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Flexural behaviour of GFRP reinforced high strength and ultra high strength concrete beams

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HIGHLIGHTS

- HSC and UHSC GFRP-RC beams reinforced with GFRP bar were tested to investigate flexural behaviour.
- Failure modes of HSC and UHSC GFRP-RC beams were identified.
- FRP design recommendations were compared with experimental results.
- Over-reinforced HSC and UHSC GFRP-RC beams showed an amount of pseudo "ductility".

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ABSTRACT

FRP bars are considered alternatives to steel bars for reinforcing concrete structures in harsh environments. FRP bars are non-corrosive, light weight, non-magnetic and have high longitudinal strength and low thermal and electric conductivity. This paper experimentally investigated the flexural behaviour of high strength concrete (HSC) and ultra-high strength concrete (UHSC) beams reinforced with glass fiber reinforced polymer (GFRP) bars that has not been addressed in the literature before. Beams of 2400 mm long, 100 mm wide and 150 mm high were tested under quasi-static loading (three point loading). Influence of reinforcement ratio and compressive strength of concrete (HSC and UHSC) on the load carrying capacity, deflection, energy absorption, strains in the concrete and reinforcement, and failure modes were investigated. Test results found that over-reinforced HSC and UHSC GFRP bar reinforced concrete (GFRP-RC) beams showed an amount of pseudo "ductility" compared to under-reinforced HSC and UHSC GFRP-RC beams, where failure was brittle, without any prior warning. Energy absorption capacities were found to be higher for UHSC GFRP-RC beams for the same amount of reinforcement compared to HSC GFRP-RC beams. FRP design recommendations in ACI (2015) and CSA (2012) were compared with experimental data. FRP design recommendations for the calculation of flexural strength were found to be conservative (load-carrying capacity was under-predicted by 36% for both HSC GFRP-RC beams and UHSC GFRP-RC beams). However, FRP design recommendations for the calculation of deflection at the load carrying capacity were found to be un-conservative (deflections were under-predicted by an average of 10–22% for the HSC GFRP-RC beams and UHSC GFRP-RC beams).

1. Introduction

Steel bars have been traditionally used as reinforcement for concrete structures. However, the use of steel bars is not recommended in marine and coastal areas [1]. This is due to the possibility of corrosion of the reinforcing steel in the concrete structures [2], causing structural, financial and safety concerns. To prevent corrosion, the use of Fibre-Reinforced Polymer (FRP) bars is recommended in aggressive environments [3]. Advantages of FRP bars over conventional steel bars include non-corrosive behaviour, high longitudinal tensile strength in the direction of the fibres, non-magnetic and lightweight characteristics. However, FRP bars are brittle with linear-elastic stress-strain behaviour. FRP bars do not yield like steel reinforcement. Other disadvantages of FRP bars include low elastic modulus, low shear strength and high cost. However, the use of FRP bars to reinforce marine infrastructure, where corrosion of steel is highly likely, the service life and durability of the marine structures will be increased, resulting in a decrease in overall life-cycle costs [4]. Available FRP bars for

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Nomenclature

A_f	area of FRP tensile reinforcement
b	width of beam
d	effective depth
E_1	energy absorption up to peak 1
E_2	reserve capacity of over-reinforced GFRP-RC beams
E_c	elastic modulus of concrete
E_f	elastic modulus of GFRP reinforcement
f_r	modulus of rupture
f_u	tensile strength of GFRP reinforcement
f_c^{prime}	nominal concrete strength
h	height of beam
I	moment of inertia
I_{cr}	moment of inertia of transformed cracked section
I_e	effective moment of inertia
I_g	gross moment of inertia
I_t	gross moment of inertia
k	ratio of depth of neutral axis to reinforcement depth
L	span length of GFRP-RC beam or free length of the tensile test specimen
L_a	length of steel anchors used for GFRP tensile test specimens
L_g	distance from the support to the point where $M_a = M_{cr}$ in a simply supported beam
L_{tot}	total length of GFRP tensile test specimen
M_a	applied moment
M_{cr}	cracking moment
M_n	nominal bending moment capacity
n_f	ratio of elastic modulus of FRP bar to modulus of elastic of concrete
P	load
P_{cr}	cracking load
P_n	nominal load carrying capacity
P_u	experimental load carrying capacity
y_t	distance from centroidal axis of gross section, neglecting reinforcement, to tension face
α_1	stress block factor
β_1	factor taken as 0.85 for concrete strength up to and including 28 MPa. Factor is reduced at a rate of 0.05 per each 7 MPa of strength greater than 28 MPa but not taken less than 0.65
β_d	reduction coefficient used in calculating deflection
γ	integration factor
δ	deflection
δ_{max}	maximum deflection
Δ	deflection
Δ_{exp}	experimental deflection
Δ_{pred}	predicted deflection
$\varepsilon_{c.avg}$	average strain in concrete from the two concrete strain gauges
ε_{cu}	assumed ultimate strain in concrete, taken as 0.003 or 0.0035
$\varepsilon_{frp.avg}$	average strain of the GFRP strain gauges on the tensile reinforcement
ε_{fu}	rupture strain of the GFRP tensile reinforcement
η	$1 - I_{cr}/I_g$
λ	modification factor reflecting the reduced mechanical properties of lightweight concrete
ρ_f	GFRP longitudinal reinforcement ratio
ρ_{fb}	balanced GFRP longitudinal reinforcement ratio
$\varnothing$	diameter of GFRP reinforcement bar

commercial use include glass FRP bars (GFRP), carbon FRP (CFRP), aramid FRP (AFRP) and basalt FRP (BFRP). These types of FRP bars have varying mechanical and physical properties as well as different surface configurations.

The flexural behaviour of FRP-reinforced concrete (FRP-RC) beams has been extensively studied [4–14]. In these studies, the effects of normal and high strength concrete on the flexural behaviour of FRP-RC beams were investigated. Majority of the previous studies investigated beams with concrete strengths ranging from 20 to 80 MPa [4–12,14]. However, there are only a limited number of studies that investigated the flexural behaviour of FRP-RC beams with concrete strengths greater than 80 MPa [13]. Faza and GangaRao [15] investigated the flexural behaviour of GFRP-RC beams and reported that the use of higher strength concrete was fundamental to exploit the high tensile strength of the GFRP reinforcement bars. Also, Nanni [16] found that the flexural strength of beams reinforced with FRP bars was highly sensitive to the compressive strength of the concrete and recommended that FRP bars be used with high strength concrete. Similarly, Kalpana and Subramanian [12] stated that the use of high strength concrete results in better performance of the GFRP-RC beams in terms of load carrying capacity and mid-span deflection. Yost and Gross [17] reported that the use of higher strength concrete resulted in more efficient use of the FRP reinforcement. Theriault and Benmokrane [13] reported that the increase or the change in concrete strength did not affect the stiffness of the FRP-RC beams. However, FRP-RC beams reinforced with larger amounts of reinforcement showed larger stiffness compared to beams reinforced with less amount of longitudinal reinforcement. Moreover, as concrete strength and reinforcement ratio increased, ultimate moment capacity increased. Getzlaf [18] stated that for over-reinforced GFRP-RC beams, increasing the concrete strength is most beneficial when higher amounts of reinforcement are used. Finally, Goldston et al. [4] reported that the use of higher strength concrete was most beneficial at controlling mid-span deflection as well as increasing bending stiffness. However, in contrast to Theriault and Benmokrane [13], concrete strength did not influence load carrying capacity of GFRP-RC beams in Goldston et al. [4]. Extensive research has been conducted into the flexural behaviour of FRP-RC beams constructed mostly with normal and to a limited extent with high strength concrete (<100 MPa). However, no studies yet investigated the flexural behaviour of GFRP-RC beams with concrete strength greater than 100 MPa.

To address this issue, this paper presents the flexural behaviour of six GFRP-RC beams constructed with concrete of nominal compressive strengths of 80 MPa (high strength concrete, HSC) and 120 MPa (ultra-high strength concrete, UHSC). It is noted that concrete strength above 100 MPa has been defined as UHSC in Vincent and Ozbakkalogu [19] and Ozbakkalogu [20]. Experimental test results were also compared with FRP-RC beam design recommendations in ACI [21] and CSA [22]. It should be noted that the design recommendations in CSA [22] are applicable for concrete strengths up to 80 MPa. While in ACI [21], no limitations of concrete strength has been specified, although the stress block parameters reach the limiting value at concrete compressive strength of 56 MPa. Thus, the experimental results were used to investigate the applicability of the FRP design recommendations in ACI [21] and CSA [22] for concrete strengths greater than 80 MPa.