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Performance evaluation of high strength concrete and steel fibre high strength concrete columns reinforced with GFRP bars and helices

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HIGHLIGHTS

- Behaviour of GFRP bar reinforced HSC (GFRP-HSC) columns is investigated.
- Behaviour of GFRP bar reinforced steel fibre HSC (GFRP-SFHSC) columns is reported.
- Axial load-bending moment (*P-M*) interactions of GFRP-HSC columns are presented.
- Axial load-bending moment interactions of GFRP-SFHSC columns are also presented.
- Procedure of establishing analytical *P-M* interaction diagrams is proposed.

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ABSTRACT

This study presents the results of an experimental investigation on high strength concrete (HSC) and steel fibre high strength concrete (SFHSC) circular column specimens reinforced longitudinally and transversely with Glass Fibre-Reinforced Polymer (GFRP) bars and helices, respectively. The Influence of the type of the reinforcement (steel and GFRP), the pitch of the transverse reinforcement, the addition of the steel fibres and the loading condition (concentric, eccentric and four-point loading) on the performance of the specimens was investigated. The study showed that the GFRP bar reinforced HSC (GFRP-HSC) specimen is as efficient as the steel bar reinforced HSC (steel-HSC) specimen in sustaining concentric axial load. However, the maximum load sustained by the GFRP-HSC specimens under eccentric axial load was 10–12% lower than the maximum load sustained by the steel-HSC specimens. GFRP bar reinforced SFHSC (GFRP-SFHSC) specimens sustained 3–13% higher axial load and 14–27% greater ductility than GFRP-HSC specimens under different loading conditions. Furthermore, reducing the pitch of the GFRP helices in GFRP-SFHSC specimens resulted in a significant improvement in the ductility and the post-peak axial load-axial deformation behaviour of the specimens.

1. Introduction

Fibre-Reinforced Polymer (FRP) reinforcing bars feature many advantageous characteristics such as high tensile strength, high durability, light weight and resistance to harsh environmental conditions. These features make the FRP reinforcing bars ideal replacements for the conventional steel bars in reinforcing concrete structures that require such features. Investigation on the structural behaviour of FRP bar reinforced concrete members became the major objective of many recent studies. The flexural behaviour of FRP bar reinforced normal and high strength concrete members were extensively investigated in the last two decades [1,2]. These studies significantly contributed in developing guidelines and standards for the design of FRP bar reinforced concrete flexural members. However, the behaviour of FRP bars under compression loads is considered complicated. This is because the nonhomogeneous and anisotropic nature of the FRP bars, which leads to micro-buckling of fibres in the FRP bars under axial compression [3]. Accordingly, The ACI 440.1R-06 [4] does not recommend reinforcing concrete columns longitudinally with FRP bars. The CAN/CSA S806-12 [5] ignores the contribution of FRP bars in the compression zone of both flexural and compression members. Moreover, the ACI 440.1R-15 [6] provides no guidelines for the use of FRP bars in reinforcing compression members. The structural behaviour of FRP reinforced compression members were investigated in few research studies [7–9]. However, these studies were limited to FRP bar reinforced concrete columns cast with normal strength concrete (NSC) with compressive strength lower than 50 MPa.

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Hence, the observations obtained from these studies may not be adequate for FRP bar reinforced HSC columns, since the behaviour of HSC columns differs significantly from NSC columns [10–12]. Given the lack of experimental investigations on HSC compression members reinforced with FRP reinforcement, this study intends to expand the current state of knowledge through experimentally investigating the structural behaviour of HSC columns reinforced longitudinally and transversely with Glass Fibre-Reinforced Polymer (GFRP) bars and helices, respectively. Investigations on the behaviour of Carbon Fibre Reinforced Polymer (CFRP) and Aramid Fibre Reinforced Polymer (AFRP) bar reinforced concrete columns are considered beyond the scope of this paper.

The majority of the experimental results reported in the previous studies on the behaviour of FRP bar reinforced NSC columns [13–15] were based on columns tested under concentric axial load. Only few studies provided experimental data from columns tested under eccentric axial load [16,17]. In fact, concrete columns are usually subjected to a combination of concentric axial load and bending moment rather than a pure concentric axial load. Hence, this study investigates the effect of different loading conditions (concentric and eccentric axial load as well as four-point loading) on the behaviour of GFRP bar reinforced HSC columns (GFRP-HSC).

The other focus of this study is to investigate the effect of adding steel fibres to the GFRP bar reinforced HSC (GFRP-HSC) columns. The main objective of the addition of steel fibres is to overcome the lack of ductility that might be experienced by the GFRP-HSC columns, where both HSC and GFRP bars are brittle compared to the NSC and conventional steel bars, respectively. In addition, steel fibres may improve the post-peak behaviour of GFRP-HSC columns and thus providing adequate warning before the failure of GFRP-HSC columns. Hence, the behaviour of GFRP bar reinforced steel fibre high strength concrete (GFRP-SFHSC) column is also investigated in this study.

2. Experimental program

2.1. Specimen design and preparation

The experimental tests consisted of 16 circular column specimens of 210 mm diameter and 800 mm height. The specimens were divided into four groups with four specimens in each group. The specimens in the first group (Group S60) were prepared as reference specimens for comparison purposes. The Group S60 specimens were reinforced in the longitudinal direction with six N12 (deformed steel bars with 12 mm diameter) and transversely with R10 (rounded steel bars with 10 mm diameter) helices with 60 mm pitch. Group S60 specimens satisfy the requirements of ACI 318-14 [18]. The specimens in the second group (Group G60) were reinforced with six #4 (nominal diameter = 12.7 mm) GFRP bars in the longitudinal direction and transversely with #3 (nominal diameter = 9.5 mm) GFRP helices with a pitch of 60 mm. The specimens in this group were designed to investigate the effect of the direct replacement of steel reinforcement with the same amount of GFRP reinforcement on the behaviour of HSC columns. The specimens in the third group (Group G60F) were also reinforced with six #4 GFRP bars and with #3 GFRP helices with 60 mm pitch in the longitudinal and transverse directions, respectively. In addition, steel fibres with volumetric ratio (υ_f) of 1% were added to the HSC mix used in casting the specimens in Group G60F. The specimens in this group were designed to investigate the effect of the addition of steel fibres on the behaviour of GFRP bar reinforced high strength concrete (GFRP-HSC) columns. The specimens in the fourth group (Group G30F) were reinforced longitudinally with six #4 GFRP bars and transversely with #3 GFRP helices with 30 mm pitch. As in Group G60F, steel fibres of 1% (by volume) were added to the HSC mix used in casting the specimens in Group G30F. The specimens in this group were designed to study the combined effect of the pitch of GFRP transverse reinforcement and the addition of steel fibre on the strength and ductility of GFRP bar reinforced HSC columns. The test matrix of the specimens is presented in Table 1. The dimensions and reinforcement configurations of the specimens are shown in Fig. 1.

The first specimen of each group was concentrically loaded. The second and the third specimens of each group were tested under eccentric axial load with eccentricities of 25 mm and 50 mm, respectively. The fourth specimen of each group was tested as beam under four-point loading in order to assess the pure flexural behaviour of the specimens. The loading conditions used in this study (including the 25 and 50 mm eccentric axial loads) were selected based on the testing facilities available at the University of Wollongong, Australia.

The specimens are labelled by a series of letters and numbers corresponding to the reinforcement type, configuration of the transverse reinforcement, loading conditions and the presence of the steel fibres (Table 1). The first letter in each specimen label refers to the reinforcement material, where "S" refers to steel reinforcement and "G" refers to GFRP reinforcement. The first number in each specimen label refers to the pitch of the helices. The second letter "E" and the second number in each specimen label stand for the loading condition: E0 refers to concentric load; E25 and E50 refer to axial loads with 25 mm and 50 mm eccentricity, respec-

Table 1
Test matrix.

Group	Specimen	Longitudinal reinforcement	Transverse reinforcement	Steel fibres ratio, υ_f (%)	Loading eccentricity (mm)
S60	S60E0	Steel 6N12	Steel R10 @ 60-mm Pitch	–	0
	S60E25				25
	S60E50				50
	S60B				Four-point loading
G60	G60E0	GFRP 6 #4	GFRP #3 @ 60-mm Pitch	–	0
	G60E25				25
	G60E50				50
	G60B				Four-point loading
G60F	G60E0	GFRP 6 #4	GFRP #3 @ 60-mm Pitch	1.0	0
	G60E25F				25
	G60E50F				50
	G60BF				Four-point loading
G30F	G30E0F	GFRP 6 #4	GFRP #3 @ 30-mm Pitch	1.0	0
	G30E25F				25
	G30E50F				50
	G30BF				Four-point loading