable Differential Transducers (LVDT) and the axial deformations were measured using the demountable mechanical strain gauge. The load was applied gradually and the deflections were measured at various load stages. At the same time, axial deformation values were also measured. Initiation of crack was observed and the corresponding load was noted, ultimate load to failure and mode of failure were taken. The experimental setup for testing of columns is shown in Figure 4.

3. Results and discussions

3.1 Behaviour of axially loaded columns

The test results are given in the Table 3. The columns CRSA and GRSA were tested under axial compression and axial deformation was observed. The results are tabulated in Table 4. The specimen CRSA started yielding at a load of 428kN. This is the load under which the first crack was observed in the specimen. The deformation observed under this load was 1.21 mm. The specimen failed at a loading of 547kN. The axial deformation under this ultimate load was 1.54 mm. In the case of GRSA, the first crack was observed at a load value of 312kN and the corresponding deflection was 1.12kN. The specimen failed at a loading of 407kN. The deflection at failure was 1.46kN. While comparing the first crack load and ultimate load of CRSA and GRSA, it was noted that CRSA showed a better performance under axial compression than GRSA. The yielding point load of CRSA was 37% more than that of GRSA and the ultimate load of CRSA was 34% more than that of GRSA. But the deflection of CRSA at the yielding point was 8% more than that of GRSA. The behaviour of GRSA was almost the same as stated by the previous researchers.

3.1.1 Load – axial deformation behaviour. The load- axial deformation curve was plotted for CRSA. The plotted curve was then used to compute the energy absorption and the ductility factor of the specimens. A linear variation was found until the load corresponding to the initiation of a crack. After that point, the curve was of parabolic nature. This profile of the curve revealed that the specimen started yielding from the point of initiation of a crack. The load versus axial deformation curve for

GRSA was also plotted. GRSA also showed the same load-deformation behaviour as CRSA. Figure 5 shows the comparative load-axial deformation curve for CRSA and GRSA.

Table 3. Specimen details and results of pullout test

Column designation	Yield load (kN)	Deflection at yield (mm)	Ultimate load (kN)	Deflection at failure(mm)	Energy Absorbed (kNmm)	Ductility Factor
CRSA	428.00	1.21	547.00	1.54	598.74	1.27
GRSA	312.00	1.12	407.00	1.46	426.78	1.30
CRSU	248.00	0.69	419.00	1.18	311.20	1.71
GRSU	189.00	0.67	320.00	1.12	201.40	1.67

3.1.2 Energy absorbed by specimen. The energy absorbed by the column specimens can be quantified as the area under the load-deformation curve. The energy absorbed by CRSA was 598.74kNmm while that of GRSA was 426.78kNmm. That is the energy absorbed by the steel reinforced column under the axial loading is 40% more than that of GFRP reinforced column.

3.1.3 Ductility factor. Ductility is the ability of the column to sustain inelastic deformation without significant reduction in its load carrying capacity. Ductility factor is the ratio of deformation at ultimate load to that at the onset of yielding. The ductility factor exhibited by CRSA was 1.27 while the same exhibited by GRSA was 1.30. That is the GFRP reinforced column exhibited a better ductile behavior than a steel reinforced column.

Figure 5. Load-Deflection behavior of axially loaded columns
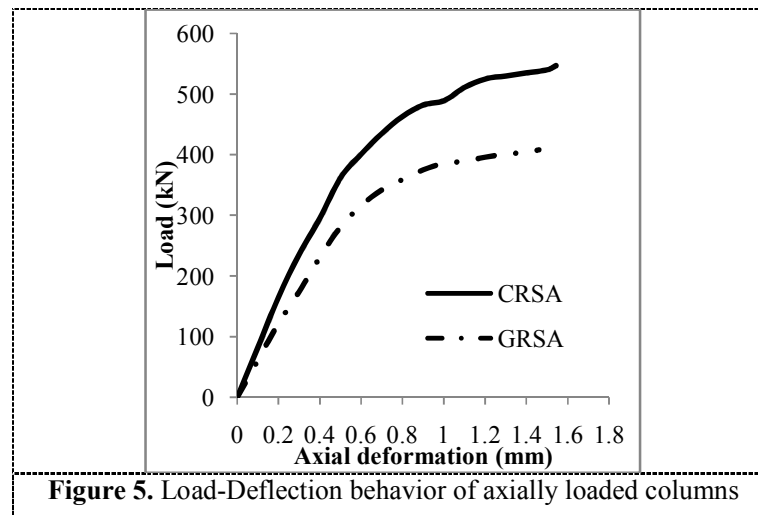
3.2 Behaviour of axially loaded columns
The column specimens CRSU and GRSU were tested under loading with a uniaxial eccentricity of 0.05D, where D is the lateral dimension of the column. That is 5mm from the axis of the column. Load versus axial deformation curves were plotted for both CRSU and GRSU. The first crack was observed on CRSU at a loading of 248kN. This is the yield point load and the corresponding deflection was 0.69mm. CRSU failed at a load of 419kN and the corresponding deflection was 1.18mm. GRSU started yielding at a load of 189kN and the deformation under this load was 0.67mm. The specimen failed at a load of 320kN and the corresponding deflection was 1.12mm. The results indicated that the yield point load of CRSU was 31% more than that of GRSU and the deflection of CRSU at the yield point was 3% more than that of GRSU. The ultimate load of CRSU was 34% more than that of GRSU and the deflection of CRSU at failure was 5% more than that of GRSU.
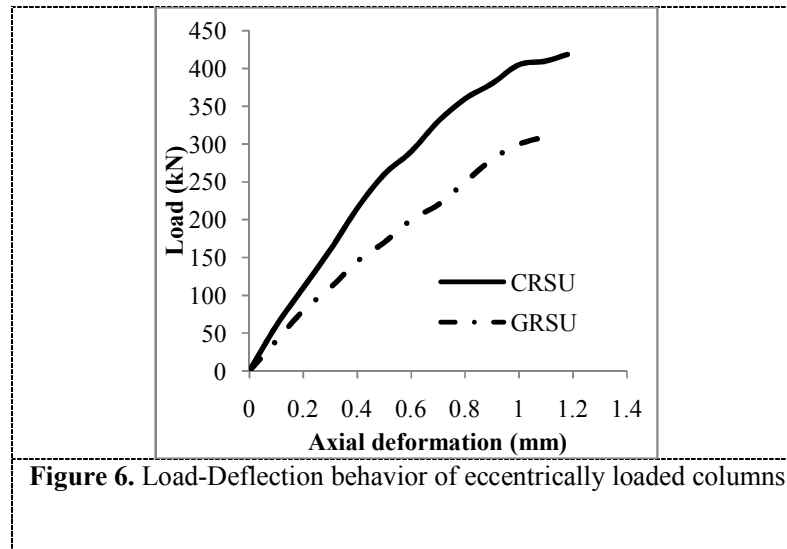
Figure 6. Load-Deflection behavior of eccentrically loaded columns

3.2.1 Load – axial deformation behaviour. The load- axial deformation curve was plotted for CRSU. The plotted curve was then used to compute the energy absorption and the ductility factor of the specimens. A linear variation was found until the load corresponding to the initiation of a crack. After that point, the curve was of parabolic nature. This profile of the curve revealed that the specimen started yielding from the point of initiation of a crack. The load versus axial deformation curve for GRSA was also plotted. GRSU also showed the same load-deformation behaviour as CRSU. Figure 6 shows the comparative load-axial deformation curve for CRSU and GRSU.

3.2.2 Energy absorbed by specimen. The energy absorbed by CRSU was 311.20kNmm and that of GRSU was 201.40kNmm. That is the energy absorption capacity of CRSU was 55% more than that of GRSU.

3.2.3 Ductility factor. The ductility factor exhibited by CRSU was 1.71 and that of GRSU was 1.67. This shows the better ductile behaviour of steel reinforced columns than that of GFRP reinforced columns.

3.3 Mode of failure
Since the load was applied at the bottom end, crushing failure was observed at the base of the specimen. Both steel reinforced and GFRP reinforced columns showed the same mode of failure due to crushing. The typical mode of failure exhibited by axially and eccentrically loaded steel and GFRP reinforced columns is shown in the Figure 7.

Figure 7. Typical failure pattern of the specimens

4. Ultimate capacity and design equations

The equation recommended by American codes for finding the ultimate load carrying capacity of conventional steel reinforced columns is as given below.

$$P_o = k_c f'_c (A_g - A_{st}) + f_y A_{st} \tag{1}$$

Where P_0 is the ultimate load carrying capacity f'_c is the compressive strength of concrete, A_g is gross sectional area of the column and A_{st} is the area of steel reinforcement.

The parameter k_c id defined as the ratio of in-place strength of concrete to the concrete cylinder strength. The value of this factor varies with respect the effect of size, shape and even with respect to the practice of concreting [1]. Previous researchers suggest a value of 0.85 for k_c [14]. Equation 2 gives the expression for ultimate load-carrying capacity with a substituted value of k_c.

$$P_o = 0.85 f'_c (A_g - A_{st}) + f_y A_{st} \tag{2}$$

Because of the poor performance of GFRP bars under compression ACI standards does not recommend the use of it. Canadian Standards [15] permits the use of GFRP bars as longitudinal reinforcements in compression members subjected to axial load only, ignoring the contribution of the bars in the load carrying capacity of the column. Equation 3 gives the recommendation of CSA (Canadian Standards Association).

$$P_o = \propto_1 f'_c (A_g - A_f) \tag{3}$$

Where A_f is the area of GFRP reinforcement and $\alpha_1 = 0.85 - 0.0015 f'_c \geq 0.67$.

The Equation 4 gives the ACI 318-11 [16] design equation ignoring the contribution of reinforcement in the load carrying capacity of the column.

$$P_o = 0.85 f'_c (A_g - A_f) \tag{4}$$

Previous researchers [1] introduces a new expression for finding the theoretical load carrying capacity of GFRP reinforced column as given in the Equation 5.

$$P_o = 0.85 f'_c (A_g - A_f) + \propto_g f_{yf} A_f \tag{5}$$

Where f_{yf} is the strength of GFRP bars and α_g is a new factor which is used to account the reduced compressive strength of GFRP bars as a function of its tensile strength. Previous researchers fix a value of 0.35 for α_g [8, 17]. The ratio of the experimental values of load carrying capacities of axially and eccentrically loaded GFRP reinforced columns to the theoretical values (that is P_o/P_{ult}),

were 1.12 and 1.02 respectively. This shows the accuracy of the equation to predict the load carrying capacity of GFRP reinforced columns.

5. Conclusion
Based on the results obtained from the experimental program the following conclusions were made.

- Under the axial loading, the yield point load showed by the steel reinforced column was 37% more than that of GFRP reinforced column and the ultimate load showed by the steel reinforced column was 34% more than that of GFRP reinforced column. When loaded eccentrically, the yield load showed by steel reinforced column was 31% more that of GFRP reinforced columns and the ultimate load at failure of the steel reinforced column was 34% more than that of GFRP reinforced column. The deficiency of GFRP reinforced columns is due to the micro buckling of fibres in the bars.
- The energy absorbed by steel reinforced column was 40% more than that of GFRP reinforced column when loaded axially and it was 55% more than GFRP reinforced column when eccentrically loaded. The poor energy absorption capacity is also attributed to the micro buckling of the fibres in the bars.
- The result of the experimental program indicates the poor performance of GFRP reinforced column under both axial and eccentric loading.
- When axially loaded the GFRP reinforced column showed a better ductile behaviour. But when loaded eccentrically steel reinforced column showed better ductility.
- An analytical model for predicting the ultimate load carrying capacity was also made and the experimental results were compared with analytical values. The values given by the equation were conforming to the experimental values obtained.
- Irrespective of the non-corrosive nature of GFRP bars, its contribution in the load carrying capacity of columns is less compared to that of steel reinforcement bars. Hence GFRP bars can be used in members where the contribution of reinforcements in load carrying capacity is less.

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