COMPARISON OF THE SHEAR BEHAVIOUR OF GEOPOLYMER CONCRETE BEAMS WITH GFRP AND STEEL TRANSVERSE REINFORCEMENTS

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Keywords: Shear behaviour, GFRP bars, Composites, Geopolymer concrete, Stirrups

ABSTRACT

This study presents a comparison of the shear behaviour of geopolymer concrete beams transversely reinforced with glass fiber-reinforced polymer (GFRP) and steel bars. Two full-scale beams with GFRP and steel stirrups spaced at 150 mm on-center were fabricated and tested up to failure using the four-point static bending test. Another beam without web reinforcements was also cast to determine the shear contribution of the geopolymer concrete. All the beams were provided with the same amount of flexural reinforcements. The beams were supported over a 1200 mm clear span with 450 mm shear span on each side. The shear span-to-depth ratio of the beams was 1.8. Based on the test results, the provision of GFRP stirrups almost doubled the shear capacity of the beam without web reinforcements. Comparable load-deflection response, shear strength, deflection capacity, and strain readings were observed between the beams with GFRP and steel stirrups. The two beams yielded similar crack pattern; however, wider cracks were developed in the former beam owing to the lower elastic modulus of GFRP bar compared with steel bar. Furthermore, both beams failed in shear, classified as a diagonal strut compression failure; however, the failure of the beam with GFRP stirrups was induced by the stirrup's lap splice failure while steel yielding caused the failure of beam with steel stirrups. This had led to a more brittle final failure of the former beam compared with the latter beam.

1 INTRODUCTION

The corrosion of the internal reinforcing steel is one of the major factors that reduced the expected service life of reinforced concrete (RC) structures, especially those that are located in harsh environments such as marine and mining areas. The fiber-reinforced polymer (FRP) bar is a viable substitute for steel bar to mitigate such problem and to enhance the durability of the structure [1, 2]. Furthermore, the use of FRP bar is beneficial for the asset owners as the costly repair and rehabilitation of damaged and deteriorating RC structures, caused by steel corrosion, can be prevented. Aside from being innately corrosion-resistant, the other two main advantages of FRP bar include high tensile strength, approximately two times the steel yield strength, and lightweight, around one-fourth of the steel density, which made them suitable for structural applications.

The geopolymer concrete, on the other hand, has the potential to replace cement-based concrete for the development of more sustainable civil infrastructures because the production of cement is a resource-and energy-intensive process. The geopolymer, unlike cement, can be synthesised from industrial waste materials like fly ash and slag that are rich in silica and alumina [3]. For every tonne of cement, 1.5 tonnes of virgin materials are needed to be processed and one tonne of CO_2 are being released in the atmosphere [4]. In fact, around 7% of the world's yearly carbon emission comes from cement industry [5]. Several studies have shown the potential of geopolymer concrete as a construction material because of their excellent physical and mechanical properties [6, 7].

The FRP bar is particularly suitable for transversely reinforcing the concrete members because web reinforcements are more susceptible to corrosion as they are nearer to concrete outer surface compared with the longitudinal bars. However, since FRP does not yield or does not exhibit ductile failure and has lower elastic modulus and shear strength compared with steel, it is anticipated that the shear behaviour of concrete beams with FRP stirrups is different from that of beams with steel stirrups [8, 9]. While there are a considerable studies available that deals with the concrete shear strength contribution, there is a relatively limited research that quantifies the FRP stirrups contribution [1, 9-11], more so, with the use of FRP stirrups in geopolymer concrete beams. These aspects are the key motivation of this study. This paper investigated the shear performance of the geopolymer concrete beam transversely reinforced with glass fiber-reinforced polymer (GFRP) stirrups and compared its performance with the beam having steel stirrups in terms of the load-deflection response, crack pattern and failure mode, shear and deflection capacities, and strains in geopolymer concrete and reinforcements.

2 EXPERIMENTAL PROGRAM

This section summarizes the materials and methods employed in the conduct of this study.

2.1 Materials and test specimen

Figure 1 shows the 9.5 mm GFRP and 10 mm steel web reinforcements used in the study. Both stirrups were 240 mm deep and 150 mm wide. The high modulus (HM) sand-coated GFRP stirrups (Grade III, CSA S807-10 [12]) were provided by V-Rod® Australia [13]. Figure 2 shows the 12.7 mm and 19.0 mm diameter HM sand-coated GFRP bars that were used to longitudinally strengthen the beams at the top and bottom, respectively. The GFRP reinforcements were manufactured through the pultrusion process of E-glass fibers impregnated with modified vinyl ester resin. Table 1 provides the physical and mechanical properties of the GFRP and steel bars as reported by the manufacturers. On the other hand, one batch of commercially produced geopolymer concrete with a proprietary mixture was utilized to fabricate all the beam specimens. The concrete mix consisted of 10 mm and 20 mm coarse aggregates, fine and medium sands, plasticizer, water, and geopolymer binder, synthesized from the alkali- activation of fly ash and slag. The average compressive strength of the cylinders tested after 28 days following the ASTM C39/C39M-04a [14] is 55 MPa.

Three full-scale geopolymer concrete beams were fabricated and tested. The first beam was transversely reinforced with GFRP stirrups spaced at 150 mm on-center, named as B1-G150, while the second beam was reinforced with steel stirrups with the same spacing, labelled as B2-S150. The third beam B3, on the other hand, was cast without web reinforcements to determine the shear contribution of the geopolymer concrete. Figure 3 shows the typical layout of the beams. Each beam had a total length of 1500 mm and was designed as over-reinforced using 2-12.7 mm top GFRP bars and 3-19.0 mm bottom GFRP bars. Table 2 specifies the details of each beam.

3.3 Test set-up and procedure

Figure 3 shows the schematic diagram of the test setup. The four-point static bending test was employed to investigate the shear performance of the beams. The beams were loaded with two concentric loads, 300 mm apart at midspan, yielding a shear span of 450 mm on both sides. The span-to-depth (*a*/*d*) ratio of the beam is 1.8. The location of the electrical gauges was also shown in the figure. The applied load and strain in geopolymer concrete and reinforcements were measured and recorded using a data logger attached to the machine while the midspan deflection was measured using a Laser Displacement Sensor. The crack pattern was documented during the test via visual inspection.

Figure 1 GFRP and steel stirrups.

Figure 2 Sand-coated GFRP bars.

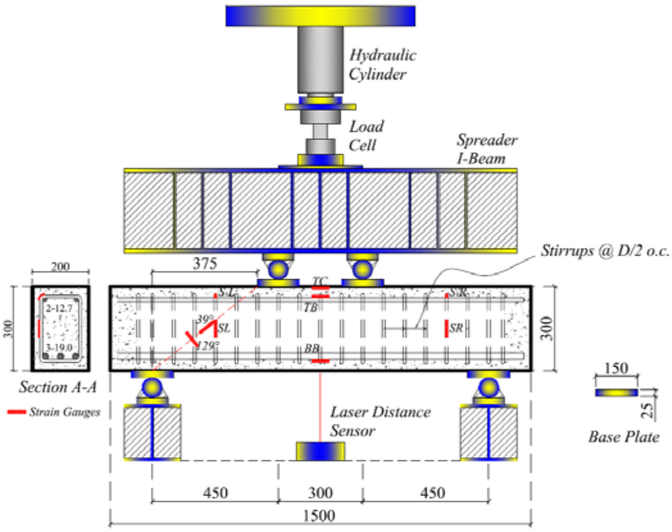


Figure 3 Beam layout and four-point static bending test set-up.

Table 1 Mechanical properties of the GFRP bars.

$Ø_f$ (mm)	f_p^* (MPa)	f_{bend} (MPa)	E_f (GPa)	Glass Content** (% Mass)
9.5	1029	463	50	77.6
12.7	1312	-	65.6 ± 2.5	84.1
19.0	1105	-	63.7 ± 2.5	84.0
$Ø_s$ = 10	f_y = 540		E_s = 200	-

*Guaranteed tensile strength: Average value – 3x standard deviation (ACI 440.1R-06)
**ASTM D3171: Method G, Procedure 1 (Pultrall Inc., 2012)

Table 2 Details of the tested beams.

Beam	Spacing (mm)	ρ_f (%)	ρ_v (%)	$\rho_{fv}E_{fv}/E_s$ (%)
B1-G150	150	1.7	0.47	0.47
B2-S150	150	1.7	0.47	0.12
B3	-	1.8	0	0

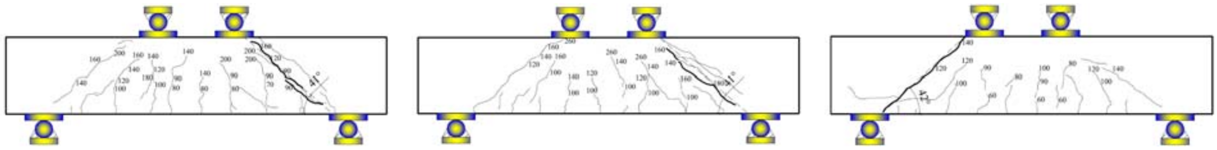
3 RESULTS AND DISCUSSION

This section summarizes the experimental results including the crack pattern and failure mode, load-deflection response, shear load and deflection capacities, and geopolymer concrete and reinforcement strains.

3.1 Crack pattern and failure mode

Figure 4 shows the crack pattern just before the final failure of the tested beams. Several vertical flexural cracks occurred within the constant bending-moment zone after exceeding the geopolymer concrete tensile strength. With further loading, inclined cracks developed at the mid-depth of the beam and then propagated in both directions. These cracks are known as web-shear cracks. The crack inclinations near the supports were gentler compared with that of the cracks near the loading points. The B1-G150 and B2-S150 beams accumulated higher number but narrower cracks compared with the B3 beam, owed to the stirrups' ability to distribute the cracks along the beam span. In fact, the crack spacing in these beams was nearly the same their stirrups spacing. Generally, similar crack pattern and propagation was observed between B1-G150 and B2-S150 beams; however, B1-G150 produced wider cracks compared with B2-S150 beams. The major failure crack angles for all beams varied from 41˚ to 42˚.

Figure 5 presents the failure mode of the tested beams. All the beams exhibited a shear type of failure. The failure of the B3 beam can be classified as a diagonal strut tension (DST) failure wherein the initial inclined cracks, developed at mid-depth of the beam, propagated towards the loading point and support; along the geopolymer concrete strut direction that resulted to longitudinal splitting of the strut. Secondary anchorage failure due to splitting action along the main reinforcement was also observed during the experiment. The B1-G150 beam failure, on the other hand, can be considered as a diagonal strut compression (DSC) failure. The stirrups confining effect prevented the longitudinal splitting, thereby subjecting the strut to extreme compression stress. The lateral expansion of the compression field between the support and the point-load application, however, resulted in the failure of the lap splice located in the stirrup's bent zone that subsequently lead to the beam's failure. The beam also exhibited secondary concrete crushing in the flexural compression zone. The B2-S150 beam experienced the same failure mode as the B1-G150 beam, however, it undergone a more ductile and lesser degree of failure compared with the B1-G150 beam due to steel stirrups yielding.



a. B1-G150 b. B2-S150 c. B3

Figure 4 Crack pattern of the tested beams.

a. DSC failure of B1-G150 b. DSC failure of B2-S150 c. DST failure of B3

Figure 5 Failure mode of the tested beams.

3.2 Load-deflection response

Figure 6 shows the relationship between the applied shear load and the midspan deflection for all the tested beams. Generally, the response of the beams can be categorised into two stages: the pre-cracking and the post-cracking stages. The first stage was characterised by an initial linear response with stiff slope. At this stage, the gross moment of inertia of the geopolymer concrete section was fully utilised. The second stage, on the other hand, was represented by another linear response up to failure but with a reduced stiffness, owed to the successive flexural and shear cracking that reduced the geopolymer concrete beam's moment of inertia. Slight stiffness degradation and nonlinear behaviour occurred in the B1-G150 and B2-S150 beams before reaching the peak load due to the widening of shear cracks and crushing of the geopolymer concrete in the compression zone.

3.3 Shear strength and deflection capacity

Table 3 summarises the applied shear loads when the vertical flexural and shear cracks appeared in the beams, $V_{cr,f}$ and $V_{cr,s}$, respectively. These values were recorded during the test and were verified from the shear load-deflection (Figure 3) and shear load-strain (Figures 9) curves of the tested beams. The $V_{cr,f}$ ($V_{cr,s}$) of B1-G150, B2-S150, and B3 were 25 kN (60 kN), 25 kN (50 kN), and 23 kN (60 kN), respectively. As can be expected, the beams yielded comparable $V_{cr,f}$ ($V_{cr,s}$) since this parameter mainly depends on the tensile strength (shear strength) of the concrete which is a function of its compressive strength. Furthermore, the beams had similar configuration and amount of flexural reinforcements. The slight variation can be attributed with the nonhomogeneous and anisotropic characteristics of the geopolymer concrete.

Table 3 also shows the ultimate shear load capacity V_n and deflection capacity Δ_n of the tested beams. The B3 specimen yielded the lowest V_n (147 kN) and Δ_n (11 mm) among the tested beams. With the provision of GFRP stirrups, however, the V_n and Δ_n of B3 almost doubled amounting to 267 kN and 19 mm, respectively. Generally, these results can be attributed to the stirrups effectiveness in distributing the stresses along the beam shear span and therefore more energy was absorbed, thereby enhancing the load capacity and ductility of the beam. Interestingly, the V_n (267 kN) and Δ_n (11 mm) of B2-S150 were comparable to that of B1-G150. In this study, the shear contribution of the transverse reinforcement V_s was determined by subtracting the shear contribution of the geopolymer concrete V_c, the V_n of B3, from the V_n of each specimen. Obviously, the B1-G150 and B1-G150 yielded an almost similar V_s. It was evident from these values that, in general, the transversely reinforced beams have better capability of sustaining higher loads and higher deflection capacity compared with the beam without web reinforcement, owing to the additional vertical shear contribution and confinement effect of the stirrups.

Table 3 Shear load and deflection capacities of the tested beams.

Beam	$V_{cr,f}$ (kN)	$V_{cr,s}$ (kN)	V_n (kN)	V_s (kN)	Δ_n (mm)	Failure Mode[†]
B1-G150	25	60	267	120	19	DSC
B2-S150	25	50	266	119	19	DSC
B3	23	60	V_c = 147	-	11	DST

[†]DSC = diagonal strut compression failure; DST = diagonal strut tension failure

3.4 Geopolymer concrete and reinforcement strains

Figures 7 and 8 present the strains in the top and bottom reinforcements and at the topmost section of the geopolymer concrete surface, respectively, when plotted against the applied shear load. It was evident from the figures that with the provision of GFRP stirrups, the peak strains achieved by the geopolymer concrete and the longitudinal GFRP bars increased. The B1-G150 and B1-S150 beams recorded almost similar peak strains.

The strain readings at the stirrup's straight leg, located 150 mm mm from the support, are shown in Figures 9. Immediately after the initiation of inclined cracking, the B1-G150 yielded higher strain readings compared with B1-S150 owing to the lower elastic modulus and shear strength of GFRP bar compared with steel bar.

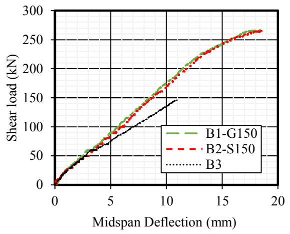


Figure 6 Shear load-midspan deflection relationship.

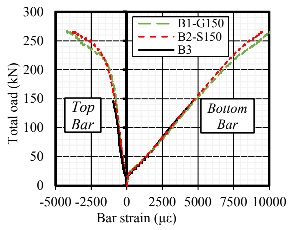


Figure 7 Shear load-longitudinal bar strain relationship.

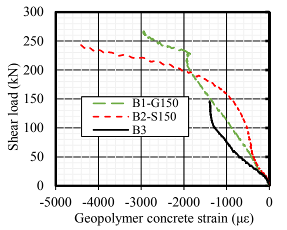


Figure 8 Shear load-geopolymer concrete strain relationship.

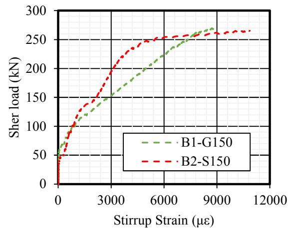


Figure 9 Shear load-stirrup strain relationship.

8 CONCLUSIONS

Based on the four-point static bending test of the geopolymer concrete beam reinforced with GFRP and steel stirrups, the following generalisations were made:

- The load-deflection response, shear strength, deflection capacity, and strain readings of the beam with GFRP stirrups were comparable to that of the beam with steel stirrups.

- The two beams yielded similar crack pattern; however, wider cracks were developed in the former beam owing to the lower elastic modulus of GFRP bar compared with steel bar.
- Although the two beams exhibited similar shear failure mode, compression failure of the diagonal strut, the final failure of the former beam was more explosive as it was induced by GFRP stirrups' lap splice failure while steel yielding caused the latter beam's failure.
- The beams with GFRP transverse reinforcements showed better capability of sustaining higher loads and higher deflection capacity compared with the beam without stirrups because of the added vertical shear contribution and confining effect of the stirrups.
- From the experimental results, it shows that GFRP bars can be a viable substitute for steel bars as transverse shear reinforcements. Further works, however, are needed to support this claim.

ACKNOWLEDGEMENTS

The authors would like to express their special tanks to V-ROD® Australia for providing the materials, the Natural Science and Engineering Research Council of Canada (NSERC), and the technical staff of the Centre of Excellence in Engineered Fibre Composites (CEEFC) at University of Southern Queensland.

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