RESEARCH PAPER

Evaluation of the flexural strength and serviceability of geopolymer concrete beams reinforced with Glass-Fibre-Reinforced Polymer (GFRP) bars

(Title contains 17 words)

Running headline: Evaluation of the flexural strength and serviceability of geopolymer concrete beams reinforced with Glass-Fibre-Reinforced Polymer (GFRP) bars (126 characters)

by

G.B. Maranan[1], A.C. Manalo[1], B. Benmokrane[2], W. Karunasena[1], and P. Mendis[3]
[1] Centre of Excellence in Engineered Fibre Composites (CEEFC),
Faculty of Health, Engineering and Sciences (FoHES),
University of Southern Queensland, Toowoomba 4350, Australia
[2] Department of Civil Engineering, University de Sherbrooke, Sherbrooke, Quebec, Canada J1K 2R1
[3] Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia

Submitted to
Engineering Structures

Corresponding Author:

Allan Manalo
Senior Lecturer in Civil Engineering (Structural)
Centre of Excellence in Engineered Fibre Composites (CEEFC),
Faculty of Health, Engineering and Sciences,
University of Southern Queensland,
Toowoomba, Queensland 4350, Australia
Tel: +61 7 4631 2547 Fax: +61 7 4631 2110
E-mail: allan.manalo@usq.edu.au

Manuscript summary:

Total pages	29 (including 1-page cover)
Number of figures	8
Number of tables	8

Evaluation of the flexural strength and serviceability of geopolymer concrete beams reinforced with Glass-Fibre-Reinforced Polymer (GFRP) bars

G.B. Maranan[1], A.C. Manalo[1,*], B. Benmokrane[2], W. Karunasena[1], and P. Mendis[3]

[1] Centre of Excellence in Engineered Fibre Composites (CEEFC), Faculty of Health, Engineering and Sciences (FoHES), University of Southern Queensland, Toowoomba 4350, Australia

[2] Department of Civil Engineering, University de Sherbrooke, Sherbrooke, Quebec, Canada J1K 2R1

[3] Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia

Email: ginghis.maranan@usq.edu.au; allan.manalo@usq.edu.au; bbenmokrane@andrew.sca.usherb.ca; karu.karunasena@usq.edu.au; pamendis@unimelb.edu.au

Abstract

Geopolymer concrete reinforced with glass-fibre-reinforced polymer (GFRP) bars can provide a construction system with high durability, high sustainability, and adequate strength. Few studies deal with the combined use of these materials, and this has been the key motivation of this undertaking. In this study, the flexural strength and serviceability performance of the geopolymer concrete beams reinforced with GFRP bars were evaluated under a four-point static bending test. The parameters investigated were nominal bar diameter, reinforcement ratio, and anchorage system. Based on the experimental results, the bar diameter had no significant effect on the flexural performance of the beams. Generally, the serviceability performance of a beam is enhanced when the reinforcement ratio increases. The mechanical interlock and friction forces provided by the sand coating was adequate to secure an effective bond between the GFRP bars and the geopolymer concrete. Generally, the ACI 4401.R-06 and CSA S806-12 prediction equations underestimate the beam strength. The bending-moment capacity of the tested beams was higher than that of FRP-reinforced concrete beams from the previous studies.

Keywords: Geopolymer concrete; glass-fiber-reinforced polymer (GFRP) bars; Flexural strength; Serviceability; Effective bond; FRP-reinforced concrete.

*Corresponding author, tel. +61 7 4631 2547; fax. +61 7 4631 2110
E-mail addresses: allan.manalo@usq.edu.au (A. C. Manalo)

1. Introduction

Reinforced concrete (RC) is one of the most commonly used composite materials in the construction of roads, bridges, buildings, and other civil infrastructures. The demand for this material is expected to increase in the future owing to the rise of infrastructure needs in many developing and industrialised countries. In fact, it is estimated that the total global infrastructure demand amounts to USD 4.0 trillion with a gap of at least USD 1.0 trillion per year [1]. Due to the serviceability and economic issues owing to the costly repair and rehabilitation of damaged RC structures caused by the corrosion of the steel bars and the sustainability issue owing to the extremely resource- and energy-intensive process of producing steel and cement materials, however, many engineers and researchers have sought viable alternatives. Among the solutions that are currently being employed are replacing cement-based concrete with geopolymer concrete and replacing steel bars with fibre-reinforced polymer (FRP) bars. Neither, however, can solve the issues altogether.

Geopolymer concrete is considered as a highly sustainable material since it can be manufactured from industrial waste materials that are rich in silica and alumina, like fly ash and blast-furnace slag. A number of studies have shown that geopolymer concrete has properties making it suitable as a construction material [2-5]. On the other hand, aside from being innately corrosion resistant, FRP bars are lightweight, electromechanically neutral, and fatigue- and chemical-resistant, as well as having high tensile-strength properties [6-8]. Given the advantages of these materials, their combined use should yield a durable, cost-effective, and sustainable construction system. As the demand for the rehabilitation of existing RC structures and the construction of new infrastructure increases, accompanied with the mounting fly-ash production mainly in China, India and Australia [9], there is an urgent need for a thorough investigation of the proposed system so as to increase its uptake in the construction industry.

Generally, the behaviour of concrete beams reinforced with FRP bars (FRP-RC) is different from the traditional RC beams in many ways, mainly because of the differences between the physical and mechanical properties of FRP and steel reinforcements [10]. First, FRP-RC beams exhibit lower serviceability performance owing to the lower modulus of elasticity of FRP bars compared to steel bars [11-13]. Secondly, FRP-RC beams are usually designed as over-reinforced because concrete crushing failure is less brittle and less catastrophic compared to FRP rupture failure owing to the rigid and brittle behaviour of FRP bars. Lastly, since the surface geometries and mechanical features of FRP bars are different from steel bars, they bond differently to concrete than steel bars. Some researchers [14-16] predicted the structural behaviour of the FRP-RC system using the existing equations developed for the conventional RC with some modifications to account for these differences.

The flexural performance of steel-reinforced geopolymer concrete (S-RGC) beams is found to be superior even to traditional RC beams. Rangan et al. [17] stated that the behaviour and strength of fly-ash-based RGC beams are similar to those of beams made with Portland cement and suggested that the current design provisions can be used to design fly-ash geopolymer-concrete structural members. Some researchers [9, 18, 19] reported, however, that S-RGC beams have better load-carrying capacity, mainly because of the enhanced mechanical properties of geopolymer concrete compared to conventional concrete of the same grade. This enhancement can be attributed to the better bonding of geopolymer paste compared to cement paste [9]. Even though the strength is different, the load-deflection characteristics, crack patterns, and failure modes of RGC beams are analogous to RC beams [18, 19].

While there are numerous references in the literature about the strength and serviceability performance of FRP-RC and S-RGC beams, few studies have investigated the behaviour of geopolymer concrete beams reinforced with FRP bars, which is the novelty of this research. The direct pullout test conducted by Maranan et al. [20] showed an adequate bond between glass-fibre-reinforced polymer (GFRP) bars and geopolymer concrete resulting from the mechanical interlock and friction force provided by the sand coating on the surface of the GFRP bars indicating their suitability as reinforcement to geopolymer concrete. In this study, the strength and serviceability performance of the geopolymer concrete beams reinforced with GFRP bars were evaluated with a four-point static bending test. The parameters investigated were the nominal bar diameter, the reinforcement ratio, and the anchorage system.

2. Experimental Program

2.1. Materials

2.1.1. Geopolymer Concrete

The geopolymer concrete used in this study was a commercially produced concrete with a proprietary mixture. The geopolymer concrete mix was composed of fine and medium sands, 10 mm and 20 mm coarse aggregates, design water, plasticizer, and a geopolymer paste produced from the chemical activation of two industrial by-products (Class F fly ash and blast furnace slag) using an alkaline liquid. Four 100 mm diameter by 200 mm high geopolymer concrete cylinders were subjected to compression test. Figure 1 shows the compression stress-strain curves of the geopolymer concrete. The average compressive strength and modulus of elasticity of the 28-day geopolymer concrete were 38.2 MPa and 38.5 GPa, respectively.

Furthermore, the modulus of rupture test of four geopolymer concrete prisms with a cross-sectional area of 75 mm by 75 mm and a length 250 mm yielded an average value of 3.86 MPa. This value was computed using Equation 7 in Table 8.

2.1.2. GFRP Bars

The GFRP bars used in this study were provided by V-ROD® Australia [8] and were manufactured by pultrusion process of E-glass fibres impregnated in modified vinyl ester resin. High modulus (HM) GFRP bars (Grade III, CSA S807-10) of varying nominal diameters were considered in this study (Figure 2): 12.7 mm, 15.9 mm, and 19.0 mm nominal diameter sand-coated GFRP bars with fibre contents in percent by weight of 84.1, 83.9, and 84, respectively [21]. Straight (without anchor head) and headed (with anchor head) GFRP bars were used to investigate the influence of the anchorage system on the flexural behaviour of the specimens. The guaranteed properties of GFRP bars as reported by the manufacturer [21] are given in Table 1. The tensile strength and elastic modulus were calculated using nominal cross-sectional area. For the purpose of comparison, 16.0 mm deformed steel bars were utilised as longitudinal reinforcement in one of the tested beams. Table 2 presents the mechanical properties of the steel bar.

2.2. Test Specimens

Five GFRP-reinforced and one steel-reinforced geopolymer concrete beams (the control specimen) were fabricated and tested. The beams had nominal dimensions of 200 mm wide, 400 mm deep, and 3100 mm long. Figure 3 gives the cross-sectional geometry and reinforcement details of the beams. Two 12.7 mm diameter GFRP bars were used for compression-zone reinforcement. The beams were also provided with 9.53 mm diameter GFRP stirrups spaced at 100 mm on-centres. The test parameters were nominal bar diameter, longitudinal tensile reinforcement ratio, and anchorage system. Table 3 summarises the label and classification of the tested beams. The specimens were designated based on the type and amount of bottom longitudinal reinforcement. The first two letters indicate the reinforcement type such as SG for straight GFRP bars (without anchor head), HG for headed GFRP bars (with anchor head), and DS for deformed steel bars. The abbreviation RGC stands for "reinforced geopolymer concrete" followed by a numeral that specifies the number of bottom bars. The last numeral represents the corresponding nominal bar diameter. For example, the specimen identified as SG-RGC-2-19.0 means that it is a geopolymer concrete beam reinforced with two 19.0 mm diameter straight GFRP bars. In this study, Equations 1 (3) and 2 (4), recommended by CSA-S806-12 [22] and ACI 440.1R-06 [23] (ACI 318-08 [24]), were used to calculate the actual reinforcement ratios ρ_f (ρ_s) and the balanced reinforcement ratios ρ_{fb} (ρ_b), respectively, of the geopolymer concrete beams reinforced with GFRP bars (steel bars). Table 8 provides these equations. The equivalent rectangular stress-block factors, α_1 and β_1, were calculated from Equation 5 for CSA code and from Equation 6 for ACI code, both equations can be found also in Table 8. SG-RGC and HG-RGC beams were designed as over-reinforced ($\rho_f/\rho_{fb} > 1.0$), while DS-RGC beam was designed as under-reinforced ($\rho_s/\rho_b < 1.0$). The ultimate strains were assumed equivalent to 0.0035 and 0.003, as per CSA and ACI, respectively.

2.3. Test Setup and Procedure

The four-point static bending test was employed to investigate the flexural performance of geopolymer concrete beams reinforced with GFRP and steel bars. Figure 4 shows the test setup and schematic diagram. The load was gradually applied over a simply supported beam with a clear span and a shear span of 2900 mm and 1100 mm, respectively, through a spreader I-beam using a 2000 kN capacity hydraulic jack at a rate of approximately 3 mm/min. A laser-optical-displacement (LOD) device was placed at midspan to monitor the deflection. In addition, the beams were instrumented with electrical-resistance strain gauges at midspan—bonded to the top surface of the geopolymer concrete and on the top and bottom reinforcement—to measure the longitudinal strains during loading. The strain gauges and sensor were connected to a data-acquisition unit to record their readings continuously.

3. Test Results and Observations

This section summarises the experimental results, including the load–deflection relationship, mode of failure, flexural capacity, midspan deflection, strains in the bars and geopolymer concrete, and cracking behaviour of the tested beams.

3.1. Load–Deflection Relationship

Figure 5 shows the relationships between the experimental bending load and the midspan deflection of SG-RGC and HG-RGC. Generally, the load–deflection curves of SG-RGC have three segments, differing from the typical two-segment curves observed in previous studies [25, 26] for FRP-reinforced concrete, and an unloading curve segment. The first segment is a steep linear branch wherein the deflection increases linearly with the applied load. This phase represented the beam's uncracked condition and was identical for all the tested beams because, at this stage, the load-carrying capacity of the beam was governed predominantly by the geopolymer concrete properties. When the applied load exceeded the geopolymer concrete's tensile strength, vertical cracks appeared at the bottom within the constant moment zone, reducing the beam stiffness. This marked the beginning of the cracked condition of the beam, represented by the second and third segments of the curve. The second segment is composed of an almost linear response up to the peak compressive strain of the geopolymer concrete, followed by a nonlinear response up until the geopolymer concrete crushing failure in the compression zone. The observed nonlinearity was caused by either the extensive cracking at the bottom or the extensive crushing of the geopolymer concrete and not due to yielding of GFRP bars [27, 28]. As the figure shows, the stiffness of the second segment is similar for beams with the same reinforcement ratio. The slope, however, increases as the amount of reinforcement increases. These findings seem to be consistent with the results obtained in FRP-reinforced concrete beams [26, 29, 30]. Afterwards, a sudden load drop occurred, indicating that concrete crushing failure had transpired. Interestingly, the beams did not readily lose their load-carrying capacity after this failure; instead, they continued to sustain additional loads. This behaviour can be attributed to the confinement effect provided by the GFRP stirrups that enhanced the beam ductility and strength. This section represents the third segment of the curve, which has a lower flexural stiffness owing to the initiation of failure in GFRP bars. To avoid any mishaps, the maximum applied load was limited to a magnitude marginally lower than the capacity of the load applicator. Similarly, the behaviour during load removal was recorded to create an unloading curve. This tends to show the elastic characteristic of the beams at higher loads, even after exhibiting nonlinear behaviour or even after the concrete crushing failure. On the other hand, the load–deflection relationship of HG-RGC is comparable to that of SG-RGC with similar amount of reinforcements. Noting that the bars are fully bonded in geopolymer concrete, this result corroborates with the findings of Maranan et al. [31] , which stated that, as the embedment length increases, the bond strength of the straight and headed GFRP bars become analogous to each other.

DS-RGC also yielded a three-segment load–deflection curve, with a different post-cracking nature, and an unloading curve. As can be anticipated, the second segment slope of this beam is steeper compared to those reinforced with GFRP bars owing to the higher modulus of elasticity of the steel bars. As the applied load exceeded the yield strength of the steel bar, a typical yielding plateau occurred: this designates the third segment of the curve. SG-RGC and

HG-RGC did not exhibit this plastic behaviour. Upon the removal of the applied load, an unyielding curve occurred, but the residual deflection of this beam was much higher than that of SG-RGC and HG-RGC.

3.2. Mode of Failure

Table 4 summarises the observed failure modes of the tested beams. As depicted in Figure 6, the over-reinforced SG-RGC and HG-RGC failed in flexure due to geopolymer concrete crushing in the compression zone. The ACI 440.1R-06 and CSA S806-12 codes recommend this mode of failure for any concrete beams reinforced with FRP bars since this type of failure is more gradual, less brittle, and less catastrophic with higher deformability compared to the tensile rupture of FRP bars [32, 33]. On the other hand, Figure 7 shows that the under-reinforced DS-RGC also failed in flexure but steel yielding induced the failure. Since all the tested beams failed according to their intended failure, it can be deduced that the beams were designed satisfactorily.

3.3. Flexural Capacity

3.3.1. Cracking moment

The loads at which the first crack appeared were recorded during the experiment and were verified from the load–deflection and moment–strain relationships. Table 4 presents the experimental cracking moment $M_{cr\text{-}exp}$ of the tested beams. Nearly similar $M_{cr\text{-}exp}$ values were obtained because this parameter mainly depends on the geopolymer concrete tensile strength. The average $M_{cr\text{-}exp}$ was 10.9 kN-m that translates to a modulus of rupture f_r of 3.64 MPa, which is comparable to the f_r (3.86 MPa) of the geopolymer concrete prisms.

3.3.2. At service condition

In this study, two benchmarks were employed to determine the bending-moment capacity at service condition $M_{s\text{-}exp}$. The first criterion was based on ISIS-07 [34], which defines the $M_{s\text{-}exp}$ as the bending-moment that corresponds to a tensile-strain of 2000 με in the reinforcement. Using this principle, the $M_{s\text{-}exp}$ of SG-RGC and HG-RGC were relatively comparable with each other with an average value of 26.2 kN-m. The $M_{s\text{-}exp}$ of DS-RGC, however, was 1.85 times higher than that of SG-RGC and HG-RGC because of the higher elastic modulus of steel bars compared with GFRP bars. The second criterion was based on Bischoff et al.'s [35] recommendation wherein the $M_{s\text{-}exp}$ is approximated as 30% of the beam's bending-moment capacity at failure ($0.3M_{u\text{-}exp}$). All beams reinforced with GFRP bars, except SG-RGC-2-19.0, recorded comparable $M_{s\text{-}exp}$ values. Based on this criterion, however, DS-RGC yielded a lower $M_{s\text{-}exp}$ compared with SG-RGC and HG-RGC due to its lower $M_{u\text{-}exp}$.

3.3.3. At failure

Table 4 provides the experimental bending-moment capacity $M_{u\text{-}exp}$ of SG-RGC and HG-RGC at geopolymer concrete crushing failure and of DS-RGC at steel yielding. The $M_{u\text{-}exp}$ of SG-RGC-2-19.0 (91.4 kN-m), SG-RGC-3-15.9 (104.8 kN-m), SG-RGC-4-12.7 (96.1 kN-m), SG-RGC-5-15.9 (99.3kN-m), and HG-RGC-3-15.9 105.0 kN-m were relatively equivalent to each other. The slight variation can be attributed to the intrinsic nonhomogeneous and anisotropic characteristic of the geopolymer concrete. On the other hand, the early yielding of steel bars prior to geopolymer concrete crushing failure resulted in a lower $M_{u\text{-}exp}$ for DS-RGC-3-16.0 (85.4kN-m) compared with SG-RGC and HG-RGC having similar ρ_f, thereby showing the superiority of the GFRP bars over the steel bars in terms of load-carrying capacity.

3.3.4. At peak

All the tested beams continued to carry additional loads after the concrete crushing failure, yielding another peak named as peak bending-moment capacity $M_{peak\text{-}exp}$ in this study. The $M_{peak\text{-}exp}$ of SG-RGC-2-19.0, SG-RGC-3-15.9, and SG-RGC-4-12.7 were 110.1 kN-m, 104.7

kN-m, and 109.3kN-m, respectively. The initial 25 mm gap between the beam and the load applicator yielded a relatively lower $M_{peak-exp}$ for SG-RGC-3-15.9 compared with the other beams. The 113.8 kN-m and 118.9 kN-m $M_{peak-exp}$ of HG-RGC-3-15.9 and SG-RGC-5-15.9 were slightly higher than that of SG-RGC-3-15.9. Nevertheless, the $M_{peak-exp}$ of the former beams could be much higher than that of the latter beam if the beams were taken to final failure. On the other hand, the $M_{peak-exp}$ achieved by DS-RGC-3-16.0 (74.2 kN-m) was much lower compared to SG-RGC beams of similar ρ_f.

3.4. Midspan Deflection

3.4.1. At service load

Table 5 summarises the immediate midspan deflection at service condition Δ_{s-exp} of the tested beams. The ISIS-07 criterion-based Δ_{s-exp} were 8.7 mm, 7.1 mm, and 10.6 mm for SG-RGC-2-19.0, SG-RGC-3-15.9, and SG-RGC-4-12.7, respectively, while the Δ_{s-exp} based from Bischoff's recommendation were 8.8 mm, 12.3 mm, and 11.5 mm, respectively. Generally, comparable results were obtained for each criterion. The Δ_{s-exp} (7.3 mm and 8.0 mm based on ISIS-07 and Bischoff, respectively) of SG-RGC-5-15.9 was generally lower than that of SG-RGC with lower ρ_f. HG-RGC-3-15.9, on the other hand, yielded similar Δ_{s-exp} as SG-RGC with comparable ρ_f, 10.0 mm based on ISIS-07 and 11.3 mm based on Bischoff's criterion. In general, the Δ_{s-exp} from Bischoff's recommendation were more conservative than that of ISIS-07 in terms of deflection limits set by ACI 440.1R-06 and CSA S806-12 (*L*/240 or 10.8 mm). Thus, the criterion set by Bischoff should be used as the basis for designing GFRP-reinforced geopolymer concrete beams. The Δ_{s-exp} of DS-RGC-3-16.0 was generally higher than that of its SG-RGC counterparts.

3.4.2. At failure

The measured $\Delta_{u\text{-}exp}$ of SG-RGC-2-19.0, SG-RGC-3-15.9, and SG-RGC-4-12.7 were 43.4 mm, 52.5 mm, and 53.2 mm, respectively. Except for SG-RGC-2-19.0, the recorded deflections were almost analogous with each other. SG-RGC-5-15.9 yielded a lower $\Delta_{u\text{-}exp}$ (42.0 mm) compared with the other beams due to its higher stiffness, owed to its higher amount of reinforcements. This finding was also observed by Yoo et al. [30]. The $\Delta_{u\text{-}exp}$ of HG-RGC-3-15.9 (54.1 mm) was nearly comparable to SG-RGC with similar reinforcement ratios. The $\Delta_{u\text{-}exp}$ (28.4 mm) of the DS-RGC beam is much lower than that of the SG-RGC.

3.4.3. At the unloading phase

After removing the applied load, all the beams reinforced with GFRP bars tended to return to their original position. The residual deflections, $\Delta_{res\text{-}exp}$, of SG-RGC were comparable to that of the HG-RGC beam, approximately equivalent to 14 mm. This finding proves the effective flexural bond of the sand-coated GFRP bars in the geopolymer concrete. Furthermore, it also shows the inherent elastic behaviour of the SG-RGC, mainly because of the partial development of the tensile strength of the GFRP bars. The $\Delta_{res\text{-}exp}$ of DS-RGC was approximately four times higher than that of SG-RGC owing to the inelastic yielding of the steel bars.

3.5. Strain Distribution

Figure 8 shows the relationship between the applied moment and the midspan strains at the top and bottom reinforcements, TB and BB, respectively, and on the top surface of the geopolymer concrete (GC). The analogous curvature of the moment–strain curves in TB, BB, and GC indicates the effectiveness of sand coating in anchoring the GFRP bars in the geopolymer concrete. Interestingly, the shape of the moment–strain curves of the reinforcement is similar to their load–deflection curves, including an initial linear segment with a steep slope, linear and nonlinear segments with reduced slope after cracking, and a nonlinear segment after the crushing failure of the geopolymer concrete. The moment–strain curves of the geopolymer concrete in compression zone consisted only of the first two segments since the strain gauges were damaged after the crushing failure. The top GFRP bars, however, continued to provide strain readings. This can be due to the confinement effect provided by the stirrups that protected the bars from buckling and/or kinking.

Table 6 summarises the bar and concrete strains at service condition as defined by Bischoff, at concrete crushing failure, and at peak load. SG-RGC with similar reinforcement ratios yielded nearly comparable strains at different load stages. The tabulated values make it clear, however, that increasing the reinforcement ratio would generally result in lower strains at the bottom GFRP bars. The strain readings at service condition of DS-RGC were generally lower than that of SG-RGC.

3.6. Cracking Behaviour

For all the tested beams, a few fine vertical flexural cracks first developed within the pure bending-moment zone after the in-plane bending-moment exceeded the cracking moment of the beams. As the applied load increases, these cracks became wider and propagated upward, while new vertical cracks formed along the beams' shear span. The vertical cracks in SG-RGC and HG-RGC, at service condition, were generally wider than that of DS-RGC, owing to the lower elastic modulus of GFRP bars compared with steel bars. With further loading, the vertical cracks in the pure bending zone became even wider, while the inclined cracks, induced by shear stress, formed along the shear span and then propagated towards the points of load application. The rate of progress of the inclined cracks, however, slowed down with the initiation of concrete crushing in the compression zone, thereby redistributing the stresses within the zone. At the final loading stage, a marginal number of inclined cracks reached the crushed zone of the geopolymer concrete. Furthermore, all the beams experienced significant flexural cracking before the inclined cracks joined the flexural cracks, thereby assuring that the beams failed in flexure and not in shear.

Figure 9 depicts the crack pattern at peak of the tested beams. The number of cracks developed along the span of DS-RGC was smaller than that of SG-RGC and HG-RGC, but the cracks were wider and mostly concentrated at midspan, owing to yielding of the steel bars in this region. The figure clearly shows that the cracks were distributed uniformly along the span of SG-RGC, with a crack spacing of about 100 mm, similar to stirrup spacing. Ehsani et al. [36] and Faza & Gangarao [6] also reported this uniform crack distribution for concrete beams reinforced with sand-coated FRP bars. The tendency of the cracks to form at the stirrups location was due to the loss of bond between the GFRP bars and the geopolymer concrete. The stirrups caused the discontinuity of the mechanical interlock and friction force resistance of the sand coating, thereby yielding a spike in the concrete stresses. This could also explain the reason why there is no significant effect on the crack spacing upon doubling the amount of the GFRP reinforcement, as was also reported by Theriault et al. [29] and Masmoudi [37]. The absence of transverse reinforcements would increase the contact area between the longitudinal GFRP reinforcements and the geopolymer concrete that would lead to an increase in the rate of stress transfer from the reinforcements to the geopolymer concrete, thereby reducing the crack spacing. The study conducted by Kassem et al. [26], on the other hand, showed that the beams with bundled sand-coated FRP bars developed fewer cracks with wider spacing than those with single bars owing to the better bond quality for single bars compared with bundled bars. This crack spacing mechanism described as a function of bond between the reinforcement and the concrete has been well researched and presented in the previous studies [38-43].

Comparable crack patterns were observed between SG-RGC and HG-RGC with similar ρ_f. The figure also demonstrates that the anchor heads have no significant influence on beam cracking behaviour and that an adequate bond can be secured with sand coating alone.

4. Discussion

This section summarises the influence of the nominal bar diameter, reinforcement ratio, and anchorage system on the flexural performance of the geopolymer concrete beams reinforced with GFRP bars. A comparison between the experimental and theoretical results was also presented in this section. The published results on FRP-reinforced concrete beams were compared with the experimental results.

4.1. Influence of the Nominal Bar Diameter

This study utilised 12.7 mm, 15.9 mm, and 19.0 mm GFRP bars as longitudinal reinforcement for geopolymer concrete beams. Based on the experimental results, the nominal bar diameter had no significant effect on the flexural strength and serviceability performance of the geopolymer concrete beams reinforced with sand-coated GFRP bars. Generally, SG-RGC-2-19.0, SG-RGC-3-15.9, and SG-RGC-4-12.7 yielded similar flexural strengths, load–deflection characteristics, crack patterns, and deflections. The comparable behaviour of these beams can be expected, since these beams were designed as over-reinforced and consequently, their flexural behaviour would mainly depend on the properties of the geopolymer concrete and not on the diameter of the GFRP bars. Furthermore, noting that all the tested beams were manufactured with a single batch of geopolymer concrete, it can expected that beams with similar reinforcement ratios would yield similar flexural performance.

4.2. Influence of the Reinforcement Ratio

The flexural stiffness of the beams after cracking or the slope of the second segment of their load-deflection curves increases as the reinforcement ratio increases. Thus, it can be deduced from the experimental results that the serviceability performance of a GFRP-reinforced geopolymer concrete beam can be enhanced by increasing the amount of longitudinal reinforcement. This improvement can be clearly understood by imagining the bars as parallel springs. As the number of bars increased, the overall stiffness also increased, thereby lowering the deflection after cracking, limiting the crack width, and decreasing the strain in the reinforcement. Yoo et al. [28] reported that the flexural stiffness increased with increasing longitudinal rigidity (A_fE_f) and suggested that the reinforcement ratio should be increased in order to control crack width effectively.

The cracking moments of all the tested beams are similar, since this parameter mainly relied on the properties of the geopolymer concrete. The results also showed that doubling the reinforcement ratio would not significantly enhance the beam load-carrying capacity up to the point of geopolymer concrete crushing failure. This can be expected since all the tested beams were over-reinforced and their strength would be predominantly controlled by the properties of the geopolymer concrete. After the geopolymer concrete crushing failure, the GFRP bars began to sustain several damages and hence, at this stage, the beam strength was influenced by the amount longitudinal reinforcements. The load-carrying capacity of the beam with larger ρ_f was higher than that of beams with lower ρ_f, although the increase was just marginal. This result seems to corroborate with that of Kassem et al. [26] findings wherein they found out that increasing ρ_f by 50% and 100% will marginally increase the flexural capacity by just 4% and 16 %, respectively. The study conducted by Kara et al. [44] showed that, for over-reinforced FRP-reinforced concrete beams, a large increase in FRP reinforcement produced a modest increase in normalised capacity. El-Nemr et al. [6], however, suggested that the influence of ρ_f

on the strength of FRP-reinforced concrete beams could be fully realised when ρ_f is increased three to four times.

4.3. Influence of the Anchorage System

The strength and serviceability performance of HG-RGC was nearly comparable to that of SG-RGC. This can be expected since the straight and headed bars were fully bonded in the geopolymer concrete, thereby yielding similar results. As reported by Maranan et al. [31], the bond strength of the straight and headed GFRP bars approached similar performances as the embedment length increased. Thus, it can be deduced that a composite action can be achieved between the straight bars and the geopolymer concrete by fully embedding the bars in the geopolymer concrete and that the friction and mechanical interlock resistance provided by the sand coating were sufficient to produce a composite action between the GFRP bars and the geopolymer concrete.

4.4. Comparison with Current Design Provisions

In this study, the empirical equations recommended by the CSA S806-12 and ACI 440.R-06 were employed to assess the strength and serviceability performance of SG-RGC and HG-RGC, while the ACI 318-14 code was adapted for the DS-RGC beam. Using Equation 7, the theoretical cracking moments, $M_{cr\text{-}theo}$, based on CSA and ACI are 11.1 kN-m and 11.5 kN-m, respectively. The f_r was calculated from Equation 8 for the CSA code. Equation 9, on the other hand, was used for the ACI codes with the assumption that λ is equivalent to 1.0. Generally, the predicted values were relatively close to the experimental results, with the ACI code providing a more conservative estimate.

The theoretical flexural capacity at concrete crushing failure, $M_{u\text{-}theo}$, of SG-RGC and HG-RGC were determined with Equation 10. In CSA S806-12, the bar stress, f_f, was computed by solving first the neutral axis location, c, from Equation 11 and then substituting this value to Equation 12. For ACI 440.1R-06, the f_f was calculated with Equation 13. On the other hand, Equation 14, recommended by ACI 318-08, predicted the flexural capacity of DS-RGC at steel yielding failure. Table 4 summarises the $M_{u\text{-}theo}$ of the tested beams. The values estimated according to CSA S806-12 were higher than those predicted by ACI 440.1R-06, owing to the β_1 factor and the higher ε'_{cu} normally assumed in CSA (0.0035) compared to ACI (0.003). Generally, both prediction equations underestimated the flexural capacity of all the tested beams. The average theoretical strengths of the beams based on ACI 440.1R-06 and CSA S806-12 are 76 % and 81%, respectively, of the experimental flexural strengths. Generally, this finding can be attributed to three major factors. First, the assumed concrete compressive strains (0.003~0.0035) used in the predictions are lower compared to the actual strain recorded during the flexural tests, which reached higher values ranging from 0.0042 to 0.0048. Second, the prediction equations did not include the contribution of the reinforcement in the compression zone. Finally, the confinement effect due to the lateral ties (stirrups) provided in the pure bending-moment zone were not considered.

Equations 18 and 19 show the deflection formula recommended by the CSA S806-12 and ACI 440.1R-06 codes, respectively. In CSA S806-12, the coefficient η was computed from Equation 20. In the case of ACI 440.1R-06, the effective moment of inertia (I_e) formula, a concept that is used to describe presented in Equation 21 was employed to calculate the midspan deflection. This formula, is Branson's formula for steel-reinforced concrete (Equation 23) modified with by incorporating a reduction factor β_d (Equation 22) to account for the reduced tension stiffening in the FRP-reinforced members [45]. Table 5 summarises the predicted midspan deflections at service condition $\Delta_{s\text{-}theo}$ of the tested beams based on ACI 4401.R-06. In general, the prediction equations underestimated the experimental results. The estimated values based on Bischoff's recommendations were more conservative than ISIS-07 in terms of deflection limit L/240. Table 5 also shows the predicted midspan deflection at failure $\Delta_{u\text{-}theo}$ of the tested beams. Again, both design equations did not conservatively estimate beam $\Delta_{u\text{-}theo}$. The degree of underestimation increased with an increase in the applied load, owing to the overestimation of the tension stiffening parameter. Furthermore, these equations were developed from a full-interaction analysis of transformed section wherein it is assumed that no slip between the concrete and the reinforcements, which is not the case in the actual condition. Visintin et al. [38] suggested the use of partial-interaction theory that allows the slip between the reinforcement and concrete. Thus, considering the mentioned factors and the concept of partial-interaction theory, an appropriate prediction equation is now being developed for the proposed system.

4.5. Comparison between the Experimental Results and the FRP-Reinforced Concrete Beams

Table 7 presents a comparison between the normalised bending-moment capacity (M_u/f'_cbd^2) of the tested beams and the GFRP-reinforced concrete (GFRP-RC) beams obtained from the previous studies. The considered GFRP-RC beams had dimensions, concrete strengths, and reinforcement ratios nearly comparable to the tested beams. Furthermore, the GFRP bars were also sand-coated and all the beams were designed as over-reinforced, such that they failed due to crushing of concrete in the compression zone. Generally, the bending-moment capacity of the tested beams was higher than the bending-moment of the GFRP-RC beams, mainly due to the following factors. First, the geopolymer concrete had enhanced mechanical properties compared to the conventional concrete of the same grade (higher compressive strain capacity based on the flexural test of the beams and better tensile strength and improved modulus of elasticity according to the compression test of the cylinders). Second, all the tested beams had lateral ties within the pure bending-moment span, which provided confinement of the geopolymer concrete core, thereby increasing the beam strength and ductility. Lastly, the tensile strength (617 MPa to 695 MPa) and modulus of elasticity (40 GPa to 55 GPa) of the GFRP bars used in the previous studies were lower than the tensile strength and the modulus of elasticity of the bars used in this study. The high compressive strain capacity of geopolymer concrete was coupled with GFRP bars having a high tensile strength resulted in a beam with high flexural strength and ductility. Table 6 shows the amount of tensile strains in the bottom GFRP bars at geopolymer concrete crushing failure. These strains translate to a tensile stresses than can reach up to 892 MPa. If the beams were reinforced with GFRP bars of lower tensile strength, the beams will fail earlier due to bar rupture, yielding lower flexural strengths.

5. Conclusion

This paper presented an assessment of the strength and serviceability of geopolymer concrete beams reinforced with GFRP bars subjected to four-point static bending testing. Based on the experimental results and theoretical predictions, the following can be concluded:

- The load-deflection curves of the beams with GFRP bars consist primarily of three segments, including a steep linear branch that corresponds to cracked response of the beam; linear and nonlinear segments with reduced slope that represent the cracked response of the beam; and a nonlinear segment after the crushing failure of the geopolymer concrete.
- The beams reinforced with GFRP bars failed by concrete crushing failure, since they were designed as over-reinforced, while the under-reinforced beam with steel bars failed due to reinforcement yielding.
- The bending-moment capacities at concrete crushing failure of GFRP-reinforced geopolymer concrete beams were 1.2 to 1.5 times greater than that of steel-reinforced geopolymer concrete beam with similar reinforcement ratio.

- The uncracked response of all the tested beams was similar since, at this stage, the flexural performance of the beam was governed by the geopolymer concrete properties.
- For beams with similar reinforcement ratios, it appears that the GFRP bar nominal diameter had insignificant effect on their flexural behaviour.
- Increasing the reinforcement ratio would enhance the serviceability performance of the GFRP-reinforced geopolymer concrete beams. Doubling the reinforcement ratio, however, did not increase the beams load-carrying capacity at concrete crushing failure since the beams were designed as over-reinforced and therefore, their strength would be dependent on the geopolymer concrete strength and not by bar rupture.
- The mechanical interlock and friction force resistance provided by the sand coating, bonded on the surface of the GFRP bars, were found to be adequate to secure a composite action between the bars and the geopolymer concrete.
- Generally, both the ACI-440.1R-06 and CSA S806-12 prediction equations underestimated the flexural capacity of GFRP-reinforced geopolymer concrete beams. This may be due to the following factors: lower compressive strains used in the prediction (0.003 and 0.0035, respectively) compared to the actual strains (0.0042~0.0048); neglection of the compression strength contribution of top GFRP bars; and exclusion of the confinement effect of stirrups located in the pure bending-moment zone.
- The bending-moment capacity of GFRP-reinforced geopolymer concrete beams seems to be higher than that of GFRP-reinforced concrete beams mainly because of the enhanced mechanical properties of the geopolymer concrete compared to the conventional concrete of the same grade. Further investigations, however, are needed to support this generalisation.

Nomenclature

a	beam shear span
b	beam width
c	neutral axis depth from the top compression fibre
d	beam effective depth
E_c	modulus of elasticity of the geopolymer concrete
E_f	modulus of elasticity of the GFRP bars
E_s	modulus of elasticity of the steel bars
$f_{r\text{-}exp}$	experimental modulus of rupture of the geopolymer concrete
$f_{r\text{-}theo}$	theoretical modulus of rupture of the geopolymer concrete
f_{fu}	guaranteed tensile strength of the GFRP bars
f_f	tensile stress in the GFRP bars
f_y	yield strength of the steel bars
f'_c	compressive strength of the geopolymer concrete
h	beam total depth
I_{cr}	cracked moment of inertia
I_e	effective moment of inertia
I_g	gross moment of inertia
L	beam clear span
L_g	uncracked beam length
$M_{a.}$	actual bending-moment
$M_{cr.}$	cracking moment
$M_{cr\text{-}exp}$	experimental cracking moment
$M_{cr\text{-}theo}$	theoretical cracking moment
$M_{peak\text{-}exp}$	experimental peak bending-moment
$M_{s\text{-}exp}$	experimental bending-moment at service condition

$M_{u\text{-}exp}$	experimental bending-moment at geopolymer concrete crushing failure
$M_{u\text{-}theo}$	theoretical bending-moment at geopolymer concrete crushing failure
Y	neutral axis depth from the top compression fibre
P	applied load
α_1	constant variable
β_1	constant variable
Δ	midspan deflection
$\Delta_{peak\text{-}exp}$	experimental midspan deflection at peak
$\Delta_{s\text{-}exp}$	experimental midspan deflection at service load
$\Delta_{u\text{-}exp}$	experimental midspan deflection at concrete crushing failure
$\Delta_{u\text{-}theo}$	theoretical midspan deflection at concrete crushing failure
$\Delta_{unl\text{-}exp}$	experimental midspan deflection at the unloaded phase
ε'_{cu}	usable compressive strain of the geopolymer concrete
$\varepsilon'_{cu\text{-}exp}$	experimental compressive strain at geopolymer concrete crushing failure
ε'_{c}	peak strain, compressive strain at peak stress of the geopolymer concrete
ε_{fu}	ultimate usable tensile strain of the GFRP bars
η	constant variable
$Ø_f$	nominal diameter of the GFRP bars
$Ø_s$	diameter of the steel bars
ρ_b	balanced reinforcement ratio of the steel bars
ρ_f	reinforcement ratio of the GFRP bars
ρ_{fb}	balanced reinforcement ratio of the GFRP bars
ρ_s	reinforcement ratio of the steel bars

Acknowledgement

The authors would like to express their special thanks to V-ROD® Australia for providing the materials, the Natural Science and Engineering Research Council of Canada (NSERC), and the technical staff of the structural lab at University of Southern Queensland.

References

[1] Ascione L, Razaqpur AG, Spadea S. Effectiveness of FRP stirrups in concrete beams subject to shear. In: El-Hacha R, editor. The 7th Interntional Conference on FRP Composites in Civil Engineering (CICE 2014). Vancouver, Canada: International Institute for FRP in Construction (IIFC); 2014. p. 368-73.

[2] Hardjito D, Wallah SE, Sumajouw DMJ, Rangan BV. On the development of fly ash-based geopolymer concrete ACI Materials Journal. 2004;101:467-72.

[3] Sumajouw DMJ, Hardjito D, Wallah SE, Rangan BV. Fly-ash based geopolymer concrete: Study of slender columns. Journal of Materials Science. 2007;42:3124-30.

[4] Fernandez-Jimenez AM, Polomo A, Lopez-Hombrados C. Engineering properties of alkali-activated fly ash concrete. ACI Materials Journal. 2006;103:251-7.

[5] Sofi M, Deventer JSJv, Mendis PA, Lukey GC. Engineering properties of inorganic polymer concretes (IPCs). Cement and Concrete Research. 2007;42:3107-16.

[6] Faza SS, Gangarao HVS. Theoretical and experimental correlation of behaviour of concrete beams reinforced with fibre reinforced plastic rebars American Concrete Institute. 1993;SP138:599-614.

[7] Karbhari V, Seible F. Fiber-reinforced polymer composites for civil infrastructure in the USA. Structural Engineering International. 1999;9:186-94.

[8] V-ROD. V-ROD® Australia: Composite reinforcing rod. Inconmat Australia.

[9] Abraham R, Raj S D, Abraham V. Strength and behaviour of geopolymer concrete beams. International Journal of Innovative Research in Science, Engineering and Technology. 2013;2:159-66.

[10] Ribeiro SEC, Diniz SMC. Reliability-based design recommendations for FRP-reinforced concrete beams. Engineering Structures. 2013;52:273-83.

[11] Matos B, Correia JR, Castro LMS, Franca P. Structural response of hyperstatic concrete beams reinforced with GFRP bars: Effect of increasing concrete confinement. Composite Structures. 2012;94:1200-10.

[12] Mousavi SR, Esfahani MR. Effective moment of inertia prediction of FRP-reinforced concrete beams based on experimental results. ASCE Journal of Composites for Construction. 2012;16.

[13] Nawy EG, Neuwerth GE, Philips CJ. Behaviour of fibre glass reinforced concrete beams. ASCE Journal of Structural Division. 1971;97:2203-15.

[14] Noel M, Soudki K. Estimation of the crack width and deformation of FRP-reinforced concrete flexural members with and without transverse shear reinforcement. Engineering Structures. 2014;59:393-8.

[15] Adam MA, Said M, Mahmoud AA, Shanour AS. Analytical and experimental flexural behavior of concrete beams reinforced with glass fiber reinforced polymer bars. Construction and Building Materials. 2015;84:354-66.

[16] Au FTK, Du JS. Deformability of concrete beams with unbonded FRP tendons. Engineering Structures. 2008;30:3764-70.

[17] Rangan BV, Sumajouw D, Wallah S, Hardjito D. Reinforced low-calcium fly ash-based geopolymer concrete beams and columns. Our World in Concrete and Structures. Singapore: CI-Premier PTE LTD; 2006.

[18] Dattatreya JK, Rajamane NP, Sabitha D, Ambily PS, Nataraja MC. Flexural behaviour of reinforced geopolymer concrete beams. International Journal of Civil and Structural Engineering. 2011;2:138-59.

[19] Kumaravel S, Thirugnanasambandam S. Flexural behaviour of geopolymer concrete beams. International Journal of Advanced Engineering Research and Studies. 2013;3:4-6.

[20] Maranan GB, Manalo AC, Karunasena W, Benmokrane B. Bond Stress-Slip: Case of GFRP bars in Geopolymer Concrete. ASCE Journal of Materials in Civil Engineering. 2014.
[21] Pultrall. V-ROD FRP reinforcing bars data sheet. 2012.
[22] CSA. Design and construction of building structures with fibre-reinforced polymers. CSA S806-12. Mississauga, Ontario, Canada: Canadian Standards Association; 2012.
[23] ACI. Guide for the design and construction of structural concrete reinforced with FRP bars. ACI 4401R-06. Farmington Hills, MI, USA: American Concrete Institute; 2006.
[24] ACI. Building code requirements for structural concrete. ACI 318-08. Farmington Hills, MI, USA: American Concrete Institute; 2008.
[25] El-Nemr A, Ahmed EA, Benmokrane B. Flexural behavior and serviceability of normal- and high-strength concrete beams reinforced with glass fiber-reinforced polymer bars. ACI Structural Journal. 2013;110:1077-88.
[26] Kassem C, Farghaly AS, Benmokrane B. Evaluation of flexural behavior and serviceability performance of concrete beams reinforced with FRP bars. ASCE Journal of Composites for Construction. 2011;15:682-95.
[27] Balendran RV, Tang WE, Leung HY, Nadeem A. Flexural behaviour of sand coated glass-fibre reinforced polymer (GFRP) bars in concrete. Our World in Concrete and Structures. Singapore2004. p. 203-12.
[28] Razaqpur AG, Svecova D, Cheung MS. Strength and deformations of FRP reinforced flat slab structures. In: Taerwe L, editor. Proceedings of the Second International RILEM Symposium (FRPRCS-2): E & FN Spon; 1995.
[29] Theriault M, Benmokrane B. Effects of FRP reinforcement ratio and concrete strength on flexural behaviour of concrete beams. ASCE Journal of Composites for Construction. 1998;2:7-16.

[30] Yoo DY, Shin HO, Kwon KY, Yoon YS. Structural behavior of UHPFRC beams according to reinforcement ratio of internal GFRP bar. In: El-Haacha R, editor. The 7th International Conference on FRP Composites in Civil Engineering (CICE 2014). Vancouver, British Columbia, Canada: International Institute for FRP in Construction (IIFC); 2014.

[31] Maranan GB, Manalo AC, Karunasena W, Benmokrane B. Pullout behaviour of GFRP bars with anchor head in geopolymer concrete Composite Structures. 2015;132:1113-21.

[32] Gangarao HVS, Tally N, Vijay PV. Reinforced concrete design with FRP composites: CRC Press; 2007.

[33] Kakizawa T, Ohno S, Yonewa T. Flexural behavior and energy absorption of carbon FRP reinforced concrete beams. American Concrete Institute. 1993;138:585-98.

[34] ISIS. Reinforcing concrete structures with fibre-reinforced polymers. ISIS Design Manual No 3. Winnipeg, Manitoba, Canada: Intelligent Sensing for Innovative Structures (ISIS) Canada; 2006.

[35] Bischoff PH, Gross S, Ospina CE. The story behind the proposed changes to the ACI 440 deflection requirements for FRP-reinforced concrete. In: Ospina C, Bischoff PH, Alkhrdaji T, editors. Serviceability of concrete members reinforced with internal/external FRP reinforcement. Farmington Hills, MI: American Concrete Institute; 2009. p. 53-76.

[36] Ehsani MR, Saadatmanesh H, Tao S. Bond behaviour of deformed GFRP rebars. Journal of Composite Materials. 1997;31:1413-30.

[37] Masmoudi R, Benmokrane B, Chaallal O. Cracking behaviour of concrete beams reinforced with FRP bars. Canadian Journal of Civil Engineering. 1996;23:1172-9.

[38] Visintin P, Oehlers DJ, Muhamad R, Wu C. Partial-interaction Short Term Serviceability Deflection of RC Beams. Engineering Structures. 2013;56:993-1006.

[39] Yankelevsky DZ, Jabareen M, Abutdul AD. One-dimensional analysis of tension stiffening in reinforce concrete with discrete cracks. Engineering Structures. 2008;30:206-17.

[40] Visintin P, Oehlers DJ, Wu C, Haskett M. A mechanics solution for hinges in RC beams with multiple cracks. Engineering Structures. 2012;36:61-9.

[41] Oehlers DJ, Ali MSM, Haskett M, Lucas W, Muhamad R, Visintin P. FRP-Reinforced concrete beams: Unified approach based on IC theory. Journal of Composites for Construction. 2011;15:3-293-303.

[42] Marti P, Alvarez M, Kaufmann W, Sigrist V. Tension chord model for structural concrete. Structural Engineering International. 1998;8:287-98.

[43] Muhamad R, Ali MSM, Oehlers DJ, Sheikh AH. Load-slip relationship of tension reinforcement in reinforced concrete members. Engineering Structures. 2011;33:1098-106.

[44] Kara IF, Ashour AF. Flexural performance of FRP reinforced concrete beams. Composite Structures. 2012;94:1616-25.

[45] Issa MS, Metwally IM, Elzeiny SM. Influence of fibers on flexural behavior and ductility of concrete beams reinforced with GFRP bars. Engineering Structures. 2011;33:1754-63.