Journal of Civil Engineering (IEB), 47 (1) (2019) 31-45

Journal of Civil Engineering IEB

Shear strength of RC beams made with brick aggregate without shear reinforcement

Md. Tarek Uddin[1], Md. Kamal Hossain Shikdar[2] and Jamil Ahmed Joy[1]

[1]Department of Civil and Environmental Engineering
Islamic University of Technology, Gazipur, Bangladesh
[2]Structural Design Engineer
BCL Associates Limited, Dhaka, Bangladesh

Received 06 December 2018

Abstract

Shear strength of reinforced concrete (RC) beams made with brick aggregate (BA) was investigated without shear reinforcement. For investigation, 16 RC beams of size 200 mm by 300 mm by 2100 mm and 200 mm by 300 mm by 2400 mm were made with BA. The investigated variables were longitudinal tensile steel ratio, shear span to depth ratio, and compressive strength of concrete. In the shear span of the beam specimens, no shear reinforcements were provided. The beams were designed to ensure shear failure according to ACI 318-14. Shear strengths of the beams without shear reinforcement were evaluated by four-point loading test. Shear strength of concrete beams was also evaluated by using different codes and fracture mechanics approaches. These results were compared with the experimental results. The results obtained from this study were also compared with the results of the shear database. It is revealed that the existing codes and fracture mechanics approaches can be used safely for evaluation of the shear capacity of RC beams made with BA.

Keywords: Shear strength, brick aggregate, steel ratio, compressive strength, shear span to depth ratio.

1. Introduction

Bangladesh is a land of a delta. Due to the lack of availability of stone aggregate, Clay burnt brick coarse aggregate (here defined as brick aggregate (BA)) is widely used in many RC structures. BA is also used in other countries, such as Nepal, Pakistan, India, Sri Lanka, etc. for making RC structures. In Bangladesh, the design codes, particularly Bangladesh National Building Code (BNBC) and ACI 318 are used to design RC structures made with BA. However, these design codes arebasically developed for capacity evaluation or design of RC structural members made with stone aggregate. Several studies were conducted to understand the mechanical properties of concrete made with BA (Mohammed, et al., 2014; Akhtaruzzaman & Hasnat, 1986; Khaloo, 1994). Mohammed et al. 2014 also conducted another study on the utilization of brick aggregate for making high strength concrete. Based on these studies, it is understood that BA can be used for making structural concrete even for strength level over 40 MPa. It is also found that the correlations between mechanical properties of concrete, such as compressive strength and tensile strength of concrete, compressive strength and modulus of elasticity concrete, etc. do not follow the correlations provided in the design codes, such as ACI 318 and BNBC 2006. It indicates the necessity of verifications of existing code provisions against shear design and flexural design of RC beam made with BA. Therefore, a study was conducted by Mohammed et al. 2017to understand the flexural behaviour of RC made with BA. From this study, it is revealed that existing design provisions of ACI code can be safely used for the design of RC members made with BA.

Table 1
Properties of coarse (BA) and fine aggregates

Type of Aggregate		Specific gravity	Absorption	Unit weight (SSD) Kg/m^3	Abrasion	FM
Fine Aggregate	Sand	2.46	3%	1574	-	2.6
Coarse Aggregate	BA	1.98	10.5%	1209	39%	6.6

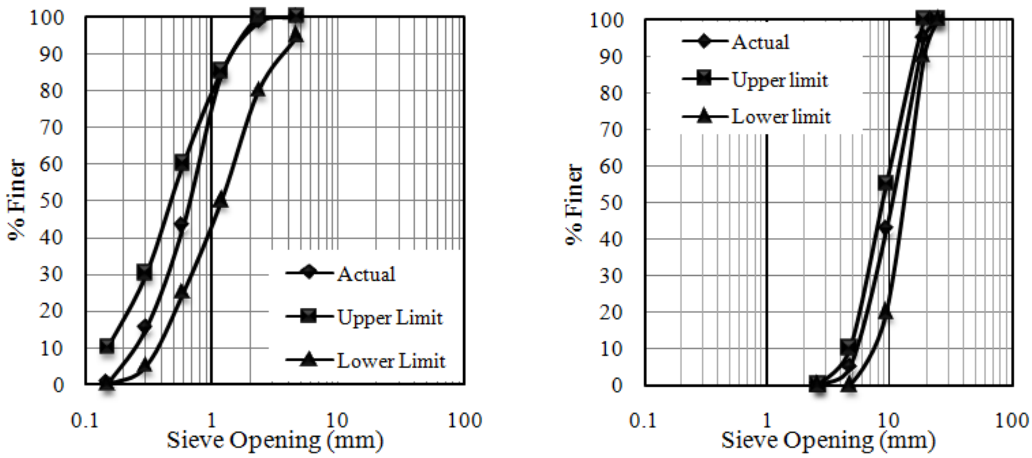


Fig. 1. Grading curves of fine aggregate and coarse aggregate (BA).

By exploring the literature on diagonal shear capacity of RC beam, it is found that a large number of investigations was conducted on this topic. The variables investigated were the ratio of longitudinal reinforcement content (Eyþór & Sigurður, 2011; Hamrat, et al., 2010),thewidth of the beam (Kani, 1966), the compressive strength of concrete (Hamrat, et al., 2010), shear span to depth ratio (Hamrat, et al., 2010), type of aggregate (Janaka Perera & Mutsuyoshi, 2013), and maximum size of coarse aggregate (Weijian, et al., 2017; Derek, R. D., 2015). It was found that steel ratio has a significant influence on the shear capacity of RC beams(Hossain, 1984; Habibullah, 1967), the diagonal shear capacity of concrete is increased with the increase of steel ratio; the shear strength is decreased with the increase of shear span to depth ratio; the shear strength is increased with the increase of compressive strength of concrete; the shear strength has no effect on changing the width of the beam (Kani, 1966). By careful observation of the types of aggregate investigated, it is found that most of the investigations were conducted on RC beams made with stone aggregate. A limited number of investigations can be found on shear capacity of RC beams made with BA(Akhtaruzzaman & Hasnat, 1986; Hossain, 1984). Therefore, this study has been planned to evaluate the diagonal shear capacity of RC beams made with BA to validate the provisions of shear capacity of RC beams of existing design codes. For investigation, 16 RC beam specimens of 200 mm by 300 mm by 2100 mm and 200 mm by 300 mm by 2400 mm were made with the variation of compressive strength of concrete, amount of longitudinal steel, and shear span to depth ratio.

Diagonal shear capacity of the beams was evaluated by four-point loading and compared with different codes, such asACI, AASHTO, CSA, BS, JSCE, Model Code 2010, and Euro code. Also, the results were compared with corresponding results obtained from equations formulated based on the fracture mechanics approach by Bazant (2005), Gastebled (2001), Xu (2012), Zsutty (1968)and Niwa (1986). Furthermore, the results were compared with the existing shear database to understand the position of the data points with respect to the database formulated based on the results obtained by many researchers.

Table 2
Mixture proportions with cases investigated

Notation	Com. strength of concrete (MPa)	Unit Content (kg/m^3)				Amount of steel %	Shear span to depth ratio (a_s/d)
		Cement	Sand	BA	Water		
B1-0.82-24-2.04*	23.68	360	670	809	180	0.82	2.04
B2-0.82-24-2.04	23.68	360	670	809	180	0.82	2.04
B3-0.82-24-2.45	23.68	360	670	809	180	0.82	2.45
B4-0.82-24-2.45	23.68	360	670	809	180	0.82	2.45
B5-0.82-29-2.04	28.71	390	645	779	195	0.82	2.04
B6-0.82-29-2.04	28.71	390	645	779	195	0.82	2.04
B7-0.82-29-2.45	28.71	390	645	779	195	0.82	2.45
B8-0.82-29-2.45	28.71	390	645	779	195	0.82	2.45
B9-1.23-24-2.04	23.68	360	670	809	180	1.23	2.04
B10-1.23-24-2.04	23.68	360	670	809	180	1.23	2.04
B11-1.23-24-2.45	23.68	360	670	809	180	1.23	2.45
B12-1.23-24-2.45	23.68	360	670	809	180	1.23	2.45
B13-1.23-29-2.04	28.71	390	645	779	195	1.23	2.04
B14-1.23-29-2.04	28.71	390	645	779	195	1.23	2.04
B15-1.23-29-2.45	28.71	390	645	779	195	1.23	2.45
B16-1.23-29-2.45	28.71	390	645	779	195	1.23	2.45

**B1 indicates a serial number of the specimen made with brick aggregate, 0.82 indicates steel ratio, 24 indicates compressive strength of concrete in MPa, 2.04 indicates shear span to depth ratio.*

2. Research significance

BA is commonly used in Bangladesh due to the lack of availability of stone aggregate. The existing design codes which are developed based on the research results on stone aggregate are generally used for strength evaluation as well as the design of RC members made with BA. Earlier, Mohammed et al. 2017 conducted a study for validation of code provisions for the flexural capacity of RC beams made with BA. Studies are still necessary for validation of shear design provisions of the existing codes for RC beams made with BA. It is also necessary to compare the experimental results of the shear capacity of RC beams made with BA with the estimated shear capacity obtained from equations formulated based on fracture mechanics approaches. Moreover, it is also necessary to compare the diagonal shear capacity of the RC beams made with BA with the existing results of the shear database with the variation of shear-span-to-depth ratio, steel ratio, and compressive strength of concrete. With this background, a detailed experimental study was conducted with RC concrete beams made with BA and recycled brick aggregate (RBA). The results related to the RBA were summarized separately (Mohammed, et al., 2019). In this report, the results related to the BA are summarized.

3. Experimental methods

3.1 Material properties

BA was collected from a local market. The grading of the aggregate was controlled as per ASTM C33. Natural sand was used as fine aggregate. Aggregates were tested for specific gravity, absorption capacity, fineness modulus (FM) and unit weight. The properties of coarse and fine aggregates are summarized in Table 1. The absorption capacity of the BA was 10.5%. During mixing concrete, saturated surface dry (SSD) aggregates were used to avoid absorption of water from mixing water by the BA. The grading of the aggregates satisfies the requirement of ASTM C33 as shown in Figure 1. CEM Type II B-M cement (as per BDS EN 197 – 01: 2003) containing 65-79% clinker and 35-21% mineral admixture including gypsum was used. Tap water was used as mixing water.

3.2 Mixture proportions

To investigate the shear strength of RC beams, a total of 16 (8 cases × 2 specimens/case) RC beams were made. The investigated cases with mixture proportions of concrete are summarized in Table 2. Fresh and hardened properties of concrete investigated in this study are summarized in Table 3.W/C ratio was kept constant at 0.50 for all cases. Air content in fresh concrete was 2%. Cement contents were 360 and 390 kg/m^3 of concrete; target strengths of concrete were 24 and 29 MPa; longitudinal steel ratios were 0.82% and 1.23%, and shear span to depth ratios were 2.04 and 2.45.The target strengths were set based on the commonly used design strengths of RC structures made with BA in Bangladesh.

Shear span to depth ratio was fixed keeping in mind the available space under Universal Testing Machine (UTM) at the laboratory as well as the data of other researchers. As the main longitudinal reinforcement, 16 mm bar was used. As lateral reinforcement at the middle third zone of the beam, 10 mm bar was used as shear reinforcement to prevent premature failure of the specimen. The yield strength of 10 mm bar was 463MPa, and for 16 mm bars was 494MPa. Mechanical properties of reinforcing steel are summarized in Table 4.

Table 3
Fresh and hardened properties of concrete

Item	Target Strength of Concrete	
	24 MPa	29 MPa
Slump (mm)	381	317.5
Air Content (%)	1.9	2.2
*Compressive Strength (MPa)	23.68	28.71
*Split Tensile Strength (MPa)	2.5	3.2

**Values represent the average of three cylinders*

Table 4
Mechanical properties of reinforcing steel

Sl. No.	Sample Diameter (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
1	16	494	688	15.6
2	10	463	649	10.1

Beam specimens of size 200 mm by 300 by 2100 mm and 200 mm by 300 mm by 2400 mm were made. Details of reinforcement are shown in Figure 2. As shown in Figure 2, shear reinforcements were not provided in the shear span of the beams to confirm shear failure during loading. A strain gauge was fastened on the tension steel at the middle of the shear span. The beams were cast by using steel molds. After mixing of concrete, slump and air content were measured. Also, concrete cylinders (100 mm by 200 mm) were made for evaluation of compressive strength, tensile strength, and modulus of elasticity of concrete. The RC beams and cylinder specimens were cured under wet jute cloths covered with a polythene sheet.

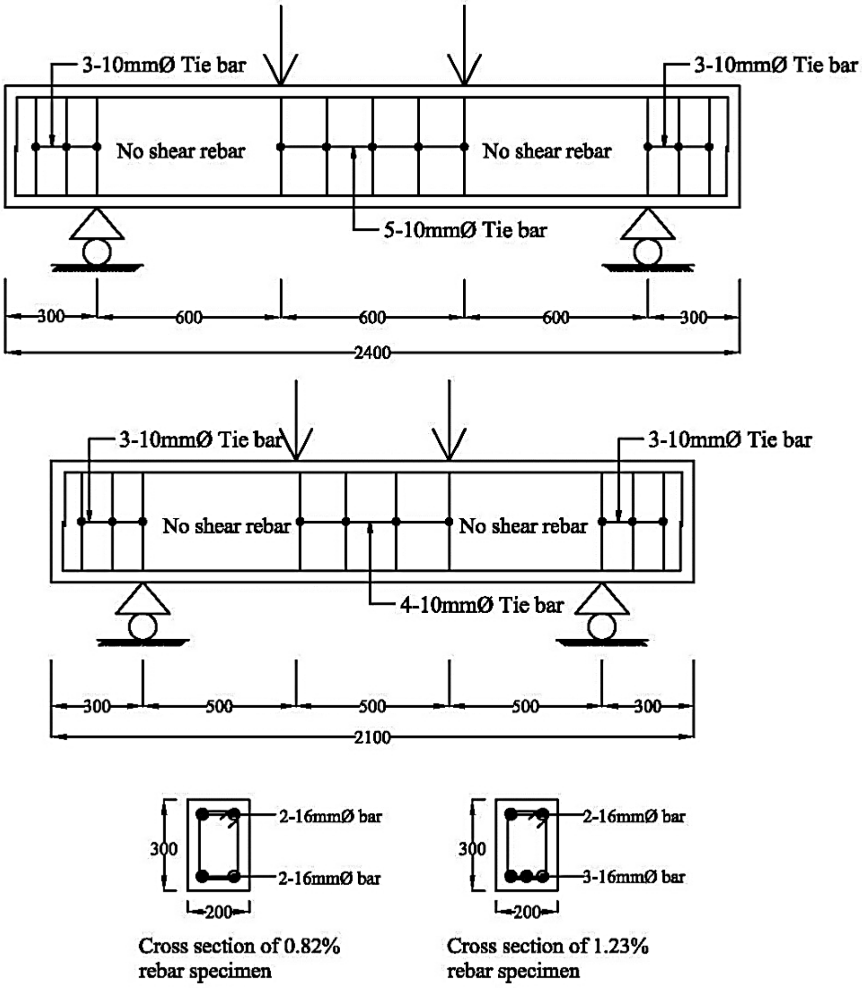


Fig. 2. Details of Reinforcement and Loading of RC Beams.

3.3 Test setup for RC beams

The beams were tested under four-point loading as shown in Figure 3 to determine shear capacity without shear reinforcement. Three linear variable displacement transducer (LVDT) sensors were used to record the displacements at the mid-span of the beam and middle points of shear spans. The load was applied by controlling displacement with a rate of 0.15 mm/min until the failure of the beam. The load cell, LVDT sensors and strain gauge were connected with a data logger for continuous recording of data at 1 second interval. A dial gauge was installed at the mid-span of the beam to measure deflection manually and compare with the results obtained from LVDT sensor installed at the same section. During the application of load, initiation of shear crack was carefully observed and the corresponding load was recorded. Propagation of cracks under load was also marked continuously on the beam. Failure pattern of the beam was also recorded.

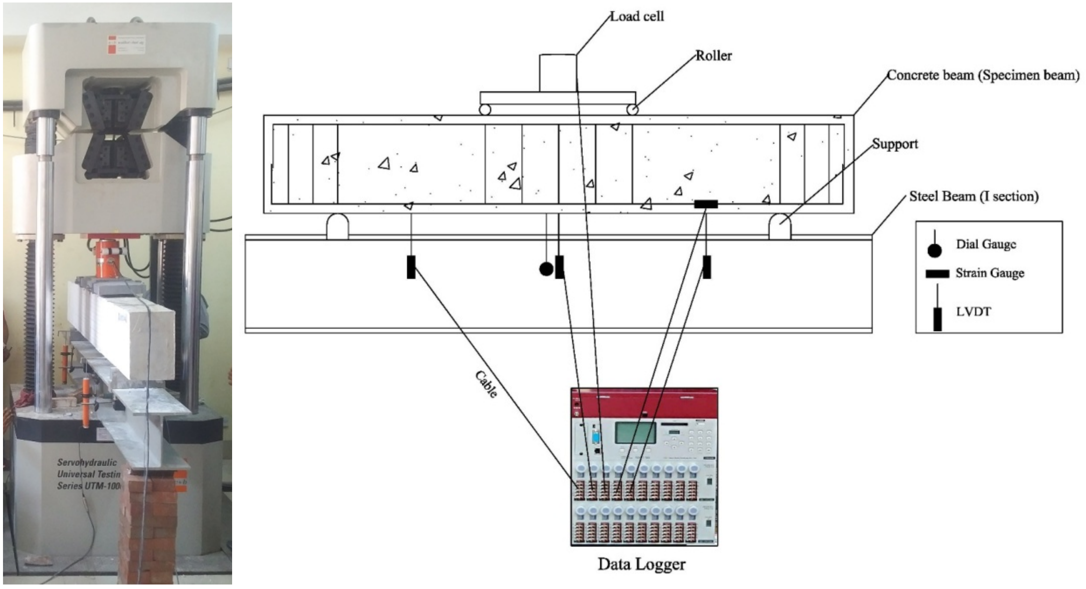


Fig. 3. Test Setup of Beams (Left – Loading in UTM Machine, Right – Connections to Data Logger).

4. Results and discussions

4.1 Load-displacement behavior

Load-displacement curves at the mid-span of RC beams made with different steel ratio and shear span to depth ratio are shown in Figure 4. From Figure 4(a) and Figure 4(b), it is observed that with the increase of steel ratio, deflection is reduced. Also, relatively less deflection is observed for cases with higher compressive strength. From Figure 4(c), it is found that with the increase of shear-span to depth ratio, the mid-span deflection is increased. These characteristics resemble other investigation (Mahdi, et al., 2014).

4.2 Strains over longitudinal reinforcement

The variations of strain over the steel bars (at the middle of shear span) for different cases are shown in Figure 5. From these curves, it is found that after the formation of a diagonal shear crack, the slope of the curve becomes flatter. It is also observed that diagonal cracking load is increased with the increase of steel ratio, the compressive strength of concrete, but significantly reduced with the increase of shear-span-to-depth ratio. Similar trends of results were also observed for deflection at the middle of shear span of RC beams.

Similar results were also observed by other researchers based on the investigation on diagonal shear cracking of RC beams made with stone aggregate (Mahdi et al., 2014)as well as the recycled brick aggregate (Mohammed et al. 2019).

4.3 Shear capacity of RC beams made with BA

The variation of shear capacities of RC beams with respect to the variation of steel ratio (0.82 and 1.23), target compressive strength of concrete (24 and 29 MPa), and shear span to depth ratio (2.04 and 2.45) are shown in Figure 6. With the increase of steel ratio, diagonal shear crack formation load is increased.

It can be explained due to the dowel action of the longitudinal steel bars. With the increase of shear span to depth ratio, the cracking load is reduced. Also, with the increase of compressive strength of concrete, the cracking load is increased. These results are matched with other researchers (Mohammed et al. 2019;Wight and MacGregor 2009; Fathifaz 2008).

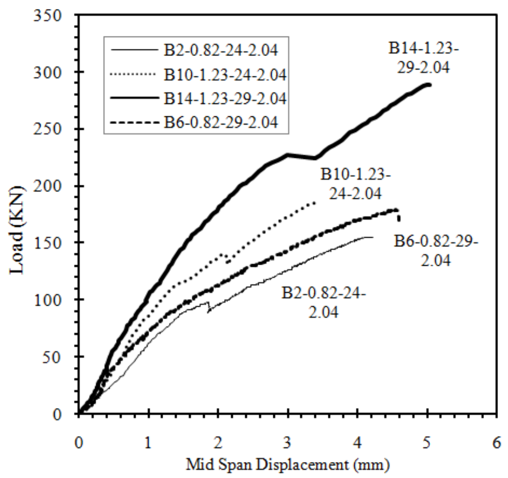


Fig. 4(a). Load-Displacement Curves of RC Beams – Shear-Span-to-Depth Ratio = 2.04

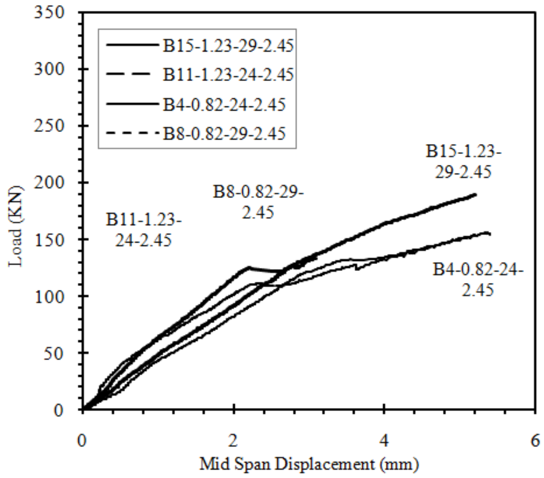


Fig. 4(b). Load-Displacement Curves of RC Beams – Shear-Span-to-Depth Ratio = 2.45

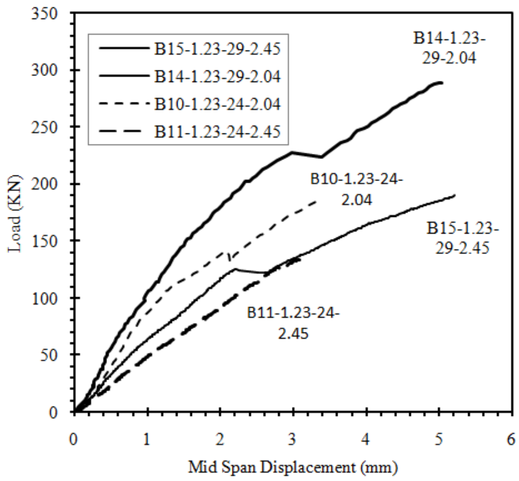


Fig. 4(c). Load-Displacement Curves of RC Beams – Steel Ratio = 1.23%

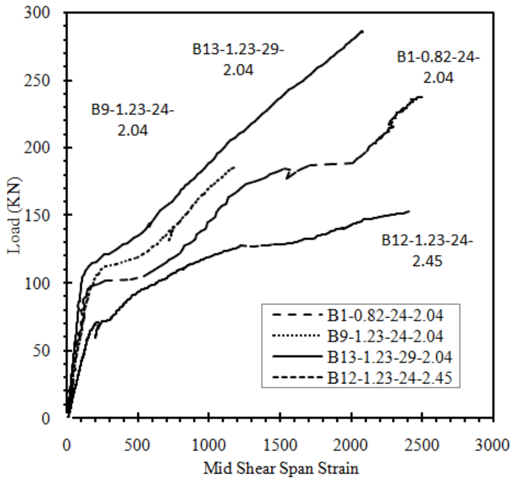


Fig. 5. Variation of strain over steel.

4.4 Prediction of shear capacity

Shear capacity of RC beams was calculated by using different codes and equations proposed by different researchers. The following empirical equations of different codes, such as ACI,AASHTO, CSA, BS, JSCE, Model Code 2010and Euro Code were used for evaluation of the shear capacity of RC beams without shear reinforcement:

4.4.1 ACI 318M-14

$$V_C = 0.17\sqrt{f'_c}\, b_w d \quad (1)$$

where f'_c is compressive strength of concrete in *MPa*, *d* effective depth in *mm* and b_w the width of the member in *mm*, V_c shear capacity of concrete in *KN*.
In complex form,

$$V_C = \left(1.9\sqrt{f'_c} + 2500\rho\frac{Vd}{M}\right) \leq 3.5\sqrt{f'_c} \quad (2)$$

where $\frac{Vd}{M} \leq 1$, f'_c is compressive strength of concrete in *psi*, ρ is longitudinal reinforcement ratio in percentage, *d* is effective depth in *inch*, *V* is total shear force in *kip*, *M* is bending moment *k-in*, and V_c is shear capacity of concrete in *psi*.

4.4.2 AASHTO LRFD 2017

$$V_C = 0.0316\beta\sqrt{f'_c}b_v d_v \tag{3}$$

where β is the factor indicating the ability of diagonal cracked concrete to transmit tension, b_v is effective width of the web taken as the minimum web width within the depth in *inch*, d_v is effective shear depth taken as the larger value of *0.9d* or *0.72h* in *inch*, f'_c is concrete compressive strength in *ksi*, and V_c shear capacity of concrete in *kip*.

4.4.3 CSA Code

$$V_{cr} = \frac{245}{1275+S_e}\sqrt{f_c'} \tag{4}$$

$$S_e = \frac{35S_x}{d_{agg}+16} \tag{5}$$

where $S_x=0.9d$, f'_c is compressive strength in *MPa*, d_{agg} is maximum aggregate size of concrete in *mm*, *d* is effective depth in *mm*.

4.4.4 BS code

$$v_{cr} = \frac{790}{\gamma_m}(100\rho)^{\frac{1}{3}}\left(\frac{0.4}{d}\right)^{\frac{1}{4}}\left(\frac{f_c'}{25}\right)^{\frac{1}{3}} \tag{6}$$

where f'_c is compressive strength in *MPa* ($f'_c<40MPa$), *d* is the effective depth in *m*, γ_w is a safety factor (=1.25), $100\,\rho < 3$ and ρ is the longitudinal reinforcement ratio in percentage and v_{cr} is critical shear strength in *KN*.

4.4.5 JSCE Code

$$V_c = 0.2 \times f'_c{}^{\frac{1}{3}} \times \rho^{\frac{1}{3}} \times \left(\frac{1000}{d}\right)^{\frac{1}{4}} \times bd \tag{7}$$

where f'_c is the compressive strength of concrete in *MPa*, ρ is the longitudinal reinforcement ratio, *b* is the width of the beam in *mm*, *d* is the effective depth in *mm*, and V_c is the shear strength in *KN*.

4.4.6 Model Code 2010

$$V_{Rd,c} = K_v \frac{\sqrt{f_{ck}}}{\gamma_c} b_w z \tag{8}$$

where $V_{Rd,c}$ is shear resistance in *N*, f_{ck} is the characteristic value of compressive strength of concrete in *MPa*, b_w is the width of the web in *mm*, *z* is the effective shear depth in *mm*, the partial safety factor γ_c=1. The parameter of the Model Code, K_V is defined by the following equation for Level I approximation:

$$K_v = \frac{180}{1000+1.250z} \tag{9}$$

4.4.7 Euro Code 2

The shear resistance of non-prestressed concrete member without shear reinforcement:

$$V_{Rk.c} = c_{Rk.c} \times k \times (100 \times \rho_l \times f_{ck})^{1/3} \times b_w \times d \tag{10}$$

$$k = 1 + \sqrt{200/d} \leq 2.0 \tag{11}$$

$$\rho_l = \frac{A_{st}}{b_w d} \leq 0.02 \tag{12}$$

where $V_{Rk.c}$ is the shear capacity in *N*. A_{st} is the area of the tensile reinforcement in mm^2, d is the effective depth in *mm*, b_w is the smallest width of the cross-section in the tensile area in *mm*. f_{ck} is the compressive strength of concrete in *MPa*, and $C_{Rk.c} = 0.18$.

Comparison of shear capacity obtained from the experiment (V_{test}) and the provisions of codes (V_{code}) is summarized in Table 5. It is found that ACI, AASHTO, CSA, BS, Model Code 2010, JSCE, and Euro codes estimate the shear capacity of RC beams made with BA conservatively including extended formula of ACI.

The ratio of V_{test} to V_{code} is greater than 1.0 irrespective of the design codes. It is understood that the provisions of these codes can be safely used to predict the shear capacity of RC beams made with BA.

Table 5
V_{test}/V_{code} for different codes

Specimen	V_{test}/V_{code}							
	ACI	AASHTO	CSA Code	BS	Model Code	JSCE	EURO CODE	ACI – Complex
B1-0.82-24-2.04	1.35	1.35	1.36	1.57	1.58	1.44	1.22	1.32
B2-0.82-24-2.04	1.33	1.33	1.27	1.54	1.56	1.42	1.20	1.30
B3-0.82-24-2.45	1.29	1.29	1.23	1.49	1.51	1.38	1.16	1.28
B4-0.82-24-2.45	1.30	1.30	1.24	1.51	1.52	1.39	1.17	1.29
B5-0.82-29-2.04	1.25	1.25	1.19	1.49	1.46	1.38	1.16	1.23
B6-0.82-29-2.04	1.23	1.23	1.17	1.47	1.44	1.36	1.15	1.21
B7-0.82-29-2.45	1.23	1.24	1.18	1.48	1.45	1.36	1.15	1.23
B8-0.82-29-2.45	1.22	1.22	1.16	1.46	1.43	1.35	1.14	1.22
B9-1.23-24-2.04	1.51	1.51	1.44	1.53	1.77	1.41	1.19	1.43
B10-1.23-24-2.04	1.54	1.54	1.47	1.57	1.81	1.45	1.22	1.47
B11-1.23-24-2.45	1.40	1.40	1.33	1.42	1.64	1.31	1.10	1.35
B12-1.23-24-2.45	1.45	1.45	1.38	1.48	1.70	1.36	1.15	1.40
B13-1.23-29-2.04	1.42	1.42	1.35	1.49	1.66	1.37	1.16	1.36
B14-1.23-29-2.04	1.38	1.39	1.32	1.46	1.62	1.34	1.13	1.33
B15-1.23-29-2.45	1.45	1.45	1.38	1.52	1.69	1.40	1.18	1.41
B16-1.23-29-2.45	1.38	1.38	1.32	1.45	1.62	1.33	1.12	1.34
Ave.	1.36	1.36	1.30	1.50	1.59	1.38	1.16	1.32
COV (%)	7.44	7.44	7.52	2.81	7.44	2.81	2.83	5.93

V_{test} includes part of the load frame, weight of load cell, and support portion of the beam (5 KN) which were not recorded by the load cells.

Shear capacity of the RC beams was also calculated using the following equations formulated based on the fracture mechanics approach:

4.4.8 Bazant and Yu

$$V_c = 10\rho^{\frac{3}{8}}\left(1 + \frac{d}{a_s}\right)\sqrt{\frac{f'_c}{1+\frac{d}{f'_c{}^{-\frac{2}{3}}3800\sqrt{d_a}}}}\,b_w d \qquad (13)$$

where ρ is the longitudinal reinforcement ratio in percentage, d is the effective depth in *inch*, a_s is the shear span in *inch*, f'_c is the compressive strength of concrete *psi*, d_a is the maximum aggregate size in *inch*, b_w width of the beam in *inch*, and V_c shear strength of beam in *pound*.

4.4.9 Gastebled and May

$$V_c = \frac{1.018}{\sqrt{d}}\left(\frac{d}{a_s}\right)^{\frac{1}{3}} \rho^{\frac{1}{6}}\left(1-\sqrt{\rho}\right) {f'_c}^{0.35}\sqrt{E_s}\, b_w d \tag{14}$$

where d is the effective depth in *mm*, a_s is the shear span in *mm*, ρ is the longitudinal reinforcement ratio in *percentage*, f'_c is the compressive strength of concrete in *MPa*, b_w is the width of beam in *mm*, E_s is the modulus of elasticity *GPa* and V_c is the shear strength of concrete in *N*.

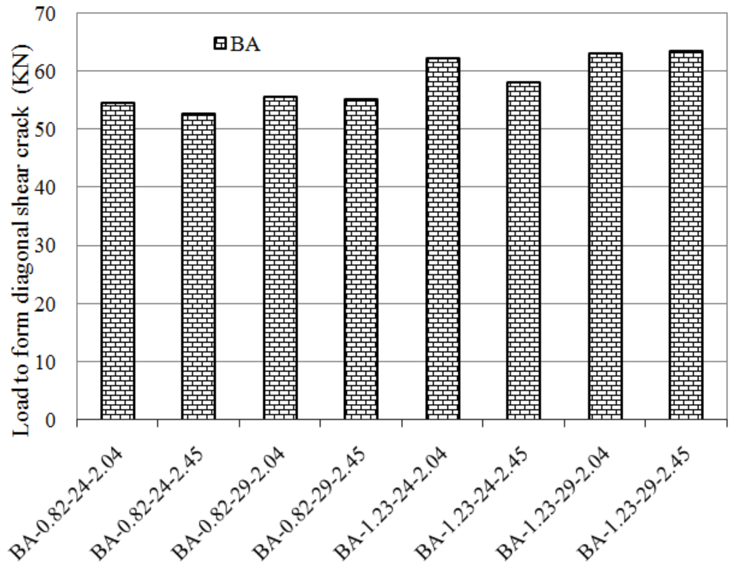


Fig. 6. Diagonal shear cracking load for BA.

Table 6
$V_{test}/V_{Fracture\ Mechanics}$ for different equations developed from fracture mechanics approaches

Specimen	$V_{test}/V_{Fracture\ Mechanics}$				
	Bazant et al.	Gastebled et al.	Xu et al.	Zsutty	Niwa et al.
B1-0.82-24-2.04	1.43	1.23	0.99	1.09	1.14
B2-0.82-24-2.04	1.41	1.21	0.98	1.07	1.13
B3-0.82-24-2.45	1.45	1.24	1.00	1.10	1.09
B4-0.82-24-2.45	1.46	1.26	1.01	1.12	1.10
B5-0.82-29-2.04	1.36	1.17	0.93	1.04	1.09
B6-0.82-29-2.04	1.34	1.15	0.92	1.03	1.08
B7-0.82-29-2.45	1.43	1.23	0.98	1.10	1.08
B8-0.82-29-2.45	1.41	1.21	0.97	1.08	1.07
B9-1.23-24-2.04	1.38	1.31	1.05	1.07	1.28
B10-1.23-24-2.04	1.41	1.34	1.08	1.09	1.31
B11-1.23-24-2.45	1.35	1.29	1.03	1.05	1.18
B12-1.23-24-2.45	1.41	1.34	1.08	1.09	1.23
B13-1.23-29-2.04	1.33	1.27	1.01	1.04	1.24
B14-1.23-29-2.04	1.30	1.24	0.99	1.01	1.21
B15-1.23-29-2.45	1.44	1.38	1.09	1.12	1.27
B16-1.23-29-2.45	1.37	1.31	1.04	1.07	1.21
Ave.	1.39	1.26	1.01	1.07	1.17
COV (%)	3.25	5.10	4.94	3.01	6.97

4.4.10 Xu et al.

$$V_c = \frac{1.018}{\sqrt{d}}\left(\frac{d}{a_s}\right)^{\frac{1}{3}} \rho^{\frac{1}{6}}(1-\sqrt{\rho})^{\frac{2}{3}}(0.0255f'_c + 1.024)\, b_w d \qquad (15)$$

where, *d* is the effective width in *m*, a_s is the span in *m*, ρ is the longitudinal reinforcement ratio in *percentage*, f'_c is the compressive strength of concrete in *MPa*, b_w is the width of the beam in *mm* and V_c is the shear strength of concrete in *KN*.

Table 7
Calculated strain (MCFT method) and experimental strain over steel

Beam Notation	*Strain Calculated, ε_s	*Strain Observed, ε_s	Strain Calc./Obs.
B1-0.82-24-2.04	1417	580	2.44
B2-0.82-24-2.04	1397	610	2.29
B3-0.82-24-2.45	1494	920	1.62
B4-0.82-24-2.45	1509	1383	1.09
B5-0.82-29-2.04	1443	770	1.87
B6-0.82-29-2.04	1423	730	1.95
B7-0.82-29-2.45	1582	1374	1.15
B8-0.82-29-2.45	1560	1086	1.44
B9-1.23-24-2.04	1060	490	2.16
B10-1.23-24-2.04	1086	703	1.55
B11-1.23-24-2.45	1084	721	1.50
B12-1.23-24-2.45	1128	663	1.70
B13-1.23-29-2.04	1100	415	2.65
B14-1.23-29-2.04	1073	436	2.46
B15-1.23-29-2.45	1241	921	1.35
B16-1.23-29-2.45	1182	1053	1.12
	Avg.=		1.77

**Micro strain*

4.4.11 Zsutty

$$V_c = 2210\left(f'_c \rho \frac{d}{a_s}\right)^{\frac{1}{3}} b_w d \qquad (16)$$

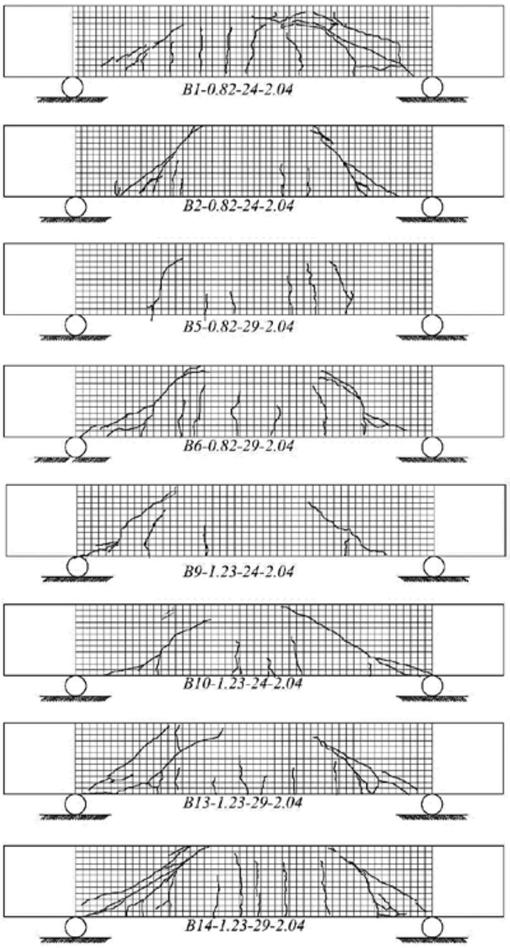
where f'_c is the compressive strength of concrete in *MPa*, *d* is the effective width in *mm*, b_w is the width of the beam in *mm* and V_c is the shear strength of concrete in *KN*.

4.4.12 Niwa et al.

$$V_c = 0.2 \times {f'_c}^{\frac{1}{3}} \times (100\rho)^{\frac{1}{3}} \times \left(\frac{1000}{d}\right)^{\frac{1}{4}} \times \left(0.75 + 1.4\frac{a}{d}\right) \qquad (17)$$

where *d* is the effective depth in *mm*, f'_c is the compressive strength of concrete in *MPa*, ρ is the longitudinal reinforcement ratio, *a* is the shear span in mm, *b* is the width of the beam in mm and V_c is the shear strength in *MPa*.

Table 6 Summarizes the shear capacity of RC beams obtained from fracture mechanics theories as explained above. Comparing the test results with calculated results it is found that equations proposed by Bazant and Gastebled conservatively estimate the shear capacity of the beams. However, equations proposed by Xu(2012), Zsutty(1968) and Niwaet al.(1986) marginally estimate the shear capacity of RC beams made with BA.



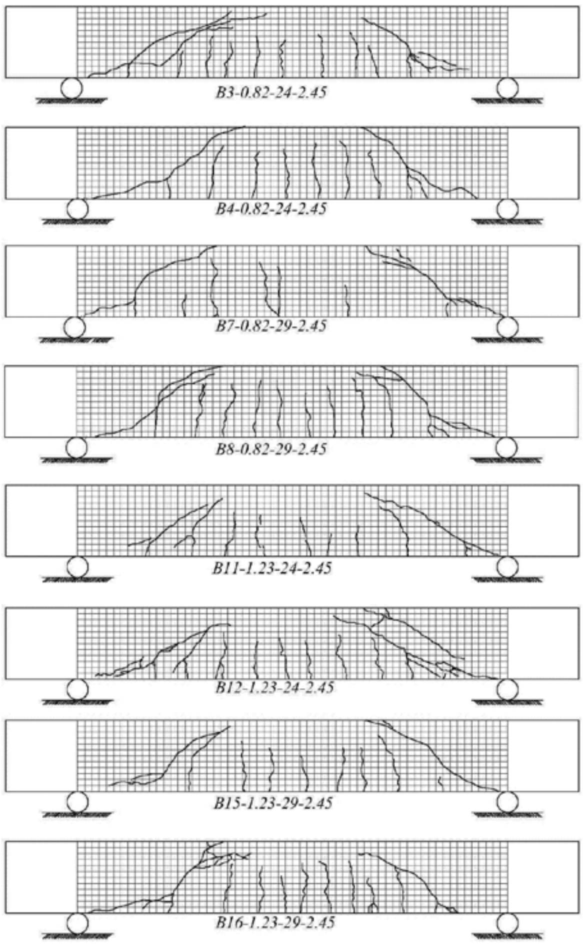


Fig. 7(a). Failure Patterns of Beams (shear-span-to-depth ratio = 2.04)

Fig. 7(b). Failure Patterns of Beams (shear-span-to-depth ratio = 2.45)

4.5 Strains over longitudinal reinforcement–observed strain and calculated strain by MCFT method

Strain over the longitudinal reinforcement was calculated by using the modified compression field theory (MCFT) method which was adopted in AASHTO LRFD-17. As per this guideline, the following equation can be used to calculate strain over the steel:

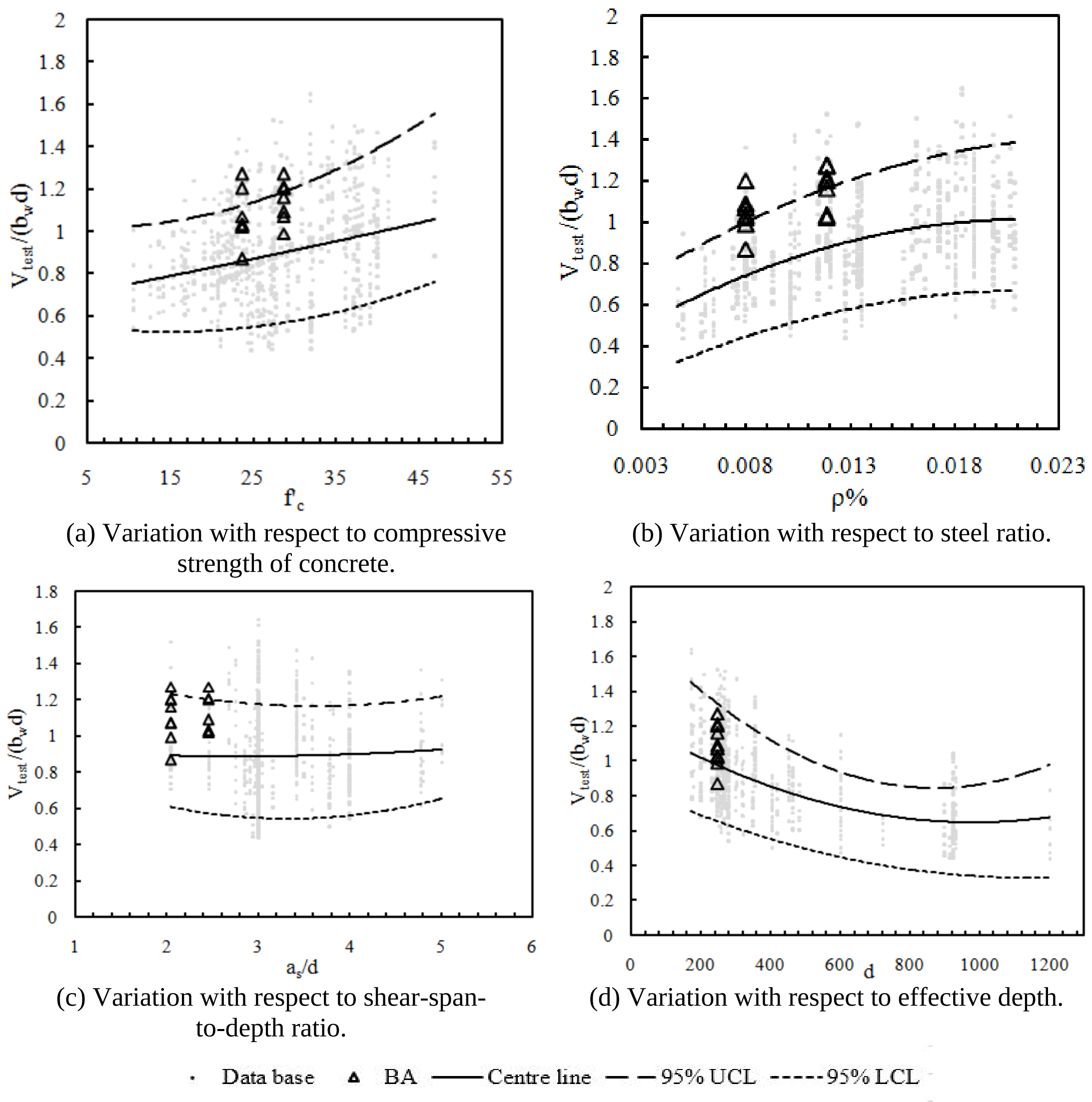
$$\varepsilon_s = \frac{\left(\frac{|M_u|}{d_v} + |V_u|\right)}{E_s A_s} \tag{18}$$

where ε_x is the strain in non-prestressed longitudinal tension reinforcement. M_u is moment at section in *kip-inch*; d_v is effective shear depth in *inch*, V_u is shear force at section in *kip*, E_s is modulus of elasticity of reinforcing bars in *ksi*, and A_s is the area of non-prestressed tension reinforcement in *square inch*.

The experimental (obtained from strain gauges fastened over longitudinal steel at the middle of shear span) and calculated results are summarized in Table 7. From this table, it is found that AASHTO LRFD-17 equation overestimates strain over the longitudinal reinforcement of RC beams made with BA.

4.6 Crack pattern

The crack maps of the RC beam are shown in Figure 7. As the load is increased, the flexural cracks appear at the middle of the beam. These flexural cracks propagate vertically and it remains below the neutral axis. With further increase of load, diagonal shear cracks are formed. Upon further increase of load, the diagonal cracks propagate to the compression face of the beam and finally causes to failure as typical shear failure. Typical shear failure of the RC beams was observed irrespective of steel ratio, shear span to depth ratio, and variation of compressive strength of concrete. Relatively more flexural cracks were observed for the beams made with more steel ratio. Similar crack and failure patterns for RC beams made with recycled brick aggregate were also reported by Mohammed et al. 2019.



(a) Variation with respect to compressive strength of concrete.

(b) Variation with respect to steel ratio.

(c) Variation with respect to shear-span-to-depth ratio.

(d) Variation with respect to effective depth.

Fig. 8. Comparison of test results with shear database.

4.7 Comparison of test results with shear database

Shear database (Shilang et al.2012) of RC beam is an important resource for comparison of the experimental results. The comparison of the test results obtained from this study was compared with data obtained from the shear database. The results are shown in Figure 8with the variation of compressive strength of concrete (Figure 8(a)), steel ratio (Figure 8(b)), shear span to depth ratio (Figure 8(c)), and effective depth (Figure 8(d)). The data points obtained from the shear database are shown in blurred color. However, the 95% of upper confidence line (UCL), average line, and 95% of lower confidence line (LCL) of the shear database are shown clearly for comparison with the experimental results. It is found that the experimental results obtained from this study are located above the average line of the shear database. Some experimental data also fall above the 95% UCL of the shear database. Therefore, it is understood that the shear capacity of the RC beam made with BA is conservatively matched with the shear database. Similar results for RC beams made with recycled brick aggregate was also reported by Mohammed et al. 2019.

5. Conclusions

Based on the results of this study conducted on the shear behavior of RC beam made with BA, the following conclusions are drawn:

- Code provisions of ACI, AASHTO, CSA, BS, JSCE, Model Code 2010 and Euro code can be conservatively used for calculating the shear capacity of RC beam made with BA.
- Equations derived from fracture mechanics approach as mentioned in this study can be conservatively used for calculating the shear capacity of the RC beam made with BA.
- Irrespective of the shear-span to depth ratio, the compressive strength of concrete, effective depth, and longitudinal tensile steel ratio experimental results of this study fall above the average line of the shear database.
- The diagonal shear capacity of RC beams is reduced with the increase of shear span to depth ratio and increased with the increase of compressive strength of concrete as well as tensile steel ratio.
- Mid-shear span deflection of the beams is reduced with the increase of steel ratio and compressive strength of concrete; however, it is increased with the increase of shear span to depth ratio. The same trend of results is also observed for the strain over the steel.

References

AASHTO, 2017. AASHTO LRFD Bridge Design Specifications. 8th ed. Washington, D.C.: American Association of State and Highway Transportation Officials.

ACI 318-14, 2014. Building Code Requirements for Structural Concrete. Farmington Hills: American Concrete Institute.

Akhtaruzzaman, A. & Hasnat, A., 1983. Properties of concrete using crushed brick as aggregate. ACI Concrete International, Design and Construction, 5(2), pp. 58-63.

Akhtaruzzaman, A. & Hasnat, A., 1986. Shear and Flexural Behavior of Brick Aggregate Concrete Beams without Web Reinforcement. ACI Materials Journal, 83(2), pp. 284-289.

ASTM C33 / C33M-16, 2016. Standard Specification for Concrete Aggregates. West Conshohocken: ASTM International.

Bazant, Z. & Yu, Q., 2005. Design against size effect on the shear strength of reinforced concrete beams without stirrups. Journal of Structural Engineering, ASCE, 131(12), pp. 1877-85.

BDS EN 197 – 01, 2003. Bangladesh Standard. Dhaka, Bangladesh: Bangladesh Standards and Testing Institution.

BNB, 2006. Bangladesh National Building Code. Dhaka, Bangladesh: Housing and building research Institute.

BS 8110, 1997. Code of Practice for Design and Construction. 2nd ed. London, UK: British Standards Institution.

CSA CAN3-A23.3, 2004. Design of concrete standards for buildings. Rexdale, Ontario: Canadian Standards Association.

Derek, R. D., 2015. The effect of maximum aggregate size on the shear strength of geometrically scaled reinforced concrete beams, West Lafayette, Indiana: Department of Civil Engineering Purdue University.

EN 1992-1-1: Eurocode 2, 2004. Design of concrete structures - Part 1-1: General rules and rules for buildings. Brussel: European Committee for Standardization.

Eyþór, R. P. & Sigurður, R. B., 2011. Shear resistance of reinforced concrete beams without stirrups. Reykjavík, Iceland: Reykjavik University.

Fathifaz, G., 2008. Structural Performance of Steel Reinforced Recycled Concrete Members, Carleton University, Ottawa, Ontario, Canada: Department of Civil and Environmental Engineering.

Gastebled, O. & May, I., 2001. Fracture mechanics model applied to shear failure of reinforced concrete beams without stirrups. ACI Structural Journal, 98(2), pp. 184-90.

Habibullah, G., 1967. Shear Strength of Brick Aggregate Concrete Beams without Web Reinforcement, Dhaka, Bangladesh: Bangladesh University of Engineering & Technology (BUET).

Hamrat, M., Boulekbache, B., Chemrouk, M. & Amziane, S., 2010. Shear Behaviour of RC Beams without Stirrups Made of Normal Strength and High Strength Concretes. Advances in Structural Engineering, 13(1), pp. 29-41.

Hossain, M., 1984. Investigation of shear capacity of brick aggregate concrete beams without web reinforcement, Dhaka, Bangladesh: Bangladesh University of Engineering & Technology.

Janaka Perera, S. & Mutsuyoshi, H., 2013. Prediction of shear strength of high- strength concrete members without web reinforcement. Concrete Engineering , 35(2).

JSCE, 2007. Standard specification for the concrete structure. Tokyo: Japanese Society of Civil Engineering.

Kani, G., 1966. How safe is our large reinforced concrete beams. ACI Journal, 64(3), pp. 128-41.

Khaloo, A., 1994. Properties of concrete using crushed clinker brick as coarse aggregate. ACI Materials Journal, 91(2), pp. 401-407.

Mahdi, A., Adam, S., Jeffery, S. V. & Kamal, H. K., 2014. An experimental study on shear strength of reinforced concrete beams with 100% recycled concrete aggregate. Construction and Building Materials, Volume 53, pp. 612-20.

Model Code 2010, 2012. Fédération Internationale du Béton (FIB). Lausanne, Switzerland: The Ernst & Sohn publishing house.

Mohammed, T. U., Ariful, H., Awal, M. A. & Shamim, Z. B., 2014. Recycling of Brick Aggregate Concrete as Coarse Aggregate. American Society of Civil Engineers, 27(7).

Mohammed, T. U., Hare, K. D., Aziz, H. M. & Awal, M. A., 2017. Flexural Performance of RC Beams Made with Recycled Brick Aggregate. Construction and Building Materials, Volume 134, pp. 67-74.

Mohammed, T. U., Shikdar, K. H. & Awal, M. A., 2019. Shear strength of RC beam made with recycled brick aggregate. Engineering Structure, Volume 189, pp. 497-508.

Niwa, J., Yamada, K., Yokozawa, K. & Okamura, H., 1986. Revaluation of the equation for shear strength of reinforced concrete beams without web reinforcement. Journal of Materials, Concrete Structures and Pavements, Volume 5, pp. 167-176.

Shilang, X. & Hans, W. R., 2005. Shear fracture on the basis of fracture mechanics. Otto-Graf-Journal, Volume 16.

Shilang, X., Xiufang, Z. & Hans, W. R., 2012. Shear Capacity Prediction of Reinforced Concrete Beams without Stirrups Using Fracture Mechanics Approach. ACI Structural Journal, 109(5), pp. 705-713.

S, X., Zhang, X. & Reinhardt, H. W., 2012. Shear capacity prediction of reinforced concrete beams without stirrups using fracture mechanics approach. ACI Structural Journal, 109(5), pp. 705-14.

Weijian, Y., Deng, Q. & Tang, F., 2017. Effect of Coarse Aggregate Size on the Shear Behavior of Beams without Shear Reinforcement. ACI Structural Journal, 114(5).

Wight, J. & Mac Gregor, J., 2009. Reinforced Concrete Mechanics and Design. 5th ed. s.l.: Pearson-Prentice Hall.

Zsutty, T. C., 1968. Beam Shear Strength Prediction by Analysis of Existing Data. ACI Journal, 65(11), pp. 943-951.