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Effect of Longitudinal Steel Reinforcement on Shear Capacity of SFRC Beams without Coarse Aggregate

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ABSTRACT— In this paper, the effect of flexural reinforcement ratio on shear capacity of steel-fiber reinforced concrete (SFRC) beams without coarse aggregate and transverse reinforcement was investigated. Six pairs of concrete beam specimens with the size of 70 mm × 125 mm × 1100 mm and shear span to effective depth ratio of 45/10.5 were tested using two-point symmetric top loading. The flexural reinforcement ratio varies from 0.0073 to 0.0782 with 0.1 percent steel fiber ratio of the total mass. The increase in shear capacity has been proven by the test results. However, this increase turns out to be insignificant as the flexural reinforcement ratio approaches its maximum value. Transverse reinforcement is required when the flexural reinforcement ratio approaches its minimum value. Fiber reinforced concrete without coarse aggregate has lower shear capacity than that of normal concrete and closes to the lower bound value of the Joint ASCE-ACI Committee's test results for normal concrete. The shear capacity contributed by concrete proposed by ACI, which remains unchanged for decades, is only applicable for normal concrete.

KEYWORDS: Coarse Aggregate, Concrete Beam, Fiber, Longitudinal Reinforcement Ratio, Shear Capacity.

1. Introduction

There are various materials used in many different type of construction. Among these materials, concrete and reinforced concrete has been commonly used in engineered construction [1]. The fast-paced development in construction industry requires the utilization of high strength concrete and other high performance materials. According to ACI 363.2R-1, a concrete is categorized as high-strength concrete when its compressive strength exceeds 55 MPa [2]. In this type of concrete, the coarse aggregates become its shortcoming. In order to furthermore increase the strength, the coarse aggregate needs to be excluded from the concrete mixture. When the compressive strength of concrete increases, the ductility of concrete, on the other hand, decreases, and thus, becomes more brittle. To improve the ductility, steel fiber was added to concrete. The random oriented fibers were distributed uniformly to concrete mix to prevent the formation of initial cracks in tension region caused by hydration heat and loading [3]. When designing reinforced concrete beams, the shear, bending moment, and torsional capacities should not be less than the corresponding ultimate shear, bending moment, and torsion, respectively [4], [5]. Due to its brittle manner, the shear failure is very critical in beams and other members. When the concrete beam is loaded, the crack can have occurred in the beam. In general, the crack can be classified as shear crack and flexure crack, as shown in Figure 1.

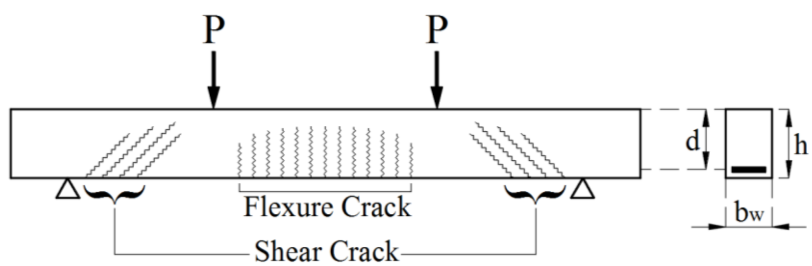

Figure 1 Shear and Flexural Cracks in Concrete Beam

1.1 No-Coarse Aggregate Concrete and Fiber Reinforced Concrete

Coarse aggregate contributes to the shear capacity of bearing by means of bearing shear force. The reduction of this contribution and the reduced ductility of very high strength concrete can be solved or improved using innovative materials, such as fiber. When a concrete is reinforced with short, randomly oriented fiber, the concrete is referred as fiber-reinforced concrete [1]. In the study, innovative materials, such as steel fiber, silica fume, marble powder, and superplasticizier, were used in making the high-strength concrete mixtures.

1.2 Concrete Shear Capacity

According to ASCE Committee 426 report, the shear strength of concrete should be taken as the shear force that causes the inclined crack and its value does not depend on the shear reinforcement [6]. The function of shear reinforcement is to resist the excess shear force which is not resisted by the concrete. In reinforced concrete, the maximum shear force (V_u) is carried by the concrete (V_c), flexural reinforcement (V_d), and shear reinforcement (V_s). The contributions of concrete and reinforcement in resisting shear can be written as:

$$V_u = V_c + V_d + V_s \quad (1)$$

The removal of transverse reinforcement was made in purpose to study the influence of longitudinal reinforcement ratio on the shear capacity of concrete only which leads to the following equation:

$$V_u = V_c + V_d \quad (2)$$

Shear crack causes concrete beam to split into two parts. The inclined crack (caused by shear) can be resisted by four aspects as follows:

1. Surface roughness and shape of aggregate contribute in resisting the shear and thus, the shear cracks. As illustrated in Figure 2, the angular and rough-surfaced aggregate is very effective in resisting the shear. This type of aggregate interlocks and makes it is hard to slip, and thus it is better in cracking resistance. The round and smooth surfaced aggregate is not able to resist the shear as effective as the angular and rough surface aggregate due to its higher potential slippage.

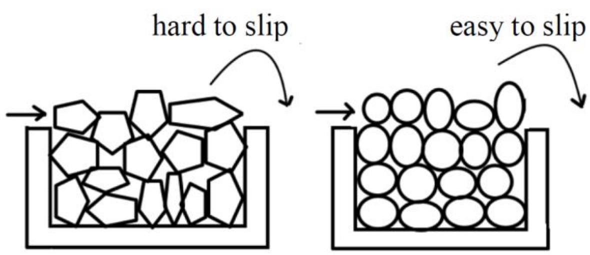

Figure 2 Angular and Round Coarse Aggregate

2. Shear cracks are resisted by concrete.
3. Shear cracks are resisted by longitudinal reinforcement [7]. Dowel action in longitudinal reinforcement provides a shear force resistance when cracks form across the longitudinal bars.

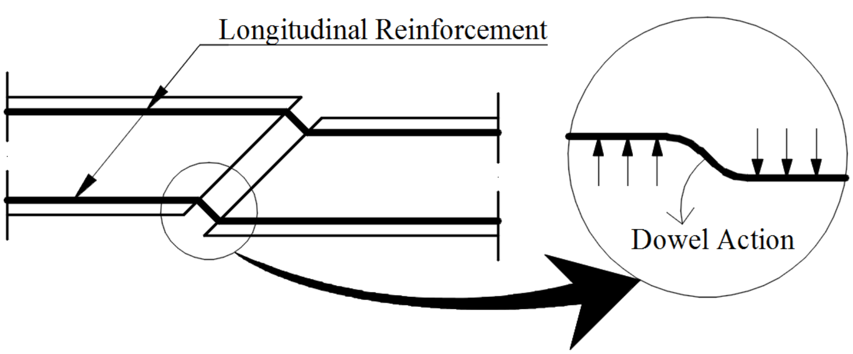

Figure 3 Dowel Action

4. Shear cracks are resisted by tensile force of transverse and inclined reinforcement as shown in Figure 4.

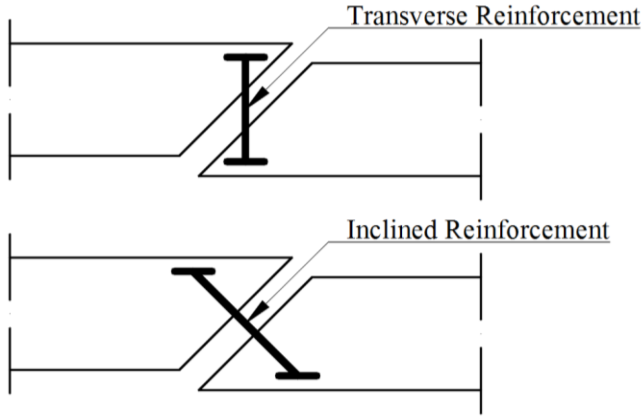

Figure 4 Transverse and Inclined Reinforcement

For members resisting the shear and bending moment, ACI 318M-19 [8] defines that the shear force capacity contributed by concrete alone with the following formula:

$$V_c = 0.17\sqrt{f'_c}\, b_w\, d \qquad (3)$$

From the above formula, it can be seen that V_c depends on the concrete compressive strength (f_c', in MPa), the width of the beam web (b_w), and the effective depth of the beam (d). The formula remains unchanged until the latest edition of the ACI Building Code [8].

1.3 Absence of Transverse Reinforcement in Concrete Beam

The stress increase and the forming of the inclined crack in concrete beams occur due to the loading. In the absence of transverse reinforcement, concrete beams immediately fail after the inclined crack occurs. Other than loading, the formation of this type of crack is affected by several following aspects [6]:

1) Aggregate interlock
Aggregate interlock transfers most of the shear forces to the supports.

2) Coarse aggregate size
As the coarse aggregate diameter increases, the crack roughness also increases, allowing higher shear stress to be transferred through the crack gap. This type of shear reduction is transferred by the aggregate interlock along the crack path.

3) Concrete tensile strength
The concrete tensile strength is influenced by the cracking of concrete. When the initial crack is a flexural crack, the elastic stress field tends to have been interfered such that the cracks occur at the principal tensile stress.

4) Beam size
As the beam depth increases, the crack width and distance tend to increase, causing a reduction of maximum shear stress contributed by the aggregate interlock transferred through the crack gap. In concrete without coarse aggregate, the shear stress reduction can reach up to 70.95 percent for the beam with h = 3b which is higher when compared to the beam with h = b [9]. The unstable condition appears when the transferred shear stress start exceeding the concrete shear strength.

5) Axial tensile force
The increase of the tensile stress in longitudinal reinforcement is due to the direct axial tensile force which leads to the increase of inclined crack width and the reduction of maximum shear stress transferred through the crack gap.

6) Ratio of Longitudinal Reinforcement
For concrete beams in which the shear reinforcement is not available, the shear capacity increases due to the presence of longitudinal reinforcement as shown in Figure 5 for a simply-supported beam with normal concrete.

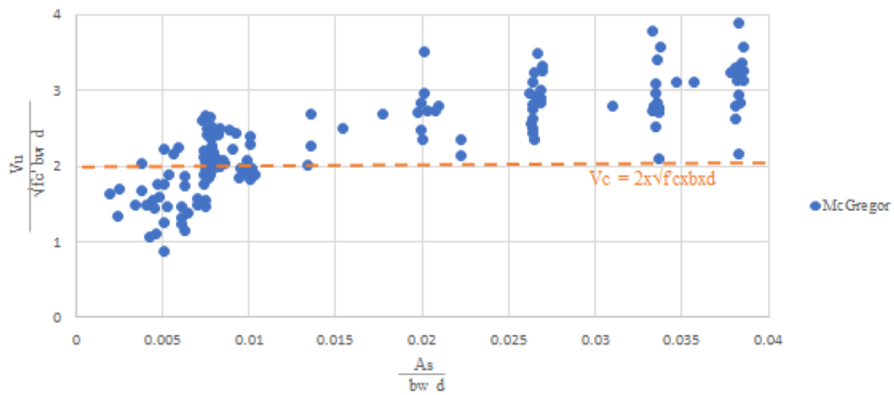

Figure 5 Influence of Flexural Reinforcement Ratio on Shear Capacity of Normal-Concrete Beams without Shear Reinforcement

7) Shear span to effective depth ratio (a/d)
The type of shear failure is greatly affected by the a/d ratio. As can be seen in Figure 6, there is the most critical a/d ratio, which value is 2.5. For a/d is less than this critical value, the shear is resisted by the arch action mechanism [10-14]. For a/d more than the critical value, the shear is resisted by the beam action mechanism [15-17].

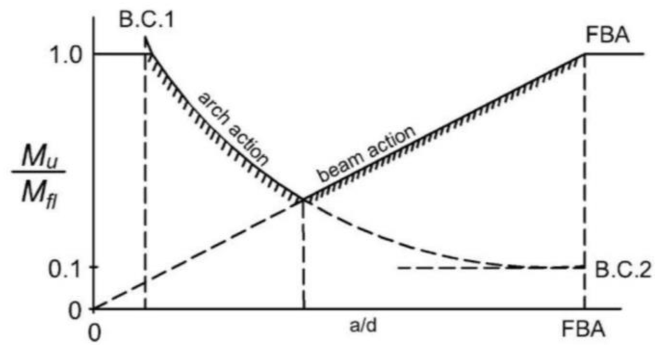

Figure 6 Influence of a/d Ratio on Beam Capacity

2. Experimental Data
In this research, water, cement, silica fume, sand, marble powder, superplasticizer, and steel fiber are used to make the specific concrete. The specific gravity and the concrete mix proportion are given in Table 1. The sand (fine aggregate) for concrete mixture used sieve analysis #30 (0.6 mm) and 50 (0.3 mm). The tested curing time was 58 days after the initial placement.

Table 1 Concrete Mix Proportion

Material	Spesific Gravity (kg/m^3)	Ratio
Water	1000	0.18
Cement	3150	1.0
Silica Fume	2200	0.2
Sand	2617.8	1.1
Marble Powder	2563	0.1
Superplasticizier	1150	0.025
Steel Fiber	7850	0.001

For each batch of concrete (specimen), two cylinder samples with the diameter of 100 mm and height of 200 mm were used for evaluating the concrete compressive strength of the specimens. To study the influence of flexural reinforcement ratio on the shear capacity, six pairs of concrete beams with the size of 70 × 125 × 1100 mm were tested without any transverse reinforcement. All beam specimens had the shear span to effective depth ratio of 45/10.5 to ensure the beam action mechanism. The longitudinal reinforcement ratio varies from a minimum of 0.0073 to a maximum of 0.0782. The concrete beams were tested using the two-point loading. To assure that the shear failure occurs prior to the flexural failure at both ends of the beam, a test setup was selected. The load was increased by steps and recorded until the beam failed and reached its maximum capacity. Figure 7 shows the setup for beams E21 and E22.

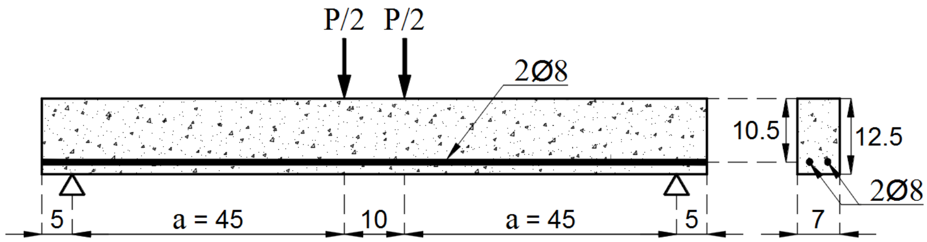

Figure 7 Beam Details and Test Setup

3. Test Results and Discussion

Compressive strength test results of the cylinder samples and the maximum loads of the beam specimens are shown in Table 2. The shear failure is shown using the representative beam E61 with the longitudinal bar diameter (d_b) of 19 mm, as can be seen in Figure 8.

Table 2 Experimental Test Results of Beam Specimens and Corresponding Cylinder Samples

Beam ID	Longitudinal Bar Diameter (mm)	Cylinder 100 × 200 mm		Beam 70 × 125 × 1100 mm		Curing Time (day)
		Load, P (kN)	f_c' (MPa)	Load, P (kN)	Type of Failure	
E11	6	617.1	78.57	15.12	Flexure	58
E12	6	636.4	81.04	14.73	Flexure	58
E21	8	514.8	65.54	16.06	Flexure + Shear	58
E22	8	479.2	61.02	17.37	Flexure + Shear	58
E31	10	429.8	54.73	17.31	Shear	58
E32	10	543.9	69.25	23.13	Shear	58
E41	12	570.2	72.61	21.05	Shear	58
E42	12	457.0	58.18	23.81	Shear	58
E51	16	570.9	72.68	29.73	Shear	58
E52	16	584.3	74.40	29.94	Shear	58
E61	19	602.5	78.57	29.11	Shear	58
E62	19	554.0	70.65	27.70	Shear	58

Figure 8 Beam E61 undergoes Shear Failure

According to the computational results, the concrete shear capacities (V_c) of beam specimens are shown in Table 3. The nominal bending moment, M_n, can be calculated using the following formula:

$$M_n = 0.85\ f'_c\ b_w\ a_c\ (d - 0.5a_c) \qquad (4)$$

Table 3 Summary of Shear Strength Capacities of Beam Specimens

Beam ID	d_b (mm)	Average f'_c (MPa)	Average P (kN)	V_c (kN)	M_n (kNm)	P_m (kN)	P_v (kN)	Type of Failure
E11 & E12	6	79.805	14.925	11.5	2.1	9.4	22.8	Flexure
E21 & E22	8	63.280	16.715	10.1	3.7	16.3	22.6	Flexure + Shear
E31 & E32	10	61.990	20.220	9.9	5.5	24.9	22.4	Shear
E41 & E42	12	65.395	22.430	10.1	7.7	34.6	22.1	Shear
E51 & E52	16	73.540	29.835	10.5	12.5	56.3	21.7	Shear
E61 & E62	19	74.610	28.405	10.4	16.1	72.8	21.4	Shear

The parametric data required to compute the values of the longitudinal reinforcement ratio, $\rho = \frac{A_s}{bd}$, and $\frac{V_u}{\sqrt{f'_c}bd}$ are given in Table 4. All beam specimens have the width (b) of 70 mm and the effective depth (d) of 105 mm. The computed values are given in a graphical representation shown in Figure 9.

Table 4 Data Required for Computing $\rho = \frac{A_s}{b.d}$ and $\frac{V_u}{\sqrt{f'_c}.b.d}$

Beam ID	d_b (mm)	Average f'_c (MPa)	Average P (kN)	V_u (kN)	A_s (mm^2)	ρ (%)	$\frac{V_u}{\sqrt{f'_c}.b.d}$
E11 & E12	6	79.805	14.925	7.6	56.5	0.73	1.325
E21 & E22	8	63.280	16.715	8.5	100.5	1.32	1.679
E31 & E32	10	61.990	20.220	10.2	157.0	2.08	2.067
E41 & E42	12	65.395	22.430	11.3	226.1	3.02	2.251
E51 & E52	16	73.540	29.835	15.0	401.9	5.47	2.870
E61 & E62	19	74.610	28.405	14.3	566.8	7.82	2.753

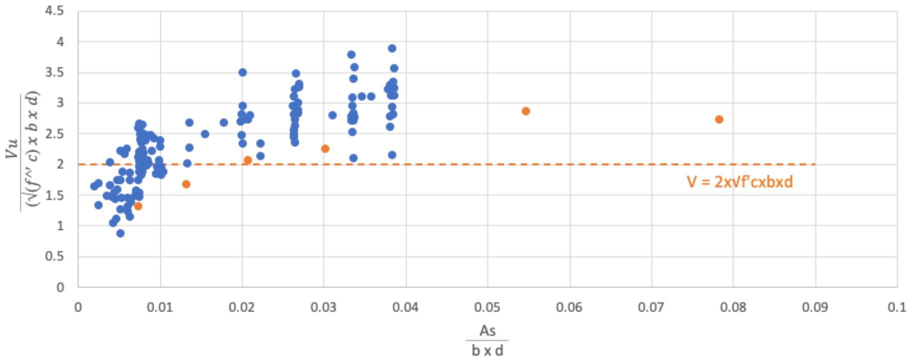

Figure 9 Effect of Longitudinal Steel Reinforcement on Shear Capacities Ratio ($\frac{V_u}{\sqrt{f'_c}.b.d}$) of Concrete Beams without Coarse Aggregate and Shear Reinforcement

Figure 10 shows the influence of flexural reinforcement ratio on the shear capacities in a graphical representation, which is given in terms of shear strength capacity ratio (V_u/V_c). The variation in concrete strength has been taken into account in the analysis. Beams with higher flexural reinforcement ratio also have higher shear strength capacity ratio.

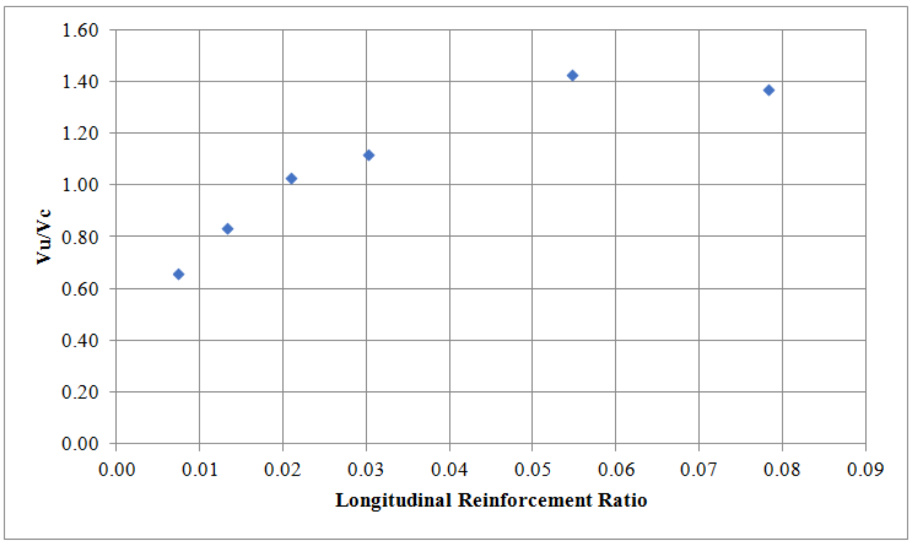

Figure 10 V_u/V_c vs. Longitudinal Reinforcement Ratio

4. Conclusion

Based on the research and discussion above, the following conclusions can be drawn:

1) The flexural reinforcement ratio greatly influences the shear strength capacity ratio (V_u/V_c) of the concrete beam with steel fiber without coarse aggregate and shear reinforcement. The shear capacity increases when the concrete beam has higher longitudinal reinforcement ratio.
2) The shear capacity of the beam with the maximum longitudinal reinforcement ratio was about 108 percent higher than that with the minimum longitudinal reinforcement ratio.
3) When the longitudinal reinforcement ratio approaches its maximum value, the increase of shear strength capacity ratio (V_u/V_c) becomes insignificant.
4) The shear strength capacity ratio becomes less than one as the ratio of longitudinal reinforcement approaches its minimum value. This phenomenon occurs due to the flexural failure as the primary failure or when less than the shear strength capacity of the ACI 318-19 [8] which is affected by the contribution of the concrete alone for normal concrete. (When this condition takes place, the transverse reinforcement is required to carry the remaining shear force. As the longitudinal reinforcement ratio approaches its maximum value, shear reinforcement is no longer required).

5) The shear strength capacity ratio (V_u/V_c) of fiber-reinforced concrete without coarse aggregate is lower than that of normal concrete. The shear strengths of the beam specimens were close to the lower bound value of the Joint ASCE-ACI Committee test results for normal concrete.

5. Acknowledgements

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6. Nomenclatures

A_s	Cross-sectional area of longitudinal reinforcement bars, mm^2
a	Shear span, equal to the distance from a point load to support, mm
a_c	Depth of equivalent rectangular stress block, mm
b_w	Width of beam web, mm
b	Width of the beam, mm
d	Effective depth of the beam, mm
f'_c	Compressive strength of concrete, MPa
h	Total height of the beam, mm
M_n	Nominal bending moment, kNm
P_m	Computed load from M_n, kN
P_v	Computed load from V_n, kN
V_c	Nominal shear strength provided by concrete, kN
V_d	Nominal shear strength provided by longitudinal reinforcement, kN
V_n	Nominal shear strength, kN
V_s	Nominal shear strength provided by transverse reinforcement, kN
V_u	Ultimate shear strength, kN
v	Shear stress, MPa
ρ	Longitudinal reinforcement ratio

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