EXPERIMENTAL STUDIES ON THE SHEAR CAPACITY OF SEA SAND CONCRETE BEAMS WITH BASALT FIBER-REINFORCED POLYMER BARS

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ABSTRACT

Basalt fiber-reinforced polymer (BFRP) bars can replace steel bars in sea sand concrete structures to prevent the corrosion of steel by chloride ions; thus, sea sand can be directly added to concrete material in construction. Shear tests on 16 sea sand concrete beams with BFRP bars (including ten beams with stirrups and six beams without stirrups) are performed, and their failure modes, shear capacities and influencing factors are analyzed. The results reveal two main failure modes for sea sand concrete beams with BFRP bars: bending failure and shear-compression failure. The shear capacity increases with the concrete strength and stirrup ratio but decreases with an increased shear-span ratio, and the longitudinal reinforcement ratio has an insignificant effect on shear capacity.

KEYWORDS

BFRP bars, sea sand concrete, concrete beam with stirrups, shear capacity, calculation formula.

INTRODUCTION

As the primary construction material of concrete, the river sand resource is being depleted, and the trend of exploitation of the abundant sea sand resource is inevitable. However, sea sand contains a high concentration of chloride ions, which can corrode bars in concrete structure and substantially affect the durability of concrete. Research on sea sand concrete in China primarily focuses on the chloride ion corrosion mechanism in sea sand concrete and the sea sand processing technology. The substitution of fiber-reinforced plastic (FRP) bars, which has superior durability, in place of bars in sea sand concrete has vast application prospects. FRP bars substituting steel bars in buildings leave much to be desired. Study on the shear capacity of sea sand concrete structures with FRP bars is one of the most important issues.

The analysis of the shear capacity of a concrete beam with FRP bars is primarily based on the rebar concrete shear model, including the variable truss model (Razaqpur *et al*. 2011) and the modified compression field theory model (Thanasis and Costas 2000). However, the shear model of a rebar concrete structure is based on plasticity theory, which considers plastic stress redistribution. A FRP bar is a linear elastic material without a distinct yield phenomenon; thus, a shear model based on elasticity theory is suitable for a FRP bar-reinforced concrete structure. Among existing FRP concrete design specifications (ACI 2006, CAN/CSA 2010, JSCE 1997), the bearing capacity calculation formulas for FRP bar-reinforced concrete beams primarily focus on influence factors, such as the concrete strength, the longitudinal reinforcement ratio, and the section size. Few specifications consider the stirrup ratio's effect, and the shear-span ratio's effect is completely disregarded. The shear capability of concrete is the main source of the shear capability of a FRP bar-reinforced stirrup-free concrete beam. Thus, the shear capability of a FRP bar-reinforced stirrup-free concrete beam increases with concrete strength (El-Sayed *et al*. 2006). Because FRP bar has a smaller elastic modulus than bar and different types of FRP bars have an extensive range of elastic moduli, some studies show that (Alakhrdaji *et al*. 2001, Sayed *et al*. 2005) an increase in the area of a FRP longitudinal reinforcement section can significantly improve the shear capacity of a structure. However, other tests reveal that the area of a FRP longitudinal reinforcement section does not have a significant effect on a structure's bearing capacity. In addition, the load position can affect the shear capability of a FRP bar-reinforced stirrup-free concrete beam. A higher shear-span ratio will result in a lower shear capability of a FRP bar-reinforced stirrup-free concrete beam. For a shear-span ratio that exceeds 2.5, the shear capacity of a FRP bar-reinforced stirrup-free concrete beam is approximately proportional to the cubic root of the product of three factors: the concrete strength, the longitudinal reinforcement rigidity and the shear-span ratio. Shear capability provided by a FRP bend-up bar or stirrup is determined by the orientation of a FRP bar and the development pattern of a diagonal crack; the stress on a FRP bar in the crack's direction is critical.

The bond performance between a FRP bar and concrete has a significant impact on the shear capacity of concrete; thus, research on the bond between a FRP bar and concrete is also an important research area. Although FRP bars exhibit excellent quality in terms of durability and anti-corrosion (Wu *et al*. 2014), water and temperature also exert a significant impact on the performance of the bond between FRP and concrete (Refai *et al*. 2014 a). A design of FRP bar in concrete should consider many factors, including service life (Banibayat and Patnaik 2013) and stress condition; therefore, comprehensive knowledge of the material properties and influencing factors of FRP bar-reinforced concrete in normal conditions is important to the application of FRP bar sea sand concrete material.

This paper is based on an experimental analysis of shear capacity for 16 BFRP bar-reinforced sea sand concrete beams (including ten beams without stirrups and six beams with stirrups). The failure mode, load-deflection curve, strains on the longitudinal reinforcements and stirrups, and the ultimate bearing capacity are analyzed. The effects of the shear-span ratio, longitudinal reinforcement section, concrete strength and stirrup ratio on the shear capacity of a BFRP-reinforced sea sand concrete beam are compared.

TEST DESIGN

Test Beam Design

Based on Chinese specifications, 16 specimens are designed for the test, including BFRP-reinforced sea sand concrete beams without stirrups and beams with stirrups. The beam length is 1200 mm, the span is 1000 m, the section size of the beam without stirrups is 150×150 mm, and is 150×250 mm for beam with stirrups. The test variable parameters primarily include the concrete strength, the BFRP bar longitudinal reinforcement section, the shear-span ratio and the stirrup ratio. To facilitate the study of how the shear failure mode of a BFRP bar sea sand concrete beam and its changes in various parameters affect the shear strength, the specimen parameters and reinforcement listed in Table 1 and Table 2 are utilized. Fig. 1 displays the reinforcement diagram for the beam with stirrups.

Table 1 Parameters of beam specimen without stirrups

Specimen No.	Concrete grade	Longitudinal reinforcement	Longitudinal reinforcement ratio ρ (%)	Shear span (mm)	Shear span ratio λ
BFS-30-1	C30	2Φ14	1.78	200	1.74
BFS-30-2	C30	2Φ14	1.78	250	2.17
BFS-30-3	C30	2Φ14	1.78	320	2.78
BFS-30-4	C30	2Φ10	0.91	250	2.17
BFS-30-5	C30	2Φ18	2.95	250	2.17
BFS-60-1	C60	2Φ14	1.78	200	1.74
BFS-60-2	C60	2Φ14	1.78	250	2.17
BFS-60-3	C60	2Φ14	1.78	320	2.78
BFS-60-4	C60	2Φ10	0.91	250	2.17
BFS-60-5	C60	2Φ18	2.95	250	2.17

Table 2 Parameters of beam specimen with stirrups

Specimen No.	Concrete grade	Longitudinal reinforcement	Stirrup	Stirrup ratio ρsv (%)	Shear span ratio λ
BFS-30-6	C30	2Φ14	Φ8@150	0.45	2.17
BFS-30-7	C30	2Φ14	Φ8@100	0.67	2.17
BFS-30-8	C30	2Φ14	Φ8@50	1.34	2.17
BFS-60-6	C60	2Φ14	Φ8@150	0.45	2.17
BFS-60-7	C60	2Φ14	Φ8@100	0.67	2.17
BFS-60-8	C60	2Φ14	Φ8@50	1.34	2.17

Test Material's Properties

The mixture ratios for the C30 and C60 sea sand concrete (JGJ55-2011 2011) are listed in Table 3, the properties of the concrete and BFRP bar provided by the vendor are listed in Table 4 and Table 5.

Table 3 Mixture ratio for sea sand concrete (kg/m^3)

Concrete grade	Water cement ratio	Water	Cement	Sand	Gravel	Water reducer
C30	0.60	168.00	280.00	741.76	1210.24	1.40
C60	0.35	159.90	456.86	549.79	1283.27	2.28

Table 4 Physical and mechanical properties of sea sand concrete

Concrete grade	Cube compressive strength f_{cu} (MPa)	Axial compressive strength f_c (MPa)	Elastic modulus E_c (GPa)
C30	35.6	28.3	30.8
C60	64.2	49.3	36.4

Table 5 Mechanical properties of BFRP bars

Material	Ultimate strength (MPa)	Elastic modulus (GPa)	Elongation
BFRP bars	1100	55	2.6%

Test Load and Measurement

In the test, the SOS500 electro-hydraulic servo dynamic and static tester is employed to add load, and a distribution beam and sensor are employed to perform two-point loading; the loading schematic is shown in Fig. 2. Displacement control is applied during loading, and the loading rate is 0.2 mm/s. During the test, the items observed and recorded include beam midspan deflection, concrete strain, FRP bar strain and crack.

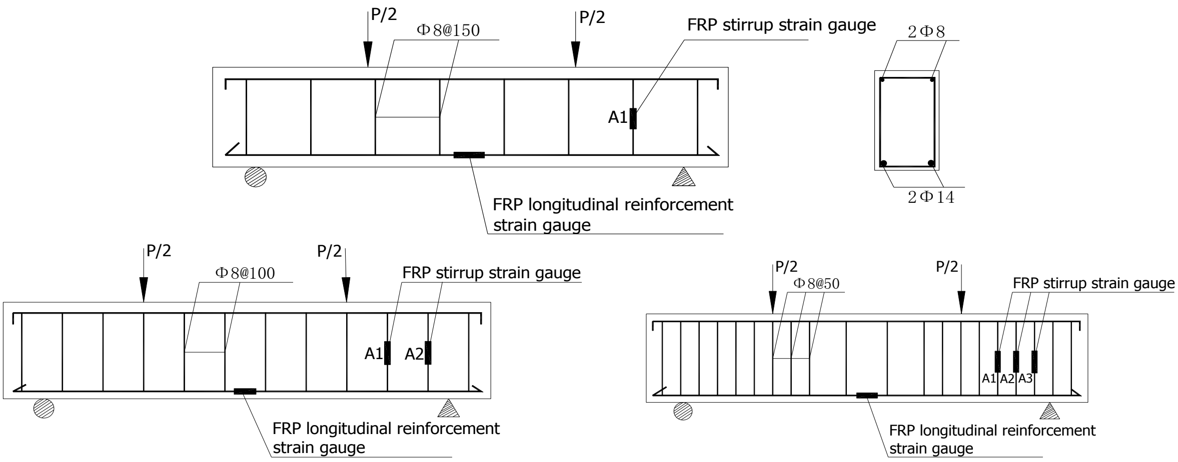

Figure 1 Different section reinforcement of beams with stirrups and measuring point layout

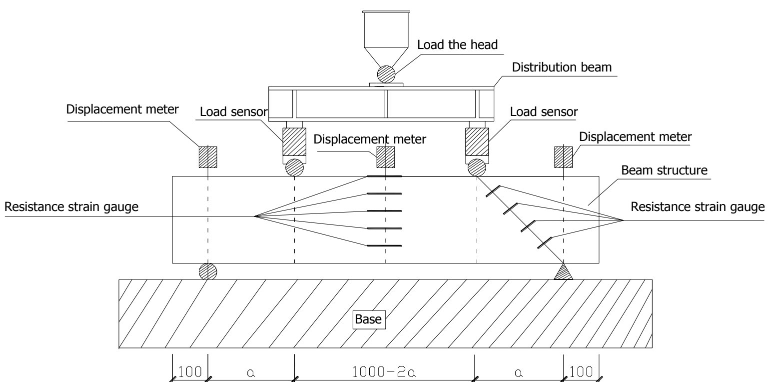

Figure 2 Loading diagram

TEST RESULTS AND ANALYSIS

Test Phenomenon and Results

The shear test for the BFRP bar-reinforced sea sand concrete beam demonstrates that the crack in BFRP bar-reinforced sea sand concrete beam rapidly expand, which is a distinct indication of brittleness. A vertical crack in the pure bending section extends at a faster rate; however, after it reaches the concrete compression area, its growth decelerates. A short horizontal crack is formed at the edge of the concrete compression area, and the crack width continues to grow with the load. In the area near the beam base that is under the load point, a vertical bending crack is observed. This bending crack grows and extends toward the load point; in the middle or at a position near the load point, it gradually inclines and evolves into a bend-shear crack toward the support base. When the load increases and approaches the ultimate shear capacity of the beam, diagonal crack penetration rapidly occurs, and local concrete crush is observed under the load point. With the exception of individual beams that experience beam normal section failure before the load reaches the shear capacity limit, which is due to concrete crush in the compression area, the majority of beams are damaged by stress on the concrete diagonal section. For all BFRP bar-reinforced sea sand concrete beams, deformation is recovered after offloading, which shows that BFRF bars have excellent linear elasticity. BFRP bar-reinforced sea sand concrete beams with or without stirrups exhibit similar crack development patterns with two common failure modes: shear-compression failure and bending failure as shown in Fig. 3 (a) and (b) and are provided in Table 6 and 7.

(a) Shear-compression failure (BFS-60-1) (b) Bending failure (BFS-60-2)

Figure 3 Failure modes of sea sand concrete beams with BFRP bars

Table 6 Test results for beams without BFRP stirrups

Specimen No.	Cracking load P_{cr} (kN)	Ultimate load P_u (kN)	Midspan deflection △(mm)	Failure mode
BFS-30-1	48.27	105.32	15.94	Bending
BFS-30-2	30.16	93.36	13.90	Shear-compression
BFS-30-3	17.82	63.38	10.42	Shear-compression
BFS-30-4	28.06	76.42	9.98	Shear-compression
BFS-30-5	38.68	108.07	21.08	Shear-compression
BFS-60-1	49.34	150.18	10.84	Shear-compression
BFS-60-2	30.18	119.54	14.70	Bending
BFS-60-3	32.24	80.20	16.44	Shear-compression
BFS-60-4	50.02	122.64	13.48	Shear-compression
BFS-60-5	28.36	120.36	14.26	Shear-compression

Table 7 Test results for beams with BFRP stirrups

Specimen No.	Cracking load P_{cr} (kN)	Ultimate load P_u (kN)	Midspan deflection △(mm)	Failure mode
BFS-30-6	136.02	269.95	11.85	Shear-compression
BFS-30-7	128.70	281.26	13.79	Shear-compression
BFS-30-8	145.96	290.92	14.37	Shear-compression
BFS-60-6	180.30	331.06	16.14	Shear-compression
BFS-60-7	201.55	350.46	14.57	Bending
BFS-60-8	198.72	368.84	16.47	Shear-compression

Relationship Between Load and Deflection

In the case of beams without stirrups, the effects of the longitudinal reinforcement ratio and the shear-span ratio on deflection are shown in Fig. 4 and Fig. 5, respectively. The load-deflection curve shows that the load-deflection curve of the BFRP bar-reinforced stirrup-free sea sand concrete beam does not have a distinct yield platform and declining trend and is similar to a bilinear graph; its turning point occurs when the test beam crack occurs, the change in the slopes before and after crack initiation is not significant, and the change in slope is smaller after crack initiation.

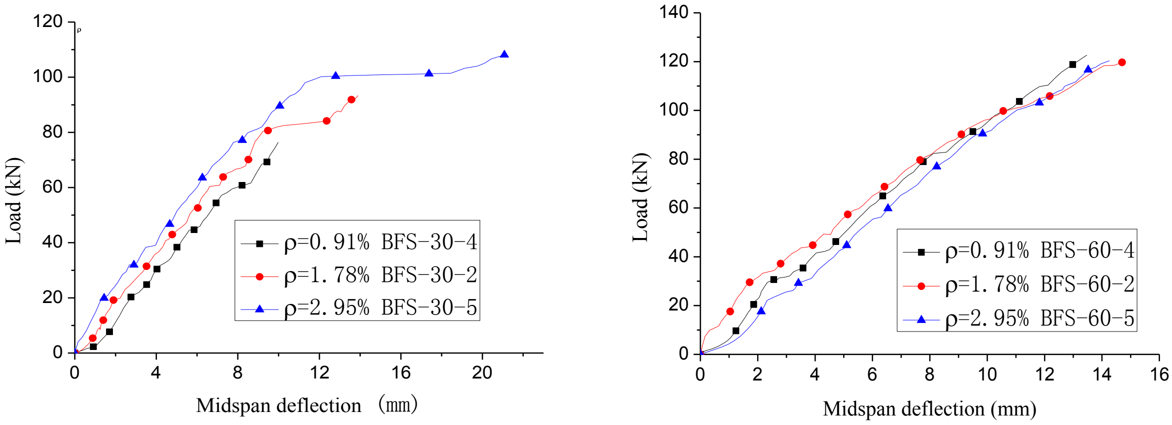

Figure 4 Effect of longitudinal reinforcement ratio on the deflection of the beams without stirrups

The load-deflection curve of the BFRP bar-reinforced stirrup-free beam assumes the form of a straight line before crack initiation because BFRP bar is a linear elastic material that differs from bar and does not have a distinct yield phenomenon. The elastic modulus of BFRP bar is approximately 25% that of bar, which does not significantly contribute to the section rigidity. The BFRP-reinforced stirrup-free beam abruptly cracks; the cracks rapidly extend to a relatively high position of the beam section. Concrete in the tensile zone ceases to bear any load, which causes an instant decline in beam section rigidity. After the beam cracks, the cracks rapidly increase, reach the edge of the concrete compression area, and stop growing. After the concrete cracks, the rigidity of the test beam section exhibits only slight changes; thus, the load-deflection curve continues to assume the form of an approximate straight line after the test beam cracks.

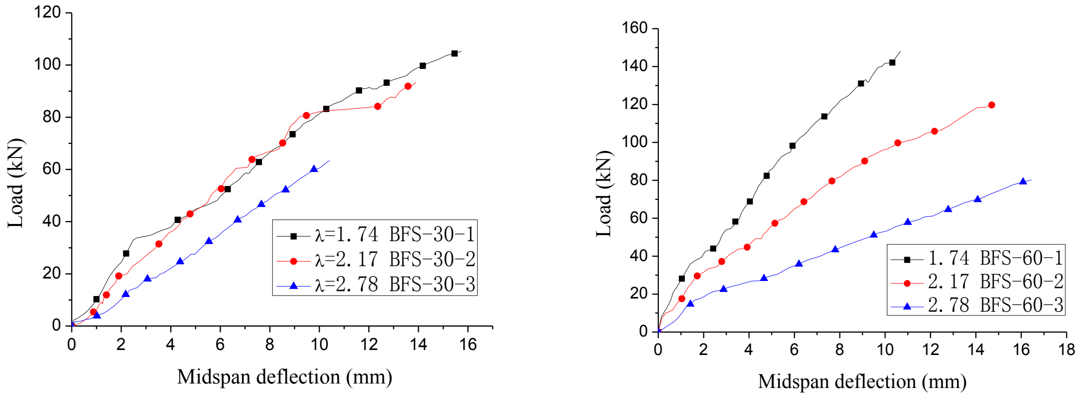

Figure 5 Effect of shear-span ratio on the deflection of the beams without stirrups

Although the elastic modulus of BFRP bar is smaller than the elastic modulus of bar, it is larger than the elastic modulus of concrete. An increase in the longitudinal reinforcement ratio indicates an increase in the bending rigidity of the test beam and a decrease in the beam deflection. As shown in Fig. 4 for the case of the C30 beam, the beam with a higher reinforcement ratio has a smaller deflection for the same level of load, and the change in deflection with an increase in load is significantly smaller than the case of the beam with a lower reinforcement ratio. In the case of the C60 beam, an increase in the reinforcement ratio has an insignificant effect on deflection because C60 concrete has a higher elastic modulus than C30 concrete, and the effect of an increase in the longitudinal reinforcement ratio on the bending resistance rigidity of the section is not as prominent as in the case of the C30 beam. As shown in Fig. 5, the deflection of the beam without stirrups increases with an increase in the shear-span ratio. In the four-point load test, the pure bending section of the beam decreases with an increase in the shear-span ratio. Consequently, the total rigidity of the concrete that counters the bending moment also decreases; thus, deflection increases. Fig. 6 is the effect of the stirrup ratio on the deflection of the beams with stirrups

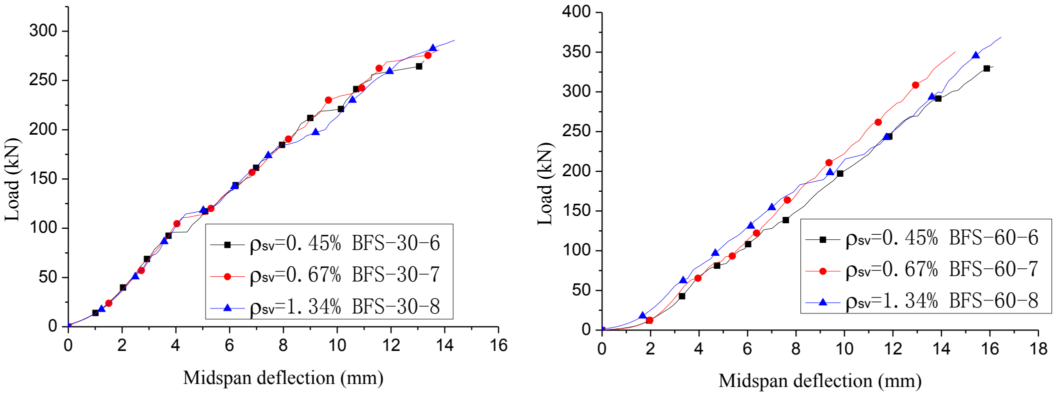

Figure 6 Effect of the stirrup ratio on the deflection of the beams with stirrups

Strains on Longitudinal Reinforcement and Stirrups

The effect of the shear-span ratio and longitudinal reinforcement ratio of a stirrup-free beam on the longitudinal reinforcement strain is shown in Fig. 7 and 8, respectively. Before concrete cracks, the strain on the longitudinal reinforcement of a BFRP-reinforced stirrup-free beam is very small—usually less than 100 $\mu\varepsilon$—because the total strain is relatively small and the tensile stress in the tensile zone is primarily created by concrete before a beam cracks. After it cracks, concrete does not carry additional stress, and tensile stress is carried by the FRP longitudinal reinforcement. After concrete cracks, the strain on the FRP longitudinal reinforcement rapidly increases in a linear pattern. However, the cracking point is likely to be the point of abrupt change for the strain on the longitudinal reinforcement of a stirrup-free beam. The main reason for this finding is that a concrete crack instantly transfers the stress that is originally carried by concrete to the FRP longitudinal reinforcement, and the vertical crack that subsequently occurs near the midspan beam will also cause an abrupt change in strain on the longitudinal reinforcement. After beam failure, the load suddenly declines, and the strain on the longitudinal reinforcement also abruptly decreases.

As shown in Fig. 7, the effect of the shear-span ratio on the longitudinal reinforcement shear-strain slope is insignificant in the case of the C30 beam. In the case of the C60 beam, the larger is the shear-span ratio, the smaller is the slope of the longitudinal reinforcement shear-strain curve, i.e., the acceleration of the increase in the strain on the longitudinal reinforcement, because the test beam's pure bending section shrinks and the midspan deflection accelerates when the shear-span ratio increases.

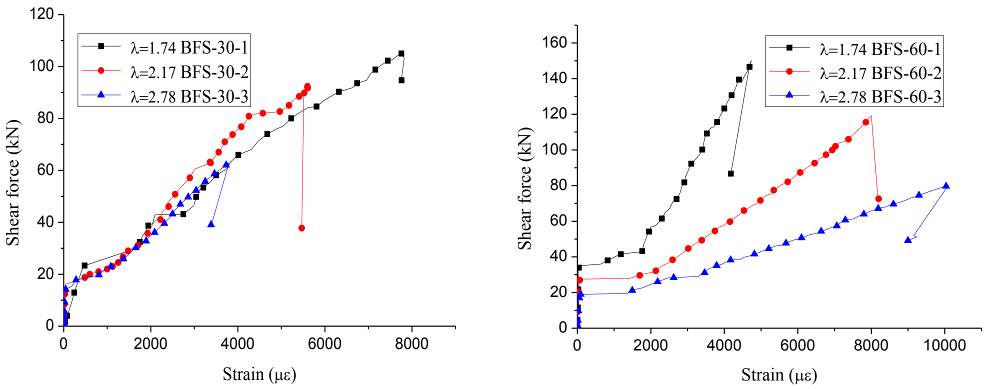

Figure 7 Effect of shear-span ratio on the longitudinal reinforcement strain of the beams without stirrups

Fig. 8 shows that the slope of the longitudinal reinforcement shear-strain curve for the C30 beam is less affected by an increase in the longitudinal reinforcement ratio of the BFRP bar, whereas the slope of the shear-strain curve for the longitudinal reinforcement of the C60 beam slightly increases with the longitudinal reinforcement ratio of the BFRP bar. The effect of the longitudinal reinforcement ratio on the longitudinal reinforcement strain is insignificant, which can be explained by the minimal contribution to the total rigidity of the beam by the BFRP bar with the smaller elastic modulus.

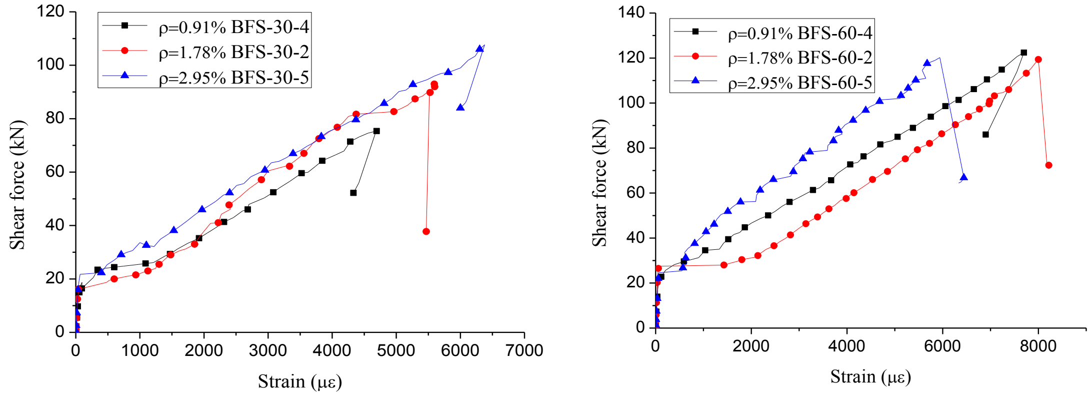

Figure 8 Effect of longitudinal reinforcement ratio on longitudinal reinforcement strain for beams without stirrups

The strains on the longitudinal reinforcement and stirrup for the beam with stirrups are shown in Figure 9. The strain on the longitudinal reinforcement for the beam with stirrups has a development pattern that is similar to the case of the longitudinal reinforcement of the stirrup-free beam: before concrete cracks, the strain on the longitudinal reinforcement is very small; after concrete cracks, the strain rapidly increases in a linear pattern. The strain on the longitudinal reinforcement for the beam with stirrups differs from the case of the beam without stirrups in the following three aspects: first, improvement in the total rigidity of the beam with stirrups increases the cracking load, the point of abrupt change for the longitudinal reinforcement strain is in a higher position than in the case of the beam without stirrups; second, the addition of stirrups effectively constrains beam crack development, and with the exception of the situation in which the beam cracks and the point of abrupt change is observed, the strain on the longitudinal reinforcement for the beam with stirrups seldom causes an additional abrupt change; and third, the maximum longitudinal reinforcement strain for the beam with stirrups is larger than the maximum longitudinal reinforcement for the beam without stirrups, the maximum strain on the C30 beam's longitudinal reinforcement is 7000 $\mu\varepsilon$, the maximum strain on the C60 beam's longitudinal reinforcement exceeds 10000 $\mu\varepsilon$, and both are approximately 2000 $\mu\varepsilon$ higher than the corresponding cases of the maximum longitudinal reinforcement strains of the stirrup-free beam.

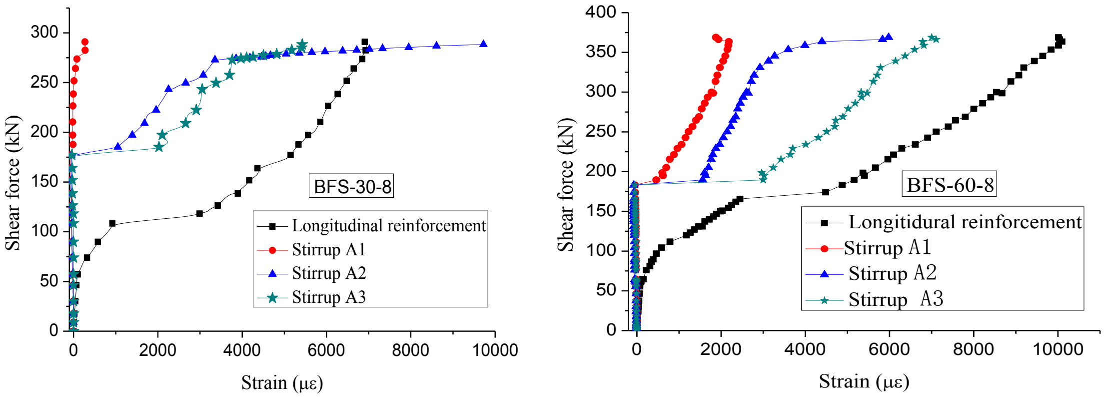

Figure 9 Strains on the longitudinal reinforcement and stirrup for the beams with stirrups

The stirrup strain for the beam with stirrups slowly increases in the initial stage, which usually occurs at approximately 100 $\mu\varepsilon$, and compressive strain will occur. After the initial crack occurs and penetrates the stirrup, the stirrup strain suddenly and rapidly increases. When the shear force approaches the beam's shear capacity, diagonal crack penetration rapidly occurs, and the stirrup strain also experiences abrupt change and exceeds 5000 $\mu\varepsilon$. As shown in Fig. 9, the BFS-30-8 stirrup A1 has not been directly penetrated by a diagonal crack, and its strain is not conspicuous in the diagram. However, for the remaining two stirrups of BFS-30-8—A2 and A3—and the stirrup of BFS-60-8, after being penetrated during the diagonal crack's extension process, the strains on the stirrups follow a linear development pattern. When a beam is about to be damaged, an abrupt change in the stirrup strain occurs, which may reach or exceed the strain on the longitudinal reinforcement. An increase in the stirrup ratio can enhance stirrup strain because a reduction in the stirrup spacing enhances the stirrup's shear capability. The stirrup ratio increase has an insignificant effect on the improvement in longitudinal reinforcement strain, which is consistent with the relationship between the stirrup ratio and the midspan deflection. The stirrups barely enhance the section bending resistance rigidity.

Influencing Factors for BFRP Bar Shear Capacity

Effect of concrete strength

Fig. 10 (a) shows the comparison between the test groups of the BFRP bar-reinforced stirrup-free beams with identical section size and shear-span ratio for the concrete strengths of C30 and C60. The ultimate shear load of the C60 beam is significantly higher than that of the C30 beam. The differences in strength for the three groups (1, 2 and 3) of beams with varying shear-span ratios (shear-span ratios of 1.74, 2.17 and 2.78, respectively) are 42%, 28% and 27%, respectively. The differences in strength for the three groups (4, 2 and 5) of beams with varying longitudinal reinforcement ratios (0.91%, 1.78% and 2.95%, respectively) are 60%, 28% and 11%, respectively. The effect of the shear-span ratio on the relationship between concrete strength and shear capacity is insignificant. The C60 beam with the modified longitudinal reinforcement ratio demonstrates a significant improvement in shear capacity compared with the C30 beam.

Fig. 10(b) shows the comparison among test groups 6, 7 and 8 for the C30 and C60 beams with stirrups with identical section size, reinforcement and shear-span ratio. The stirrup ratios for test groups 6, 7 and 8 with stirrups are 0.45%, 0.67% and 1.34%, respectively. The ultimate shear loads of the C60 beams of groups 6, 7 and 8 increased by 23%, 25% and 27%, respectively.

The ultimate loads of the first three groups of beams with identical section size and reinforcement and the ultimate loads of the last three groups of beams with identical shear-span ratio are listed in Table 8. The shear capacity of the BFRP bar concrete is approximately proportional to the square root of the concrete strength.

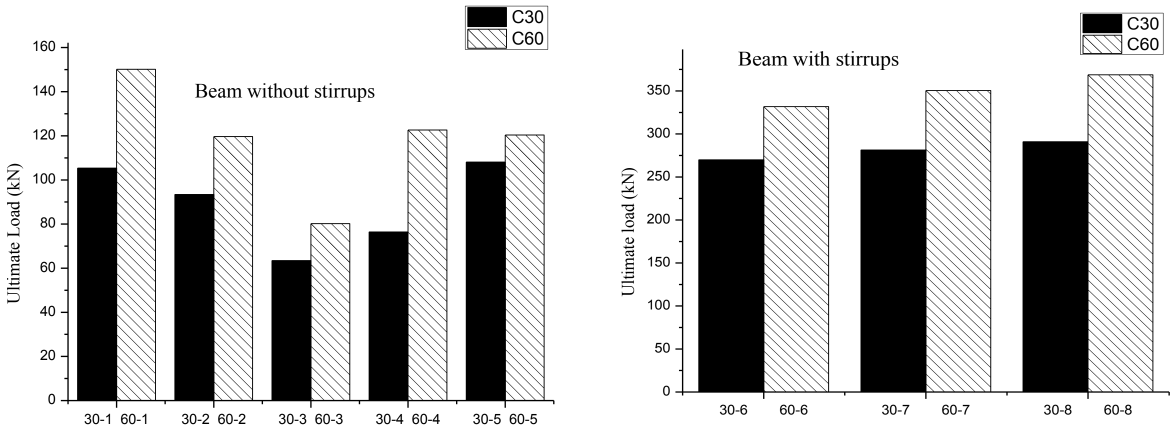

Figure 10 Effect of concrete strength on ultimate load

Effect of longitudinal reinforcement ratio

Fig. 11 shows the three groups of BFRP bar-reinforced beams with identical section size and shear-span ratio and different reinforcement ratios. The shear capacity of the C30 beam increases with reinforcement ratio, whereas the shear capacity of the C60 beam insignificantly increases with reinforcement ratio. The intrinsic shear elastic modulus of BFRP bar is relatively small, and its contribution to shear capacity primarily occurs through dowel action and its effect on the variation in the concrete compression area height. The C30 concrete beam has a lower crack position and a smaller initial crack because BFRP bar can function in tandem with concrete and its dowel action is more significant when the reinforcement ratio increases. Thus, it can enhance the shear capacity more significantly than the C60 beam. The C60 beam has a higher crack position, which is usually above the longitudinal reinforcement located position, and the crack is relatively wider because the BFRP bar's dowel action is relatively weak and the elastic modulus of C60 concrete experiences minimal change when the longitudinal reinforcement ratio increases. Thus, the reinforcement ratio has no significant contribution to the shear capacity of the C60 concrete beam.

The relation between the cracking load and the reinforcement ratio corresponds with the effect of the reinforcement ratio on the ultimate load. A beam's cracking load is determined by the concrete tensile strength and beam section rigidity. The change in the BFRP bar's reinforcement ratio has a greater impact on the section rigidity of the C30 concrete beam than that of the C60 beam. The C30 concrete beam's cracking load increases with changes of reinforcement ratio, whereas the cracking load of C60 beam experiences minimal change with the variation of reinforcement ratio.

Table 8 Effect of concrete strength on the shear capacity of sea sand concrete beams with BFRP bars

Specimen group	Beams with identical section size and reinforcement			Beams with identical shear-span ratio		
	1	2	3	6	7	8
C30	105.32	93.36	63.38	269.95	281.26	290.92
C60	150.18	119.54	80.20	331.06	350.46	368.84
Strength ratio C60/C30	1.42	1.28	1.27	1.23	1.25	1.27

Effect of shear-span ratio

Fig. 12 shows that the ultimate load and cracking load of the stirrup-free beam decrease with an increase in the shear-span ratio. For instance, when the shear-span ration for the C60 concrete beam increases from 1.74 to 2.17, the ultimate load reduces by 20%. When it increases from 2.17 to 2.78, the ultimate load reduces by 32%. When the shear-span ratio of the C30 concrete beam increases from 1.74 to 2.17 and from 2.17 to 2.78, its cracking loads decrease by 22% and 6%, respectively. The variation in the slope of the curve in the diagram shows that the shear capacity of the BFRP bar-reinforced concrete beam decreases with an increase in the shear-span ratio. The reduction is more distinct for higher shear-span ratios; the cracking load decreases with an increase in shear-span ratio, which is more prominent for smaller values of shear-span.

Effect of stirrup ratio

Fig. 13 shows the effect of the stirrup ratio on the shear capacity of a stirrup reinforced beam. The graph shows that the beam's ultimate load increases with stirrup ratio. In the case of the C30 beam, when the stirrup ratio increases from 0.45% to 0.67%, the ultimate load increases by 4.2%; when the reinforcement ratio increases from 0.67% to 1.34%, the ultimate load increases by 3.4%. For the C60 beam, when stirrup ratio increases from 0.45 to 0.67% and from 0.67% to 1.34%, the ultimate loads increase 5.6% and 5.2%, respectively. With an increase in the stirrup ratio, the C60 beam exhibits a more significant increase in ultimate load than the C30 beam, which indicates that high-strength concrete can leverage the stirrup's shear capability. When the stirrup ratio increases from 0.67% to 1.34%, the increase in beam ultimate load is smaller than the case in which the stirrup ratio increases from 0.45% to 0.67%, which shows that the stirrup's shear capability can be exploited more thoroughly in a beam with a lower stirrup ratio.

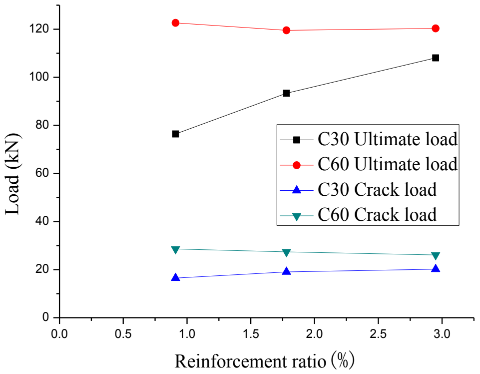

Figure 11 Effect of reinforcement ratio on shear capacity

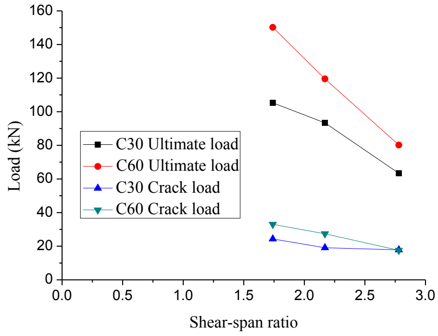

Figure 12 Effect of shear span ratio on shear capacity

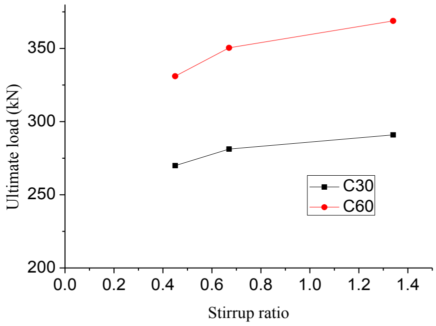

Figure13 Effect of stirrup ratio on shear capacity

With the reduction in stirrup spacing, the number of stirrups that are penetrated by diagonal cracks in the shear-span zone, the resultant forces of shear force and tensile stress carried by the stirrups, and the contribution by the stirrups to the beam's shear capacity all increase. The increase in stirrup ratio has a certain enhancing effect on the ductility of the beam section; the stirrup can effectively restrain a diagonal crack from growing too fast and excessively wide, which will indirectly help concrete in the crack zone to continue to carry shear force. Thus, when a load suddenly becomes oversized, the beam is protected from shear brittleness failure, and its shear ductility can be guaranteed.

CONCLUSIONS

An analysis of a beam's shear capacity is conducted using shear tests of 16 BFRP bar reinforced sea sand concrete beams. The following conclusions are obtained: (1) Beam failures primarily include two failure modes: bending failure and shear-compression failure. The C60 beam attains a higher crack position than the C30 beam does. (2) The load-deflection curve usually assumes the form of a bilinear graph. Deflection decreases with an increase in the shear-span ratio. The longitudinal reinforcement ratio and stirrup ratio have an insignificant effect on deflection. (3) The strain on the longitudinal reinforcement for a beam without stirrups is likely to abruptly change when cracks occur around the midspan of the test beam, whereas the shear-strain curve of the longitudinal reinforcement for the beam with stirrups is relatively smooth. The strain on the longitudinal reinforcement increases with the grade of the concrete strength and the shear-span ratio. The strain of stirrup increases with the stirrup ratio. (4) The beam's shear capacity increases with the stirrup ratio and decreases with the increase of shear-span ratio.

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REFERENCES

ACI committee 440.1R-06. *Guide for the design and construction of concrete reinforced with FRP bars*. 2006

Alakhrdaji T, Wideman M, Belarbi A. "Shear strength of GFRP RC beams and slabs". *Proceedings of International Conference on Composites in Construction*, Rotterdam: Balkema, 2001, 409-414.

Banibayat, P. and Patnaik, A. "Creep rupture performance of basalt fiber-reinforced polymer bars", *Journal of Aerospace Engineering*, 2013, 10.1061/(ASCE) AS.1943-5525.0000391, 04014074.

CAN/CSA S6S1-10. *Canadian highway bridge design code*. 2010

El Refai, A., Abed, F., and Altalmas, A. "Bond durability of basalt fiber–reinforced polymer bars embedded in concrete under direct pullout conditions", *Journal of Composites for Construction*, 2014, 10.1061/(ASCE) CC.1943-5614.0000544, 04014078.

El-Sayed A K, El-Salakawy E F, and Benmokrane B. "Shear strength of FRP-reinforced concrete beams without transverse reinforcement". *Structural Journal*, 2006, 103(2), 235-243.

JGJ55-2011. *Specification for mix proportion design of ordinary concrete*. 2011

JSCE 1997. *Recommendations for design and construction of concrete structures using continuous fiber reinforced material*. 1997

Razaqpur, A., Shedid, M., and Isgor, B. "Shear Strength of Fiber-Reinforced Polymer Reinforced Concrete Beams Subject to Unsymmetric Loading", *Journal of Composites for Construction*, 2011, 15(4), 500–512.

Sayed E, Salakawy E, Benmokrane B. “Shear strength of one-way concrete slabs reinforced with FRP composite bars”, *Journal of Composites for Construction*, 2005, 9(2), 147-157.

Thanasis C Triantafillou, Costas P Antonpoulos. Design of concrete flexural members strengthened in shear with AFRO. Journal of Composites for Construction, 2000, 4 (4), 198-205.

Wu, G., Dong, Z., Wang, X., Zhu, Y., and Wu, Z. “Prediction of long-term performance and durability of BFRP bars under the combined effect of sustained load and corrosive solutions, *Journal of Composites for Construction*, 2014, 10.1061/(ASCE) CC.1943-5614.0000517, 04014058.