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Shear Prediction of geopolymer concrete beams using Basalt / Glass FRP bars

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Abstract

Fibre Reinforced Polymer (FRP) bars are effective alternatives to steel bars. This paper performs the shear evaluation of geopolymer concrete beams reinforced with Glass (G) / Basalt (B) FRP bars with Glass/ Basalt stirrups. Totally nine beams of GFRP/BFRP/Steel bars of size 100 × 160 × 1700 mm were cast in geopolymer/conventional concrete and tested by varying the ratio of shear span to an effective depth such as 3.6, 3.9, and 4.3 with a four-point static bending test. The deflection behaviour, moment-curvature, crack pattern, propagation spacing, and the number of cracks was studied. The results are compared with steel reinforced conventional concrete. The prediction equation of the shear strength equation is also proposed and compared with existing models.

1. Introduction

The first Fibre Reinforced Polymer (FRP) bars are used as an alternative to steel bars to avoid corrosion is noticed especially in coastal and marine areas (Sun et al. 2012). Despite a higher initial material cost, the life cycle cost of the FRP reinforced structure is lower than steel. FRP rods are non-corrosive, lightweight with high longitudinal tensile strength in the direction of fibres, and do not have yield behaviour when compared with steel. Thus, in the marine environment, the durability of the structure increases at a reduced overall life cycle cost (Goldston et al. 2016; Tastani and Pantazopoulou 2006). Glass FRP (GFRP) rod is cheaper than Carbon and Aramid FRP rods and it is used in bridge deck slab as reinforcement (Bennokrane 2006).

Presently, a new technology using geopolymer concrete is used to reduce the CO2 emission into the atmosphere due to the industrial manufacturing of cement. The by-product material (Fly ash, Ground Granulated Blast furnace slag, Metakaoline, Silica fume) is mainly activated by alkali activator solution to produce geopolymer concrete through the geopolymerization process which is different from the hydration process (Ganesan et al. 2014). A geopolymer is 10-30% cost-effective than conventional concrete (Lloyd 2010). Inorganic geopolymers have high-temperature resistance, less toxic smoke in fire exposure, are handy, have UV radiation resistance when compared with organic polymers (Balaguru and Kurtz 1997; Toutanji et al. 2006). The combined usage of geopolymer concrete with FRP reinforced structures is the best solution for eco-friendly and sustainable materials.

The FRP fabrics are used as external reinforcements in deficient reinforced concrete structures for renovation (Bank 2006). The ductile and shear behaviour of GFRP bars (El Zareef and Mohamed 2018; Said 2016) were examined. Wang et al. (2018) have studied the durability properties of Basalt Fibre Reinforced Polymer (BFRP) and Glass Fibre Reinforced Polymer (GFRP) bars exposed to a combination of seawater and sea sand concrete (SWSSC) environment under different sustained stress levels and also scanning electron microscopy was employed to study the degradation mechanism of FRP bars. Li et al. (2018) conducted a fatigue test on the two sizes of Basalt FRP (BFRP) bar with sea sand concrete beams since FRP bars with sea sand concrete avoid the corrosion problem, solves the shortage of natural river sand. Also, the authors proposed a fatigue limit as a threshold for the applied load. It was observed that the failure mode of BFRP beams changes from concrete crushing to shear failure when immersed in seawater at 50°C (Dong et al. 2018). With increasing reinforcement ratios, the crack width and mid-span deflection decreases in GFRP bars reinforced concrete beams (Adam et al. 2015). The mode of shear failure and larger shear strength occurred by increasing the arching effect in laterally restrained concrete slabs along with GFRP bars (Zheng et al. 2015).

The shear behaviour of geopolymer concrete beams reinforced with glass fibre-reinforced polymer (GFRP) bars and basalt fibre reinforced polymer (BFRP) bars using M sand by varying the ratio of shear span to effective depth was investigated. Also, a prediction equation for finding shear strength is proposed and compared with existing expressions.

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2. Experimental Details

2.1 Materials used and Preliminary test on materials

2.1.1 Concrete

Aluminosilicate binders such as Fly ash and GGBS, Manufactured sand (M-sand), coarse aggregate (size 8 mm, 12 mm, and 20 mm), and alkali activator solutions were used for making geopolymer concrete. Aggregates were used in Saturated Surface Dry (SSD) condition. 53 grade of ordinary Portland cement, river sand, coarse aggregate (8 mm, 12 mm, and 20 mm), and water are used to make conventional concrete. The composition of fly ash and GGBS are given in Table 1. The physical properties of concrete materials are given in Table 2.

The geopolymer concrete mix proportion used in this investigation is 1 : 2.22 : 3.86 : 6.95 by mass is in the order of alkaline activator solutions, aluminosilicate binder, fine aggregate, and coarse aggregates. The ratio between alkaline activator solutions and binder was 0.45 and the sodium silicate (Na2SiO3) to sodium hydroxide (NaOH) ratio in alkaline activator solution was 2.5.8 M concentration of NaOH solution is used in this study comprised of 8 × 40 = 320 grams of NaOH solids per litre of the solution. The NaOH solids mass was taken as 262 grams per kg of NaOH solution. In this study, the molar ratio (SiO2/Na2O) and H2O present in the Na2SiO3 solution was used as 2.0 and 53.38%. The desired workability of geopolymer concrete is gained using 1% of superplasticizer (Conplast SP430). The mix proportions used for geopolymer and conventional concrete are given in Table 3.

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Specimens were prepared to find the mechanical properties of geopolymer concrete and conventional concrete. Cube of size 150 mm × 150 mm × 150 mm for compression, cylinder of size 100 mm diameter and 200 mm height for split tensile strength and a prism of size 100 mm × 100 mm × 500 mm for flexural strength were cast. The specimens of geopolymer and conventional concrete were cured for 28 days at room temperature and in water, respectively. The Modulus of Elasticity of geopolymer and conventional concrete is derived from the stress-strain curve as a stress to strain ratio up to the elastic limit. Modulus of elasticity is the basic property of a material that describes its stiffness. For this test, the cylinder specimen of size 150 mm diameter and 300 mm height were cast as per Indian Standard 516-1959 (1959). The stress-strain curve for conventional and geopolymer concrete from average of the three values are shown in Fig. 1.

The strength properties and modulus of elasticity of mixes of geopolymer and conventional concrete are given in Table 4.
2.2 Beam specimen details

In this study, nine reinforced concrete beams were cast and tested experimentally under a four-point static bending test. All the beam specimens were prepared with width, depth, and length of 100 mm, 160 mm, and 1700 mm respectively, and were tested for an effective span of 1500 mm in simply supported condition. The details of the beam are shown in Fig. 3.

Among nine reinforced concrete beams, three identical beam specimens were prepared each in GFRP and BFRP reinforced geopolymer concrete beams and three were steel reinforced conventional concrete beams. All the beams were doubly reinforced (i.e.) 2 numbers of 10 mm diameter of GFRP, BFRP, and Steel bars in compression zone and 2 numbers of 12 mm diameters of GFRP, BFRP, and Steel bars in the tension zone were used. The 8 mm diameters of GFRP, BFRP, and Steel bars were used as stirrups. The concrete cover was adopted as 20 mm.

The specimens are classified as X-Y-Z, where X represents the type of reinforced rod (SR-Steel Reinforced, BR-Basalt Reinforced, GR-Glass Reinforced), Y represents the type of concrete (CC-Conventional concrete, GC-Geopolymer concrete), and Z represents the ratio of shear span to the effective depth of the beam. The longitudinal reinforcement ratio and shear reinforcement ratio adopted for all the beams are 0.024 and 0.01 respectively.

2.2.1 Adhesively bonded FRP (GFRP and BFRP) stirrups

Instead of using steel stirrups in FRP beams, the 8 mm diameter FRP (GFRP and BFRP) rods were prepared by connecting vertical and horizontal rods in the required dimension and it was connected with epoxy resin. The joint was coupled with FRP mats externally wrapped using epoxy resin. For the joint strength, no testing was done on the material level. Hence no data is available to quantify the minimum requirement for the joints (Deifalla et al. 2014)
2.2.2 Specimen preparation
The binders were mixed with the saturated surface dry aggregates in the mixture machine. Alkali activated solutions were added and it was stirred for 5 minutes. Superplasticizer was then added to get the workability of geopolymer concrete. The moulds were pre-coated with oil (mould releasing) to prevent the adhesion of concrete. The cages of BFRP and GFRP reinforced beam are shown in Figs. 4(a) and 4(b). The concrete was placed in moulds in three layers and each layer was vibrated for full compaction. After 24 hours, the specimens were demoulded. Control concrete beam was cured in water and a geopolymer concrete beam was cured under room temperature for 28 days. The beam specimens were tested for evaluating shear parameters.

2.3 Test Setup and Instrumentation
The nine beam specimens were tested under a four-point static bending test, with a 1500 mm effective span. The shear span and distance between the loads were varied. The shear span to effective depth ratios is varied as 3.6, 3.9, and 4.3. A steel stiff spreader beam was used to apply the load. The details of tested beam specimens are shown in Fig. 5. The test setup and instrumentation are shown in Fig. 6.

In each shear span/depth ratio, steel bar, GFRP, and BFRP reinforced beams (Three beams) were subjected to static bending tests. The load was applied on beam specimens using the universal testing machine at every 3 kN load increment and dial gauges were used to measure the deflections. DEMEC strain gauges were used to measure the compressive strain and tensile strain at every load increment. Cracks were marked for the corresponding load intervals at the time of testing. The crack pattern until failure was also investigated.

3. Experimental results and discussions

3.1 Crack pattern and Failure modes
The crack pattern and failure mode for all the nine beams are shown in Figs. 7 (a), 7(b), and 7(c). From Figs. 7(a), 7(b), and 7(c), it is observed that, when the ratio of shear span to effective depth in SRCC was increased, new cracks were developed at the outer place of Constant Bending Moment (CBM) zone (i.e., in the shear zone). But no shear cracks were developed in SRCC-3.6. The mode of failure for SRCC is both flexure and compression with little shear failure if the shear span to effective depth ratio is increased.

The crack patterns are similar in all the beams at initial load intervals. But in BRGC and GRGC beams, the inclined cracks were developed from flexural cracks. Compared with BRGC-3.6 and BRGC-4.3, more in-
clined cracks were developed at the shear zone in BRGC-3.9. The same pattern is also observed in GRGC-3.9 when compared with GRGC-3.6 and GRGC-4.3. When the shear to effective ratio was 4.3, the beam deflection recamber to 20 mm at the ultimate load level after releasing the load for both the beams. But for BRGC-3.6, BRGC-3.9, GRGC-3.6, and GRGC-3.9, the sudden failure was observed after attaining 95% of the ultimate load level. As a result, sudden shear and flexure failure of premature has occurred. The sudden shear failure was observed in GRGC and BRGC beams due to insufficient shear reinforcement.

Shear strength at first cracking, ultimate load levels, and mode of failure are shown in Table 5. From Table 5, it is observed that the shear strength value decreases when increasing the ratio of shear span to effective depth in all the beams. The failure pattern is changed from shear to flexure when increasing the ratio from 3.6 to 4.3 in both FRP rods. But no change in the failure pattern in SRCC, when the ratio increases from 3.6 to 4.3

3.2 Crack Details
The crack details consist of the total number of cracks, crack propagation, cracks spacing, and crack width at

Fig. 7 Crack pattern and failure mode of all reinforced concrete beams.
first cracking, and ultimate load levels are given in Table 6.

3.2.1 Total number of cracks
Table 6 shows the total number of cracks at first cracking and ultimate load levels. From Table 6, it is observed that the total number of cracks increases for all the beams when the load is increased. In all the beams, the total number of cracks reached a constant after a certain load level. The number of cracks for BRGC-3.6 and BRGC-3.9 is similar to SRCC-3.6 and SRCC-3.9. At the same time, the number of cracks for GRGC-3.6 is less than BRGC-3.6 and SRCC-3.6. But the number of cracks for GRGC-3.9 is higher than BRGC-3.9 and SRCC-3.9. The number of cracks for GRGC-4.3 is similar to SRCC-4.3.

When the ratio of shear span to effective depth increases, the number of cracks for steel increases at 3.9 and decreases at 4.3. The same trend was also observed for both FRP bars. The total number of cracks in the GFRP beam is less when compared with the steel beam (Maranan et al. 2015). The number of cracks at 20 kN load level is 7, 15, and 11 for beam SRCC-4.3, BRGC-4.3, and GRGC-4.3, respectively.

3.2.2 Crack propagation
From the bottom to the top of the beam, crack propagation was measured at load intervals. The crack propagation is increased with increased load. For the particular load, the initial crack propagation is high in BRGC-3.6, 3.9, 4.3, and GRGC-3.6, 3.9, 4.3 when compared with SRCC-3.6, 3.9, 4.3. From Table 6, it is observed that the crack propagation is decreasing in trend by increasing the shear span to effective depth ratio for steel and glass rod. But in basalt reinforced geopolymer concrete beams, the crack propagation reaches a high value when the shear span to effective depth ratio is increased. The crack propagation of the basalt rod is similar when compared with the glass rod at first cracking load and yield load. But at the ultimate load level, the crack propagation is increased to maximum height for BRGC-3.9 when compared with other ratios.

3.2.3 Spacing of cracks
The spacing of crack is decreased when the numbers of cracks and loads are increased. The spacing of cracks is constant during the loading and unloading of the ultimate load level for SRCC-4.3 and GRGC-4.3. From Table 6, it is observed that crack spacing is decreased suddenly when the load level for SRCC-3.9 is increased.

3.2.4 Average crack width
The computed average crack width at different load intervals is given in Table 6. When the ratio of shear span to effective depth is increased, the average crack width is also increased. From Table 6, it is noted that compared to SRCC-4.3, the BRGC-4.3 and GRGC-4.3 registered 61% and 188% increase in average crack width at the ultimate load level, respectively. The average crack width for BRGC-3.9 and GRGC-3.9 is increased by 41%
and 51%, respectively than SRCC-3.9. Compared with SRCC-3.6, BRGC-3.6 and GRGC-3.6 is increased by 40% and 95% in crack width at the ultimate load level, respectively.

3.3 Load-central deflection

The load-central deflection behaviours of the specimens are shown in Figs. 8(a), 8(b), and 8(c). The stiffness of SRCC, BRGC, and GRGC beams by varying the ratio of shear span to effective depth are given in Table 7.

From Table 7, it is observed that, by increasing the shear span-depth ratio, all the beams showed a reduction in initial stiffness. The stiffness of the SRCC, BRGC, and GRGC beams is reduced to 40%, 27%, and 3%, respectively by increasing the shear span to effective depth ratio from 3.6 to 4.3. The stiffness of GRGC beams is low compared with BRGC and steel beams.

3.4 Load-compressive and tensile strain

The flexural stress-compressive and tensile strain of SRCC, BRGC, and GRGC for the ratio of shear span to a depth of 3.6, 3.9, and 4.3 are given in Figs. 9(a), 9(b), and 9(c). The maximum compressive strain registered for SRCC-3.6, BRGC-3.6, and GRGC-3.6 is 0.002, 0.003, and 0.005, respectively. Similarly, the maximum tensile strain observed for SRCC-3.6, BRGC-3.6, and GRGC-3.6 is 0.007, 0.009, and 0.015, respectively. The maximum compressive strain of BRGC-3.6 and GRGC-3.6 are 1.5 times and 2.5 times higher than the SRCC-3.6. The tensile reinforcement strain of fibre-reinforced geopolymer concrete is higher than the steel-reinforced conventional concrete. i.e., BRGC-3.6 and GRGC-3.6 are 1.29 times and 2.14 times higher than the SRCC-3.6. Similarly, the maximum compressive strain of BRGC-3.9 and GRGC-3.9 are 3.8 times and 4 times higher than the SRCC-3.9 and the tensile strain of BRGC-3.9 and GRGC-3.9 are 0.75 times and 1.6 times is higher than the SRCC-3.9. Continuously, the maximum compressive strain of BRGC-4.3 and GRGC-4.3 is 5 times and 3.1 times higher than the SRCC-4.3 and the tensile strain of BRGC-4.3 and GRGC-4.3 is 2.3 times and 1.2 times higher than the SRCC-4.3.

By increasing the ratio of shear span to depth for steel rod from 3.6 to 3.9 and 4.3, the maximum compressive strain value was decreased by 37% and 79% for SRCC-3.9 and SRCC-4.3 than SRCC-3.6 and tensile strains were decreased by 18% and 23%, respectively. The same trend was observed for BFRP and GFRP bars.

Table 7 Stiffness of SRCC, BRGC, and GRGC beams.

| Mix id | SRCC-3.6 | SRCC-3.9 | SRCC-4.3 | BRGC-3.6 | BRGC-3.9 | BRGC-4.3 | GRGC-3.6 | GRGC-3.9 | GRGC-4.3 |
|--------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Stiffness (kN/mm) | 12.35 | 9.38 | 7.41 | 1.80 | 1.44 | 1.32 | 1.09 | 1.08 | 1.06 |

Fig 8 Load-central deflection of (a) SRCC (b) BRGC and (c) GRGC beams for a/d 3.6, 3.9 and 4.3.

Fig 9 Stress Vs compressive and tensile strain of (a) SRCC (b) BRGC and (c) GRGC beams for a/d 3.6, 3.9, and 4.3 respectively.
as observed in steel bars in conventional concrete.

4. Predicted ultimate shear strength

The shear behaviour of reinforced concrete members is more complicated than the flexural behaviour of reinforced concrete members. The shear capacity is affected by many parameters such as non-linearity, non-homogeneity, reinforcement, etc. The shear capacity has been predicted by using different equations and design methods and it is shown in Table 8. Zsutty (1971) has proposed an equation (1) to find the shear capacity of concrete beams reinforced with steel including reinforcement ratio and shear span to effective depth ratio.

\[ V_c = 2\left( f'_c \cdot \rho \cdot \frac{d}{a}\right)^{1/3} \cdot \frac{b}{d} \]  

(1)

Wegian and Abdalla (2005) introduced an empirical equation (2) based on the Zsutty equation including the effect of conventional steel and FRP bars in reinforced concrete members.

\[ V_c = 2\left( f'_c \cdot \rho \cdot \frac{E_s}{E_f} \cdot \frac{d}{a}\right)^{1/3} \cdot \frac{b}{d} \]

(2)

Based on the experimental program conducted by Tottori and Wakui (1993) using FRP reinforced concrete members the shear capacity equation (3) has been developed and multiplied with \( (E_s/E_f)^{1/3} \).

\[ V_c = 0.2\left( 100\rho f'_c \cdot \frac{E_s}{E_f} \right)^{1/3} \left( \frac{d}{1000}\right)^{1/4} \left[ 0.75 + \frac{1.4}{(a/d)} \right] \cdot \frac{b}{d} \]

(3)

According to the ACI 318-99 guidelines (1999) in equation (4), the shear capacity has been proposed without considering the effect of shear span on effective depth ratio and FRP reinforcement.

\[ V_c = 2\sqrt{f'_c} \cdot \frac{b}{d} \]

(4)

CEP-FIP Model Code 1978 (CEP-FIP 1984) in equation (5) has proposed a model to find the shear capacity of steel-reinforced concrete members without considering the effect of FRP reinforcement.

\[ V_c = \left[ 0.15(3d/a)^{2/3} \left( 1 + \frac{\sqrt{200}}{d} \right) (100\rho f'_c)^{2/3} \right] \cdot \frac{b}{d} \]

(5)

Canadian equation (6) (Raju 2014) has been proposed to calculate the shear strength and has not considered the ratio of shear span to effective depth, FRP reinforcement, and longitudinal reinforcement ratio. Hence a new equation (7) including the longitudinal reinforcement ratio, shear span to effective depth ratio, FRP reinforcement in conventional and geopolymer concrete has been proposed.

Canadian Equation

\[ V_c = 0.2\sqrt{f'_c} \cdot \frac{b}{d} \]

(6)

Proposed Equation

\[ V_c = 3\left( f'_c \rho \frac{E_s}{E_f} \right)^{0.3} \left( \frac{d}{a} \right)^{0.6} \left( \frac{E_s}{E_f} \right)^{0.1} \cdot \frac{b}{d} \]

(7)

Tottori and Wakui (1993) equation predicts the shear strength capacity of FRP reinforced concrete beams. The equation proposed by Zsutty (1971) for finding the shear capacity of concrete beams reinforced with steel including reinforcement ratio and shear span ratio provides a better prediction if the ratio of shear span to effective depth is greater than 2.5. In this paper, the proposed equation predicts the shear capacity of both geopolymer as well as conventional concrete beams by considering compressive strength of concrete, longitudinal reinforcement ratio, shear span to effective depth ratio, modulus of elasticity of FRP and steel bars. From Table 8, it is observed that the shear capacity in the proposed equation is more relevant to the experimental values.

5. Conclusions

Experimental studies were carried out on nine beams tested under four-point flexural loads using BFRP/ GFRP beams reinforced in geopolymer concrete and steel in control concrete by varying the ratio of shear span to effective depth and the inferences are as follows:

1. The percentage increase in mechanical properties of geopolymer concrete compared to conventional

| Specimen id | a/d ratio | \( V_{\text{experimental}} \) (MPa) | Zsutty | Wegian | Tottori & Wakui | ACI 318-99 | CEP-FIP model | Proposed method |
|-------------|-----------|----------------------------------|--------|--------|----------------|-------------|---------------|----------------|
| SRCC-3.6    | 3.6       | 49.80                            | 17.86  | 17.86  | 23.66          | 174.75      | 42.17         | 34.79          |
| SRCC-3.9    | 3.9       | 47.95                            | 17.39  | 17.39  | 23.04          | 174.75      | 39.98         | 33.14          |
| SRCC-4.3    | 4.3       | 40.20                            | 16.84  | 16.84  | 22.34          | 174.75      | 37.46         | 31.24          |
| BRGC-3.6    | 3.6       | 33.45                            | 10.87  | 10.87  | 18.61          | 171.76      | 35.68         | 28.83          |
| BRGC-3.9    | 3.9       | 32.55                            | 10.35  | 10.35  | 18.12          | 171.76      | 33.26         | 27.48          |
| BRGC-4.3    | 4.3       | 32.05                            | 10.04  | 10.04  | 17.58          | 171.76      | 31.94         | 26.18          |
| GRGC-3.6    | 3.6       | 32.40                            | 10.04  | 10.04  | 15.47          | 171.76      | 29.59         | 24.81          |
| GRGC-3.9    | 3.9       | 26.65                            | 9.37   | 9.37   | 15.07          | 171.76      | 27.12         | 23.34          |
| GRGC-4.3    | 4.3       | 26.20                            | 9.04   | 9.04   | 14.61          | 171.76      | 24.75         | 21.87          |
concrete are 3.6%, 4.7%, and 5.15% of compressive strength, split tensile strength, and flexural strength respectively. The percentage decrease in modulus of elasticity of geopolymer compared with conventional concrete are 13.93%.

(2) The ultimate load-carrying capacity of SRCC, BRGC, and GRGC beams is decreased when the ratio of shear span to effective depth is increased.

(3) Due to premature failure in FRP rods, it would not be able to take more load and it could be avoided by providing more shear reinforcement in the shear zone area and by increasing the bond strength.

(4) The Shear capacity at the ultimate load level is decreased in steel and FRP rods when the ratio of shear span to effective depth values is increased. The shear strength values are decreased in FRP bars than the steel bars.

(5) The estimated shear strength based on the proposed equation in this paper is in good agreement with the experimental results and the data published by other researchers.

Notations

- $f'_c$ - Compressive strength of concrete
- $\rho$ - Longitudinal reinforcement ratio
- $a$ - Ratio of shear span to effective depth
- $d$ - Width of the beam
- $d'$ - Effective depth of the beam
- $E_f$ - Modulus of elasticity of FRP bars
- $E_s$ - Modulus of elasticity of steel bars

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