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Analytical investigation on the load-moment characteristics of GFRP bar reinforced circular NSC and HSC columns

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HIGHLIGHTS

- Procedures of establishing analytical $P-M$ interaction diagrams are proposed.
- Behaviour of GFRP bar reinforced NSC (GFRP-NSC) columns is investigated.
- Behaviour of GFRP bar reinforced HSC (GFRP-HSC) columns is investigated.
- Axial load-bending moment interactions of GFRP-NSC columns are presented.
- Axial load-bending moment interactions of GFRP-HSC columns are presented.

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ABSTRACT

In this study, the efficiency of Glass Fibre Reinforced-Polymer (GFRP) bar reinforced normal strength concrete (NSC) and high strength concrete (HSC) columns in sustaining axial and flexural loads was analytically investigated. Experimental data from available literature were used as benchmarks for the analytical investigations conducted in this study. In addition, a comprehensive parametric study was carried out to investigate the effect of different parameters (i.e., compressive strength of concrete, mechanical properties and reinforcement ratio of GFRP bars, and slenderness ratio of the columns) on the performance of concrete columns reinforced with GFRP bars. It was observed that under concentric axial load, the improvements in the axial load carrying capacity due to increasing GFRP longitudinal reinforcement ratio were more pronounced in GFRP bar reinforced NSC columns than in GFRP bar reinforced HSC columns. It was also observed that HSC columns reinforced longitudinally with GFRP bars with small longitudinal reinforcement ratio or low tensile modulus of elasticity might experience a tensile failure of the GFRP bars located on the tension side of the column cross-sections, especially if the columns are subjected to a high level of axial load eccentricity.

1. Introduction

The corrosion of steel reinforcement of concrete structures located in harsh and aggressive environments is one of the main causes of deterioration (loss in strength and serviceability) of the reinforced concrete (RC) structures. Fibre-Reinforced Polymer (FRP) reinforcement is a corrosion-resistant material. Hence, FRP bars are considered as one of the viable alternatives to conventional steel bars as reinforcement for RC members [1]. In addition to the corrosion resistance, FRP bars possess other attractive characteristics, such as high tensile strength-to-weight ratio and non-electrical and non-magnetic conductivity [2]. However, FRP bars are anisotropic and their compressive strength is comparatively smaller than their tensile strength [3]. Therefore, steel bars cannot be directly replaced with FRP bars in RC members due to the differences in the mechanical properties of the steel and the FRP bars [4].

Several research studies were conducted in recent years to investigate the effect of replacing steel bars with FRP bars on the behaviour of concentrically and eccentrically loaded circular and square normal strength concrete (NSC) columns [5–9]. It was reported that the compressive strength of the FRP bar was about 30–77% of the tensile strength [10–12]. It was also reported that FRP bar reinforced concrete columns sustained about 5–13% lower axial load than concrete columns reinforced with the same amount of steel bars [13,14]. Furthermore, it was reported that the longitudinal FRP bars contributed to about 5–15% of the total axial load carrying capacity of the FRP bar reinforced concrete columns, while

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Nomenclature

A_c	area of the concrete in the compression region of the column specimen cross-section
A_{fi}	area of the GFRP longitudinal bars
A_g	gross area (the area of the reinforced concrete core plus the area of concrete cover) of the column specimen
β_1	parameter defines the height of the equivalent rectangular stress block (ERSB)
b_{si}	width of each concrete strip
c	neutral axis depth
C_c	concrete compression force in the compression region of the column specimen cross-section
C_{ci}	concrete compression force in each individual concrete strip located in the compression zone of the column specimen cross-section
C_{cfi}	concrete compression force of the concrete area displaced by the *i*th layer of GFRP longitudinal reinforcement
d_{ci}	distance between the mid-height of the *i*th concrete strip to the extreme concrete compression fibre that has the ultimate concrete compressive strain
d_{fi}	distance between the extreme concrete compression fibre of the column cross-section to the centre of the *i*th layer of GFRP longitudinal reinforcement
e	eccentricity of the applied axial load
E_c	elastic modulus of the concrete
E_f	tensile elastic modulus of FRP bars
f_c	concrete axial stress
$\mathrm{f'}_{\mathrm{c}}$	compressive strength of concrete obtained from testing concrete cylinders at age of 28 days
f_{ci}	concrete stress in each concrete strip
f_{cfi}	concrete axial stress in the concrete area displaced by *i*th layer of GFRP longitudinal reinforcement
$\mathrm{f'}_{\mathrm{co}}$	unconfined concrete strength
F_{fi}	force in the *i*th layer of GFRP longitudinal reinforcement
f_{fi}	stress in the *i*th layer of GFRP longitudinal reinforcement
f_{fu}	ultimate tensile strength of FRP bars
h	diameter of the column specimen
κ	factor that controls the slope of the ascending and the descending branches of the concrete stress–strain curve
l	length of the column specimen
kl	the effective length of the column specimen
m	number of GFRP longitudinal bars
M	bending moment
M_{ci}	bending moment of each individual concrete strip
M_{cfi}	bending moment for the concrete area displaced by the *i*th layer of GFRP longitudinal reinforcement
P	axial load
$\Delta P_{n,CCS}$	the increase in the axial load carrying capacity of GFRP bar reinforced concrete columns due to increasing the concrete compressive strength
$P_{n,CCS_{30}}$	the axial load carrying capacity of GFRP bar reinforced 30 MPa concrete columns
P_{n,CCS_i}	axial load carrying capacity of GFRP bar reinforced concrete columns with concrete compressive strength of 40, 50, 60, 70 or 80 MPa
$\Delta P_{n,MPLR}$	the increase in the axial load carrying capacity of GFRP bar reinforced concrete columns due to increasing tensile elastic modules of FRP bars
P_{HV}	axial load carrying capacity of concrete columns reinforced longitudinally with GFRP bars having tensile elastic modules of 70 GPa
$P_{n,LV}$	axial load carrying capacity of concrete columns reinforced longitudinally with GFRP bars having tensile elastic modules of 35 GPa
$\Delta P_{n,LRR}$	the increase in the axial load carrying capacity of GFRP bar reinforced concrete columns due to increasing the GFRP longitudinal reinforcement
$P_{n,LRR_{1\%}}$	axial load carrying capacity of concrete columns with GFRP longitudinal reinforcement ratio of 1%
P_{n,LRR_i}	the axial load carrying capacity of concrete columns with GFRP longitudinal reinforcement ratio of 2%, 3% or 4%
q	concrete stress–strain curve fitting factor
r	radius of gyration of the column specimen
r_c	radius of the column specimen cross-section
t_{si}	depth of each concrete strip
$\bar{y}$	distance between the centroid of the column specimen to the centroid of concrete in the compression region column specimen cross-section
α_1	parameter defines the width of the equivalent rectangular stress block (ERSB)
α_f	reduction factor that accounts for the difference between the compressive and the tensile strengths of FRP bars
ε_c	concrete axial strain
ε_{ci}	average strain in the *i*th concrete strip
ε_{cfi}	concrete strain of the concrete area displaced by the *i*th layer of GFRP longitudinal reinforcement
ε_{co}	unconfined concrete strain
ε_{cu}	ultimate concrete compressive strain
ε_{fi}	strain in the *i*th layer of GFRP longitudinal reinforcement
θ	an angle used in expressing the area of the concrete in the compression region of the column cross-section
$\varnothing_{mid}$	the curvature at mid-height of the column
Δ_{mid}	the deflection at mid-height of the column
ρ_f	GFRP longitudinal reinforcement ratio
ρ_s	steel longitudinal reinforcement ratio

the contribution of the same amount of longitudinal steel bars ranged between 12 and 16% of the total axial load carrying capacity of steel bar reinforced concrete columns [5,6,15]. In addition, it was observed that under eccentric axial loads, GFRP bar reinforced NSC columns generally exhibited a slightly lower stiffness in the ascending part of the axial load-axial deformation curves than the steel bar reinforced NSC columns due to the lower modulus of elasticity of the GFRP bars compared to the steel bars [16,17]. It was also observed that the eccentrically loaded GFRP bar reinforced NSC columns failed due to the crushing of concrete in the compression side [16,17]. The spacing of the horizontal cracks in the tension side of the eccentrically loaded GFRP bar reinforced NSC columns depends on the pitch of the GFRP helices [16,17].

Research studies on the behaviour of FRP bar reinforced high strength concrete (HSC) columns (especially columns subjected to eccentric axial loads) are limited. Hales et al. [18] observed that the failure of GFRP bar reinforced HSC columns tested under eccentric axial loads with small eccentricities was due to the crushing of the concrete accompanied by the compressive rupture of longitudinal GFRP bars and the tensile rupture of the GFRP helices. It was also observed that the hoop strain in the GFRP helices at failure was significantly lower in HSC columns than in NSC