EXPERIMENTAL STUDY ON DIAGONAL SHEAR CRACKS OF CONCRETE BEAMS WITHOUT STIRRUPS LONGITUDINALLY REINFORCED WITH GFRP BARS


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Abstract

An experimental study on diagonal shear cracks of concrete beams without stirrups was carried out. A total of twenty four reinforced concrete beams, consisted of twelve beams reinforced with GFRP bars and twelve beams reinforced with conventional steel bars, were tested up to failure. Test variables in this study were: (1) concrete compressive strength; (2) longitudinal reinforcement ratio; and (3) shear span-effective depth ratio. Beam capacities, slope of the diagonal shear cracks, strains at the maximum concrete compression fiber and selected position of longitudinal reinforcement were observed during the test. The diagonal shear cracking loads obtained from the test were compared to that calculated using empirical equations available in ACI code and Eurocode 2. The test results showed that shear strength of beams reinforced with GFRP bars was lower than that of the beams with conventional steel bars. It was found that the ratio of longitudinal reinforcement significantly influences the failure type and crack pattern in the shear span zone. In addition, the tensile strain of longitudinal reinforcement at the support considerably increases after the occurrence of diagonal cracks.

Keywords: Concrete beams, GFRP bars, diagonal shear crack, tensile strain

1 Introduction

The occurrence of diagonal shear crack in reinforced concrete beam indicates not only a precondition to shear failure but also influences the distribution of tensile force along the

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longitudinal reinforcement. Previous test results have experimentally proven that a certain quantity of tensile force is shifted to the support after the occurrence of diagonal shear crack (Thamrin, R., and Kaku, T 2005). Even though some equations expressed the relationship between diagonal shear cracking load and tensile force at the support have been proposed (Thamrin, R., and Kaku, T 2007), there are still few studies evaluating the experimental behavior of tension force at the support due to the effect of diagonal shear crack.

The ratio of longitudinal reinforcement is one of the main factors affecting the formation of diagonal shear cracking load (Zararis, P. D. 2003). During the occurrence of diagonal crack the transverse force developed in longitudinal reinforcements, known as dowel force, contributes to the shear resistance in reinforced concrete beam. However, not many research reports the influence of longitudinal reinforcement ratio on the slope of diagonal crack in the shear span zone.

This study considered not only the occurrence of the diagonal shear cracking load and behavior of the tension force at the support but also the slope of the diagonal shear crack in the shear span zone. Test variables used in this study were: (1) concrete compressive strength; (2) longitudinal reinforcement ratio; and (3) shear span-effective depth ratio. In addition, diagonal shear cracking loads obtained from the test were compared to that value calculated using empirical equations available in ACI code and Eurocode 2.

2 Materials and Method

A total of twenty four concrete beams without stirrups, consisted of twelve beams reinforced with GFRP bars and twelve beams reinforced with conventional steel bars, were tested to failure (**Tab. 1**). The beams were simply supported and loaded with two-point loads. Beam dimensions were 130 mm wide and 230 mm deep (**Fig. 1**). Two types of shear span-effective depth ratio were obtained by using two shear span length, *Ls*, i.e. 450 mm and 600 mm. In order to avoid bond failure, the beams were designed with sufficient additional bond length, *La*, at the end of the beams. In the case of beam with 450 mm shear span length, *La* was 250 mm, and for beam with 600 mm, the shear span length, *La* was 200 mm.

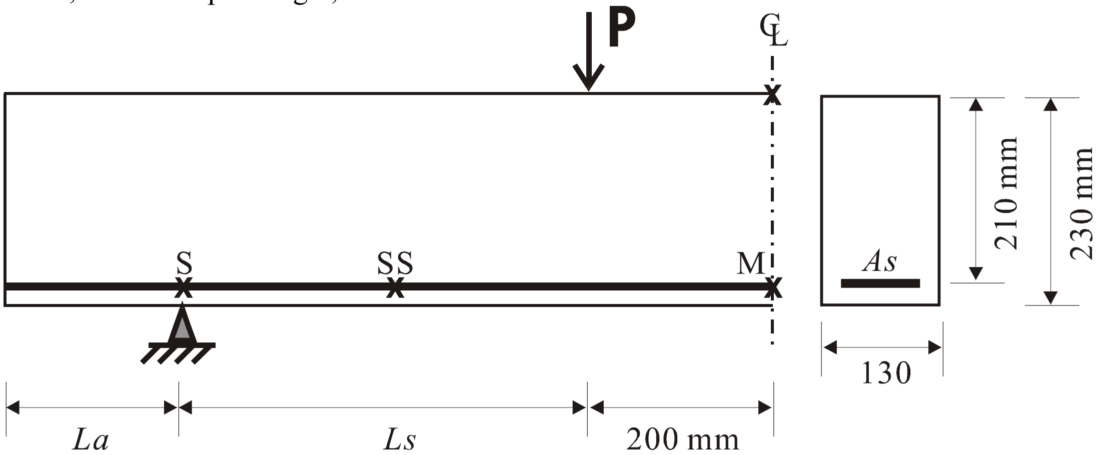


Fig. 1 Beam detail, loading position, and beam cross section

GFRP bars used were deformed and sand coated type with 9 mm diameter. The tensile strength, f_u, and modulus of elasticity, E_f, of GFRP bars were 770 MPa and 51.5 GPa, respectively. Deformed steel bars with 10mm diameter, yield strength, f_y = 746 MPa and modulus of elasticity, E_s = 209 GPa were used for concrete beam reinforced with steel bars. Two types of concrete compressive strength, f_c', used in this study were 13 MPa and 33.5 MPa.

All beams were instrumented with strain gauges at positions illustrated by marks in **Fig. 1**, to measure strain. Three positions of strain gauges attached on longitudinal reinforcement denoted as M, SS and S as shown in **Fig. 1**. Strain gauges were also attached on the top of compression fibre at midspan of the beam. In addition, the deflections at midspan and at loading points were measured using three displacement transducers.

Tab. 1 Beams properties, theoretical diagonal cracking load and test results

Beams	a/d	fc' (MPa)	Longitudinal reinforcement d_b (mm)	Longitudinal reinforcement As (mm^2)	Longitudinal reinforcement ρ (%)	ACI Vcr (kN)	EC 2 Vcr (kN)	ACI 440.1R-03 Vcr (kN)	Diagonal crack load (Exp.) Vcr (kN)	Ultimate load (Exp.) $Vult$ (kN)	Slope of crack in shear span zone	Crack distance from support (mm)	Type of failure
BSL-01	2.3	13.0	10.0	78.5	0.30	15.6	9.8	-	-	23.9	83.0	327.0	FF
BSL-02				157.1	0.60	15.6	12.4	-	19.8	42.5	55.0	245.0	SF
BSL-03				235.6	0.91	15.6	14.2	-	23.2	44.9	46.0	249.0	SF
BSN-04		33.5		78.5	0.30	25.1	13.5	-	-	27.1	75.0	365.0	FF
BSN-05				157.1	0.60	25.1	17.0	-	22.8	48.9	60.0	297.0	SF
BSN-06				235.6	0.91	25.1	19.5	-	27.7	53.9	57.0	265.0	SF
BSL-07	3.0	13.0		78.5	0.30	15.6	9.8	-	-	21.0	82.0	393.0	FF
BSL-08				157.1	0.60	15.6	12.4	-	13.3	27.4	49.0	359.0	SF
BSL-09				235.6	0.91	15.6	14.2	-	19.5	29.2	40.0	195.0	SF
BSN-10		33.5		78.5	0.30	25.1	13.5	-	-	19.5	80.0	493.0	FF
BSN-11				157.1	0.60	25.1	17.0	-	18.3	35.7	45.0	145.0	SF
BSN-12				235.6	0.91	25.1	19.5	-	18.8	43.9	45.0	302.0	SF
BGL-01	2.3	13.0	9.0	63.6	0.30	15.6	9.8	2.4	-	22.5	87.0	340.0	FF
BGL-02				127.2	0.60	15.6	12.4	4.9	17.0	27.7	56.0	274.0	SF
BGL-03				190.9	0.91	15.6	14.2	7.3	17.2	25.0	48.0	272.0	SF
BGN-04		33.5		63.6	0.30	25.1	13.5	1.5	-	17.9	64.0	296.0	FF
BGN-05				127.2	0.60	25.1	17.0	3.0	19.6	39.4	68.0	270.0	SF
BGN-06				190.9	0.91	25.1	19.5	4.6	24.4	36.3	42.0	322.0	SF
BGL-07	3.0	13.0		63.6	0.30	15.6	9.8	2.4	-	16.7	80.0	344.0	FF
BGL-08				127.2	0.60	15.6	12.4	4.9	11.4	18.6	48.0	200.0	SF
BGL-09				190.9	0.91	15.6	14.2	7.3	14.6	19.9	35.0	330.0	SF
BGN-10		33.5		63.6	0.30	25.1	13.5	1.5	-	12.7	57.0	447.0	FF
BGN-11				127.2	0.60	25.1	17.0	3.0	13.6	18.8	45.0	330.0	SF
BGN-12				190.9	0.91	25.1	19.5	4.6	19.0	23.6	45.0	340.0	SF

Note: FF = flexural failure; SF = shear failure

Tab. 2 Concrete shear strength equations from references, code and design recommendation

ACI 318-05 (2005)[1]

$$v_{cr} = \frac{1}{6}\sqrt{f_c^{'}} \tag{1}$$

Eurocode 2 (1992)[1]

$$v_{cr} = \left(0.12k(100\rho_w f_c)^{1/3}\right) \tag{2}$$

ACI 440.1 R-03 (2003)[2]

$$v_{cr} = \frac{\rho_f E_f}{90\beta_1 f_c^{'}}\left(\frac{\sqrt{f_c^{'}}}{6}\right) \tag{3}$$

[1] Equations adopted from code for steel-reinforced members; [2] Code for FRP-reinforced members

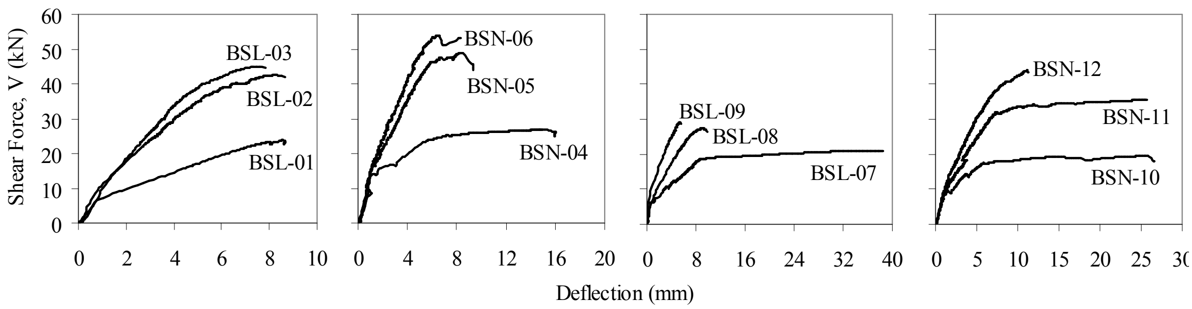
3 Results and Discussion

Failure modes and capacities of the beams are listed in **Tab. 1**. In this study, the experimental diagonal crack loads tabulated in **Tab. 1** were observed visually and described as the load when the flexural crack in the shear span zone became inclined. Furthermore, in order to estimate theoretically the concrete shear contribution, the selected existing concrete shear strength equations given in **Tab. 2** were used. **Eq. (1)** is the basic expressions for concrete contribution to shear resistance without size effect of steel-reinforced concrete members adopted from ACI 318-05 code (2005). **Eq. (2)** is the expression adopted from Eurocode 2 (1992) for concrete contribution to shear of steel-reinforced concrete members and **Eq. (3)** is the expression adopted from ACI 440.1 R-03 (2003) for concrete contribution to shear resistance of FRP-reinforced concrete members.

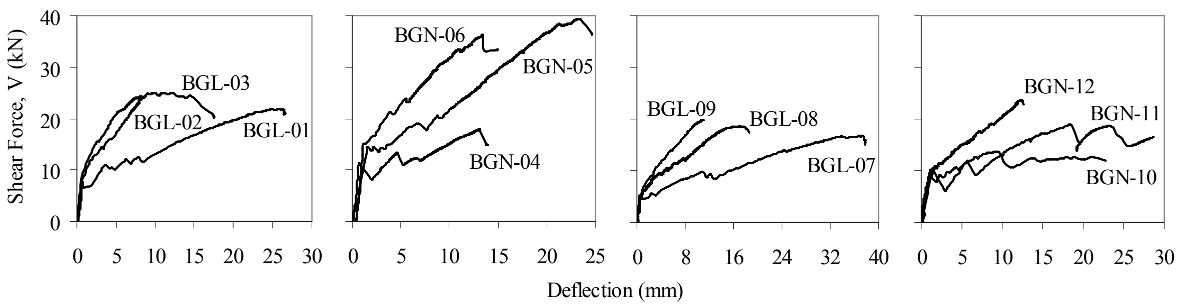
Two types of failure mode were observed from the test (**Tab. 1**). The first type of failure is Flexural Failure (FF) indicated by rupture of longitudinal reinforcement, which was occurred in beams reinforced with GFRP bars. In addition, flexural cracks were dominantly occurred in loading point zone. This type of failure was due to a low longitudinal reinforcement ratio. In these beams, diagonal shear crack was not significant in the shear span zone.

The second type of failure is Shear Failure (SF), which was consisted of two categories. The first one is, diagonal shear-tension failure indicated by sudden formation of diagonal crack in the shear span zone immediately before the beam collapsed. The second one is shear-compression failure dominated by diagonal shear crack developed gradually in the shear span zone before collapse. Failure mode and crack pattern of the tested beams are shown in **Fig. 3**.

Load deflection curves of the tested beams are shown in **Fig. 2**. It is shown that as the ratio of longitudinal reinforcement increases and as the ratio of shear span-effective depth decreases, beam capacity increases. **Fig. 2** also shows that beam capacity slightly increases as the concrete compressive strength increases. It is revealed that ratio of longitudinal reinforcement influences the type of failure and stiffness of the beams after the occurrence of the first flexural crack. In addition, in the case of beams reinforced with GFRP bars, stiffness of the beams drastically decreases even though the beams have higher longitudinal reinforcement. This was due to low modulus elasticity of GFRP bars.



(a) Beams reinforced with steel bars



(b) Beams reinforced with GFRP bars

Fig. 2 Load deflection curve of the beams

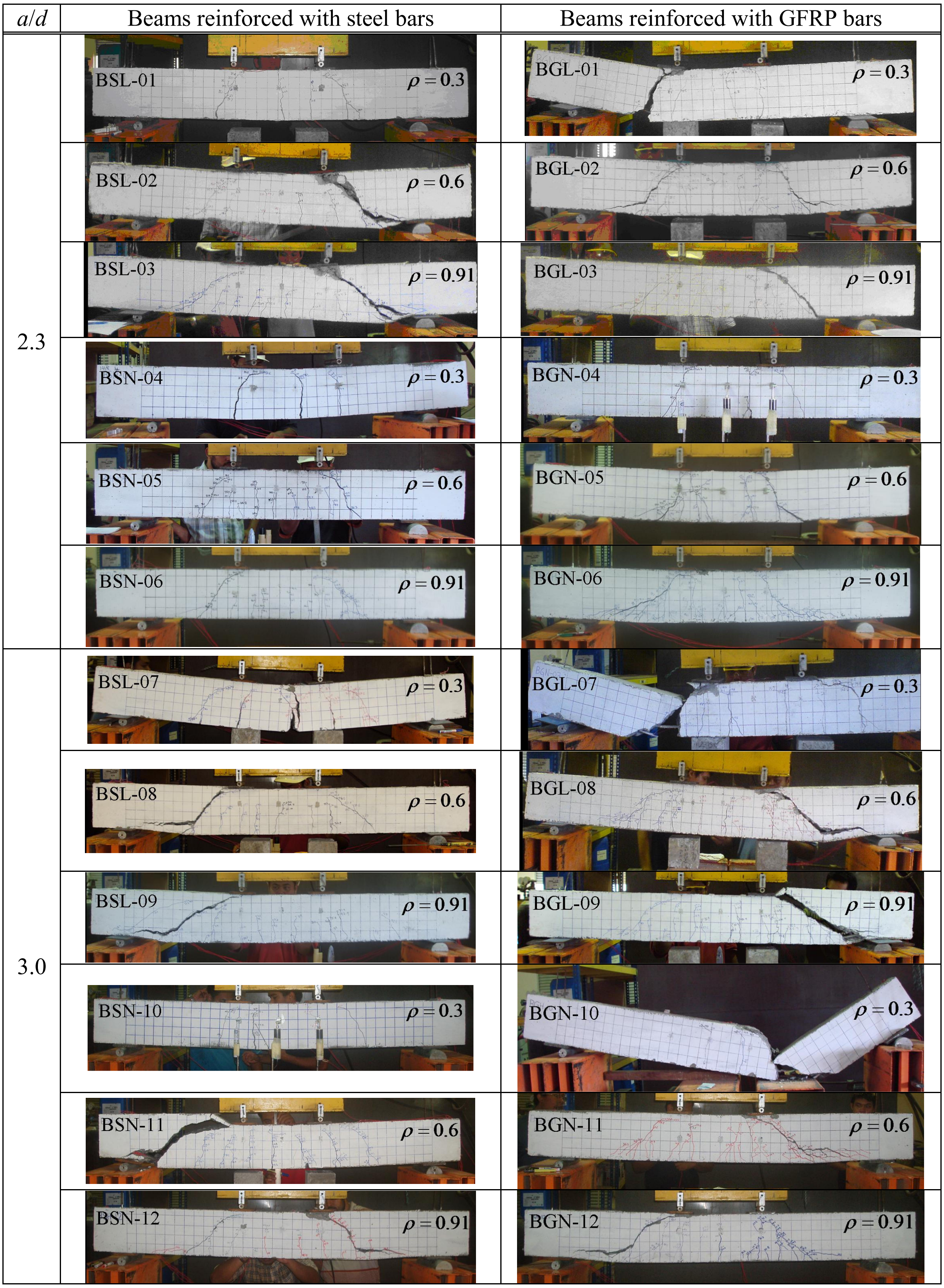


Fig. 3 Failure mode and crack pattern of tested beams

Based on the observation of failure mode and crack pattern of tested beams, it was found that the longitudinal reinforcement ratio significantly influences the crack pattern and slope of crack in the shear span zone. Flexural cracks indicated by vertical cracks developed around loading points are more dominant in beams with the lowest longitudinal reinforcement ratio (ρ = 0.3). On the other hand, diagonal shear cracks were clearly observed for beams with higher longitudinal reinforcement ratio (ρ = 0.6 and 0.91). In general, **Fig. 3** concludes that slope of diagonal crack decreases as the longitudinal reinforcement ratio increases.

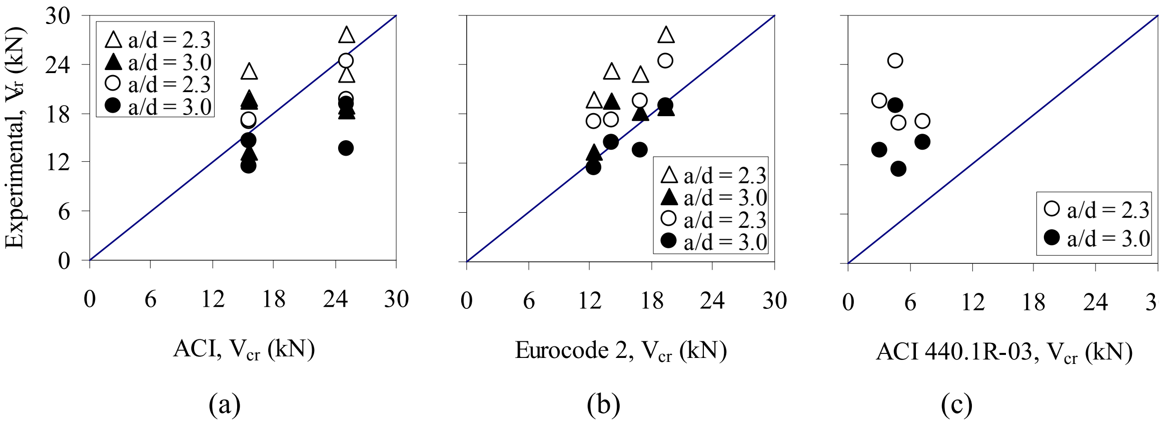


Fig. 4 Calculated concrete shear strength versus experimental diagonal shear cracking loads

Fig. 4 compares the calculated concrete shear strength with the observed values. Here, the triangle represents beams reinforced with steel bars and the circle represents for beams reinforced with GFRP bars. It is shown from the figure that **Eq. 1** overestimates the diagonal shear cracking loads in the case of beams with a/d = 3 and higher concrete compressive strength. However, since no size effect was considered in **Eq. 1**, the expectation of this comparison is to contribute additional data related to the use of this equation. **Eq. 2** conservatively predicts the diagonal shear cracking loads of concrete beams reinforced with steel and some beams with GFRP bars, while **Eq. 3** clearly underestimate the diagonal shear cracking loads for all beams reinforced with GFRP bars.

In **Fig. 5**, tension forces of longitudinal reinforcement are plotted versus shear forces to observe the influence of shear span length on tension force at the support. It is shown that the tension force at the middle of the beam and at the middle of shear span significantly increases after the occurrence first flexural crack. With further loading, the tensile force at the support considerably increases after the occurrence of diagonal cracks. But in the case of beams with a/d = 3 and reinforced with GFRP bars there were no tension force shifted to the support (**Fig. 5(g)** and **(h)**) due to low capacity of the beams. This figure also shows that with the increase of shear span length, the tension force at the support decreases. This fact reveals that the capacity of the beams decreases with the increase of shear span length. In the case of beams reinforced with steel bars, it was observed that a small amount of tension force was developed at the support after the yielding of longitudinal reinforcement. In addition, depending on the ratio of longitudinal reinforcement, tension force at the support increases as the ratio of longitudinal reinforcement increases.

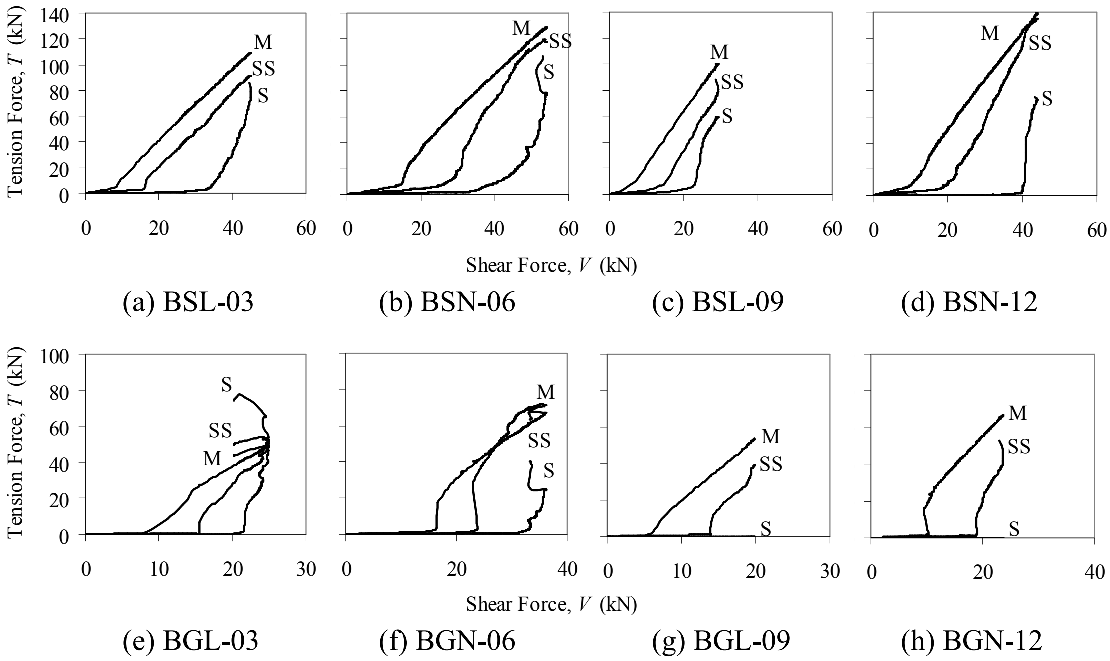


Fig. 5 Tension force of longitudinal reinforcement versus shear force curves of selected beams

4 Conclusions

A total of twenty four concrete beams, consisted of twelve beams reinforced with GFRP bars and twelve beams reinforced with steel bars, were tested to observe the diagonal shear crack and the tension force of longitudinal reinforcement. The following conclusions are noted from the results:

- Shear capacity of the tested beams is significantly influenced by the amount of shear span length and longitudinal reinforcement ratio. In this study, concrete compressive strength slightly influences the shear capacity of the beams.
- The ratio of longitudinal reinforcement also influences the type of failure and stiffness of the beams after the occurrence of the first flexural crack.
- The crack patterns as well as the slope of diagonal crack in the shear span zone were significantly influenced by the ratio of longitudinal reinforcement. In general, the slope of diagonal crack decreases as the longitudinal reinforcement ratio increases.
- A simple equation to calculate concrete contribution to shear adopted from ACI 318-05 overestimates the diagonal shear cracking loads in the case of beams with a/d = 3 and higher concrete compressive strength. The equation adopted from Eurocode 2 conservatively predicts the diagonal shear cracking loads of concrete beams reinforced with steel and some of beams with GFRP bars, while ACI 440.1 R-03 equation clearly underestimate the diagonal shear cracking loads for all beams reinforced with GFRP bars.
- The tensile force of longitudinal reinforcement at the support considerably increased after the occurrence of diagonals cracks and with increasing of shear span length the tension force at the support decreases.

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