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TESTS ON LOW STRENGTH CONCRETE COLUMNS UNDER AXIAL COMPRESSION AND SHEAR

R. T. Kabir[1], M. K. Hasan[2], S. M. N. Adnan[3], M. Ahmed[4], M. Maliha[5], S. Barua[6], A. J. Ema[7], M. A. Islam[8], R. Suzuki[9], K. Matsukawa[10], Y. Nakano[11], M. M. Rahman[12], A. F. M. S. Amin[13]

[1] *Graduate student, The University of Tokyo, rtkabir@iis.u-tokyo.ac.jp*
[2] *Graduate student, The University of Tokyo, shamimkh@iis.u-tokyo.ac.jp*
[3] *Graduate student, The University of Tokyo, nhdadnan@iis.u-tokyo.ac.jp*
[4] *Graduate student, Osaka University, murshalin_ahmed@arch.eng.osaka-u.ac.jp*
[5] *Graduate student, Tohoku University, maliha.maisha.t7@dc.tohoku.ac.jp*
[6] *Research Assistant, Bangladesh University of Engineering and Technology, swastika.barua.purna@gmail.com*
[7] *Research Assistant, Bangladesh University of Engineering and Technology, afsanaema175@gmail.com*
[8] *Junior Research Consultant, Housing and Building Research Institute, Bangladesh, arifulislam1402@gmail.com*
[9] *Taisei Corporation, Japan, szkruh00@pub.taisei.co.jp*
[10] *Research Associate, The University of Tokyo, mtkw@iis.u-tokyo.ac.jp*
[11] *Professor, The University of Tokyo, iisnak@iis.u-tokyo.ac.jp*
[12] *Professor, Bangladesh University of Engineering and Technology, mizanur@ce.buet.ac.bd*
[13] *Professor, Bangladesh University of Engineering and Technology, samin@ce.buet.ac.bd*

Abstract

Bangladesh has a potential risk of earthquakes as it lies in an earthquake-prone zone near the Eurasian plate boundary. Recent surveys reveal that many older RC buildings in the country have several shortcomings including low strength concrete, high axial load ratio on columns, insufficient transverse reinforcement and lack of seismic detailing. As a result, buildings do not meet the current seismic code requirements. A common feature of the RC buildings in Bangladesh is the use of brick chips as coarse aggregate in the concrete. In this study, the static cyclic lateral loading tests of 39 column specimens are performed to assess the shear strength of columns commonly found in older buildings in Bangladesh. Among these specimens, 22 are made of brick aggregate concrete and, 17 have stone aggregate concrete. The specimens have concrete compressive strengths ranging from 8.5 MPa to 40.3 MPa and transverse reinforcement ratios of 0.11% to 0.33%. Welded and 90° hooks are used in transverse reinforcements, and axial load ratios ranging from 0.08 to 0.70 are applied. Shear failure is observed in all specimens. The lower bound of shear strength of the specimens, Q_{su} is evaluated using existing guidelines, and an equation with a strength reduction factor, α_L for low strength concrete. The results show that the evaluated shear strength could better predict the lower bound of test results after the employment of the reduction factor.

Keywords: low strength concrete, brick aggregate, 90° hooks, transverse reinforcement, strength reduction factor

1. Introduction

Bangladesh is a South Asian country situated near the boundary of the Indian plate and the Eurasian plate. This country has experienced 5 severe earthquakes since 1869, each having a magnitude of 7.0 or higher on the Richter scale [1]. Bangladesh having a subduction zone in the east and north, the previously recorded events of earthquakes have arisen a probability of generating a 7.0–8.5 magnitude earthquake [2] in the future. As the urbanization is advancing in cities of Bangladesh, more and more RC buildings are being constructed. The country is undergoing rapid growth in urbanization. According to surveys, unsafe building practices are common [3], and the proper quality is not maintained in many buildings. Many buildings are found to have low strength concrete and lack of seismic detailing [4], which makes them highly vulnerable to seismic events. A large number of them have several shortcomings, including a high axial load ratio on columns and insufficient transverse reinforcement. The use of brick chips as coarse aggregate in concrete is a common feature in buildings of Bangladesh.

The performance of RC columns under high axial load and shear is an important concern for any buildings during seismic events. The behavior of RC structures is quite unclear in the low strength concrete zone. The shear strength of columns with concrete compressive strength below 13.5 MPa has not been well explored in previous research works. Moreover, existing guidelines for building construction do not address the construction and evaluation of buildings with such columns. These buildings need proper evaluation for retrofitting so that they can successfully survive seismic events.

The purpose of this study is to find a proper method to estimate the shear strength of columns that have low strength concrete and low transverse reinforcement ratio, which would fail in shear. This study provides the experimental work and test observation of 39 RC columns with low to medium strength concrete and low transverse reinforcement representing the columns of buildings mentioned in the surveys. The shear strengths of the columns are calculated using a column shear strength estimation equation from the Japan Building Disaster Prevention Association (JBDPA) standard [5]. This equation is derived from Arakawa et al. [6]. Another estimation equation proposed by Yasojima et al. [7] is also used to calculate the shear strength of the columns. The evaluated values from both equations are compared with the experimental results.

2. Experimental details

2.1 Test setup

Two different types of loading systems are used for the experiment. The loading system of the Test setup 1, as shown in Fig. 1 is established for testing specimens in Japan. The loading system of the Test setup 2 is established for testing specimens in Bangladesh, as shown in Fig. 2. It should be noted that 2 preliminary specimens designated as B15BD13(0.1) and B10BD16(0.1) are tested in a different setup under monotonic loading.

The Test setup 1 has 1 vertical hydraulic jack for applying axial load and 1 horizontal hydraulic jack for the static cyclic lateral loading. Test setup 2 has 2 vertical hydraulic jacks for applying the axial load and 1 horizontal hydraulic jack for applying the static cyclic lateral load. The top plane of the specimens is kept horizontal. The cyclic lateral load is applied through the mid-height of the specimens in both loading systems.

Specimens are loaded with the axial load ratio of 0.08 to 0.70 to their actual concrete compressive strength, F_c. The axial load ratio is defined as the ratio of the applied axial load to the product of F_c and the gross cross-section area, A_g of the column. The specimens are first loaded with initial axial loads mentioned in Table 1 and Table 2, and then the cyclic lateral load is applied. More details about the experiment conducted in Test setup 1, can be found in reference [8].

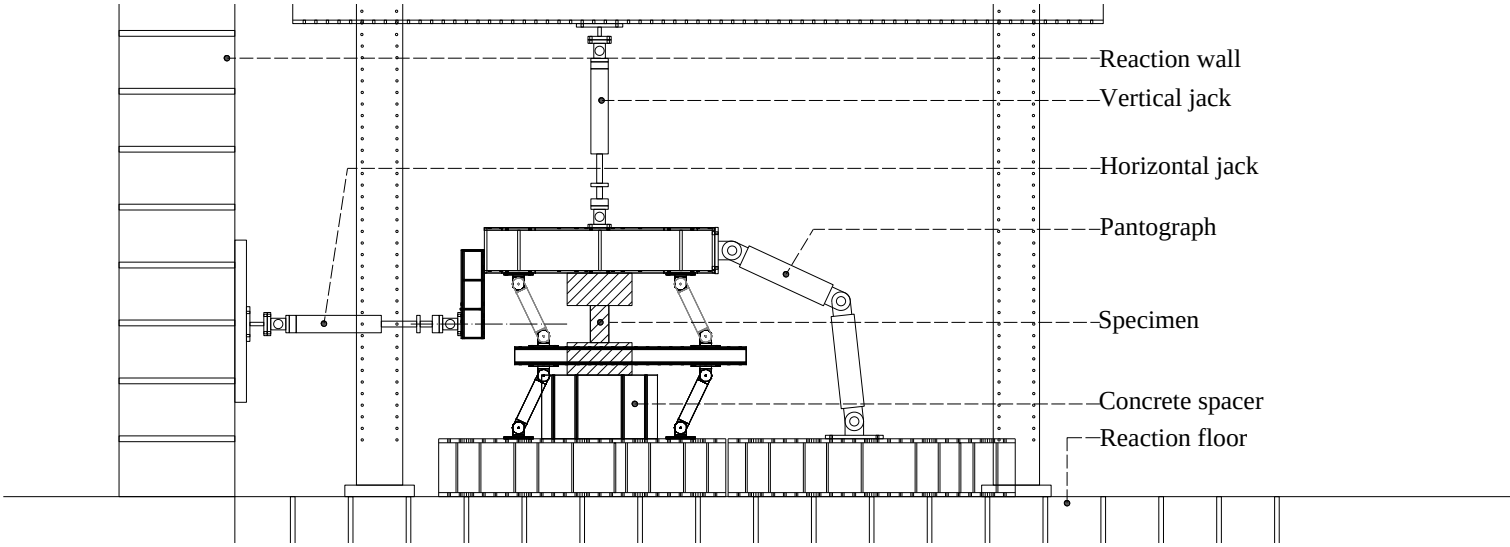

Fig. 1 – Loading system of Test setup 1

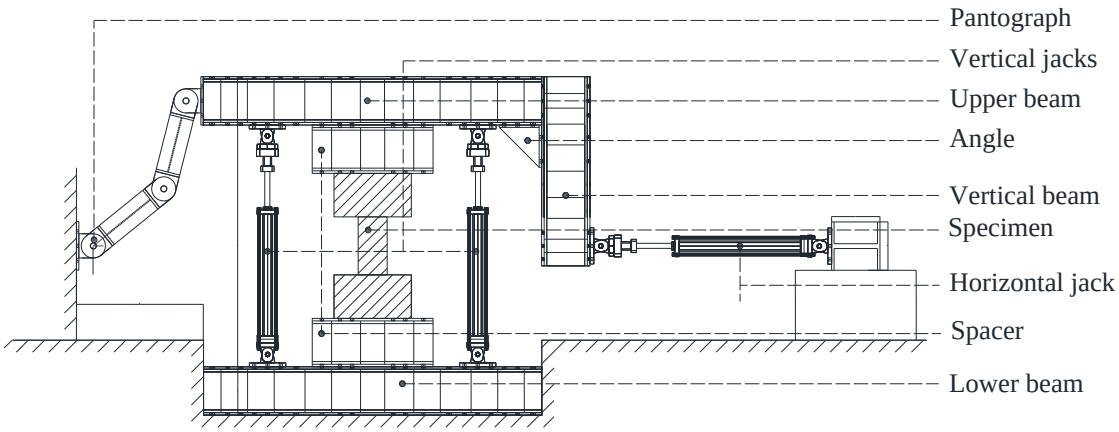

Fig. 2 – Loading system of Test setup 2

2.2 Specimen details

Thirty-nine specimens are designed and tested in the two test setups. Among them, 13 are tested in Test setup 1. The other 26 specimens are tested in Test setup 2. All the specimens are designed to fail in shear.

2.2.1 Details of specimens tested in Test setup 1

Specimens tested in Test setup 1, have a cross-section of 160×160 mm^2 and a clear height of 320 mm. Each column has 8-9.53 mm diameter bars as longitudinal bars, which results in reinforcement ratio, $p_{sl} = A_{sl} / A_g$ = 2.2%, where, A_{sl} is the total area of longitudinal reinforcement in the cross-section of the columns and A_g is the gross cross-sectional area of columns. The clear cover of the columns is 15 mm. The ratio of transverse reinforcement, having 4.23 mm diameter bars, p_w is 0.12% in 9 specimens and 0.23% in 4 specimens at the spacing of 150 mm and 75 mm, respectively. The coarse aggregate is stone in all these columns. Eleven specimens have welded hooks, and 2 have 90º hooks.

2.2.2 Details of specimens tested in Test setup 2

The Test setup 2 specimens are designed with efforts to be approximately 1.5 times the size of Test setup 1 specimens. Each specimen has a clear height of 480 mm with a cross-section of 240×240 mm^2 with a 20 mm clear cover. Eight 15.90 mm diameter bars are used as longitudinal bars, which results in the reinforcement ratio, $p_{sl} = A_{sl}/A_g$ = 2.8%. The ratio of transverse reinforcement having 6.35 mm diameter bars, p_w is 0.11% in

13 specimens, 0.22% in 11 specimens and 0.33% in 2 specimens at the spacing of 240 mm, 120 mm and 80 mm, respectively. Brick chips aggregate is used as coarse aggregate in 22 specimens, and stone aggregate is used in 4 specimens.

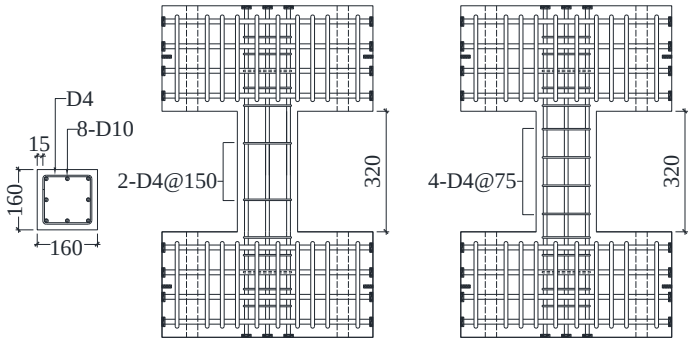

Fig. 3 – Details of specimens tested in Test setup 2 (unit: mm)

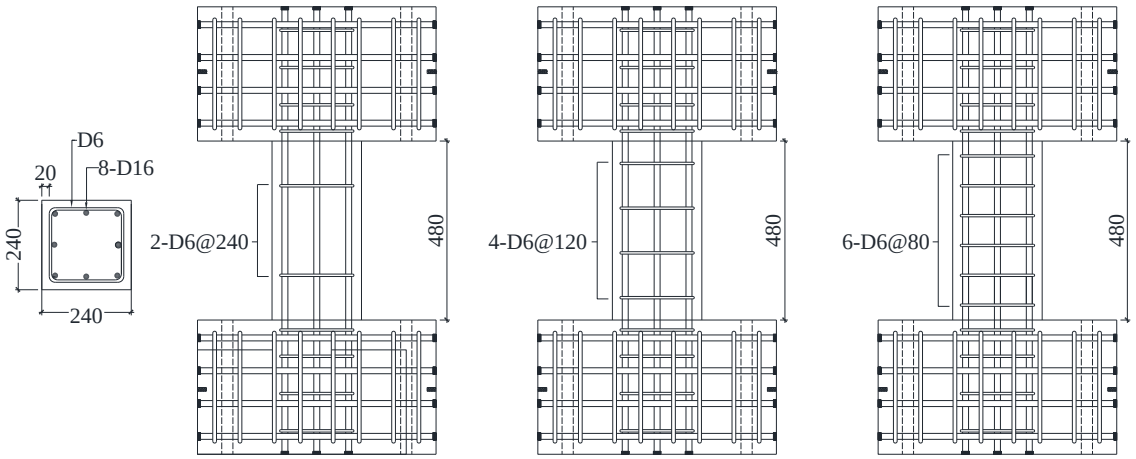

Fig. 4 – Details of specimens tested in Test setup 2 (unit: mm)

The names of specimens are given by combining the test parameters. The specimens tested in Test setup 1 are named as **AX**JP**Y(Z),** and the specimens tested in Test setup 2 are named as **AX**BD**Y(Z),** where **A**: Coarse aggregate (Brick/Stone); **X**: Target concrete compressive strength (MPa); **Y**: Specimen serial number; **Z**: Transverse reinforcement ratio up to 1 decimal; JP: Japan and BD: Bangladesh.

Table 1 – Test parameters and results of specimens tested in Test setup 1

Specimen	Transverse Reinforcement Ratio, p_w (%)	Coarse Aggregate	Hoop Detail	Testing Day F_c (MPa)	Axial Load (kN)	Axial Load Ratio	Maximum Shear Load (kN)
S10JP01(0.1)	0.12	Stone	Welding	10.9	149.2	0.53	38.7
S15JP02(0.1)	0.12	Stone	Welding	14.1	155.5	0.43	51.8
S25JP03(0.1)	0.12	Stone	Welding	26.9	148.0	0.21	60.9
S30JP04(0.1)	0.12	Stone	Welding	28.7	148.6	0.20	53.6
S10JP05(0.2)	0.23	Stone	Welding	8.7	148.4	0.67	38.5

(continued)

Table 1 – Test parameters and results of specimens tested in Test setup 1

S15JP06(0.2)	0.23	Stone	Welding	13.8	148.4	0.42	50.9
S25JP07(0.2)	0.23	Stone	Welding	26.9	148.7	0.22	57.2
S30JP08(0.2)	0.23	Stone	Welding	28.7	148.1	0.20	63.6
S10JP09(0.1)	0.12	Stone	90°	8.8	148.3	0.66	34.0
S15JP10(0.1)	0.12	Stone	90°	13.4	148.8	0.43	46.1
S10JP11(0.1)	0.12	Stone	Welding	9.2	78.6	0.33	36.4
S15JP12(0.1)	0.12	Stone	Welding	13.1	78.6	0.23	46.4
S25JP13(0.1)	0.12	Stone	Welding	23.8	78.6	0.13	66.3

Table 2 – Test parameters and results of specimens tested in Test setup 2

Specimen	**Transverse Reinforcement Ratio, p_w (%)**	**Coarse Aggregate**	**Hoop Detail**	**Testing Day F_c (MPa)**	**Axial Load (kN)**	**Axial Load Ratio**	**Maximum Shear Load (kN)**
B10BD01(0.1)	0.11	Brick	Welding	8.5	340.6	0.70	106.7
B15BD02(0.1)	0.11	Brick	Welding	14.8	340.8	0.40	139.7
B25BD03(0.1)	0.11	Brick	Welding	29.6	340.6	0.20	161.4
B30BD04(0.1)	0.11	Brick	Welding	34.1	339.8	0.17	157.5
B10BD05(0.2)	0.22	Brick	Welding	10.0	342.1	0.59	117.5
B15BD06(0.2)	0.22	Brick	Welding	15.6	341.9	0.38	151.2
B25BD07(0.2)	0.22	Brick	Welding	29.5	340.1	0.20	180.0
B30BD08(0.2)	0.22	Brick	Welding	37.9	340.9	0.16	163.9
B15BD09(0.2)	0.22	Brick	90º	15.3	339.8	0.39	147.5
B10BD10(0.2)	0.22	Brick	90º	14.6	179.8	0.21	108.0
B15BD11(0.2)	0.22	Brick	90º	14.8	182.8	0.21	128.4
B10BD12(0.1)	0.11	Brick	Welding	11.2	180.9	0.28	87.1
B15BD13(0.1)	0.11	Brick	90º	14.2	187.0	0.23	108.5
B15BD14(0.1)	0.11	Brick	Welding	17.7	179.9	0.18	129.2
B25BD15(0.1)	0.11	Brick	Welding	30.5	180.7	0.10	166.3
B10BD16(0.1)	0.11	Brick	Welding	12.3	187.0	0.26	116.0
B10BD17(0.1)	0.11	Brick	90º	10.1	338.1	0.58	96.7
B15BD18(0.1)	0.11	Brick	90º	14.2	340.9	0.42	119.7
S20BD19(0.2)	0.22	Stone	Welding	20.5	181.0	0.15	139.5
B20BD20(0.1)	0.11	Brick	Welding	22.2	340.8	0.27	139.1
B20BD21(0.2)	0.22	Brick	Welding	23.9	344.4	0.25	166.3
B20BD22(0.2)	0.22	Brick	Welding	23.0	179.8	0.14	144.0
S20BD23(0.2)	0.22	Stone	Welding	22.2	340.1	0.27	176.7
S40BD24(0.1)	0.11	Stone	Welding	40.3	186.0	0.08	181.8
S10BD25(0.3)	0.33	Stone	Welding	13.0	441.3	0.59	170.2
B10BD26(0.3)	0.33	Brick	Welding	13.0	441.9	0.59	139.7

2.3 Material properties

Table 3 shows the yield strength and diameter of the rebars used to construct the column specimens.

Table 3 – Rebar strength properties

Properties	**Test setup 1**		**Test setup 2**	
	Longitudinal	Transverse	Longitudinal	Transverse
Diameter (mm)	9.53 (D10)	4.23 (D4)	15.90 (D16)	6.35 (D6)
Yield strength (MPa)	412	407	498	473

3. Test program

3.1 Loading

The columns are first loaded to the designated axial load ratio, as in Table 1 and Table 2. A displacement-controlled loading is applied to the columns in the lateral direction. The applied lateral displacements are 0.25%, 0.5%, 1.0% and 2.0% drift of the clear height in two positive-negative cycles. However, it is not followed by several specimens because of the instability of loading due to sudden shear failure of columns. The axial compression is kept constant, and the rotation in the top beam of specimens is restricted during the whole loading.

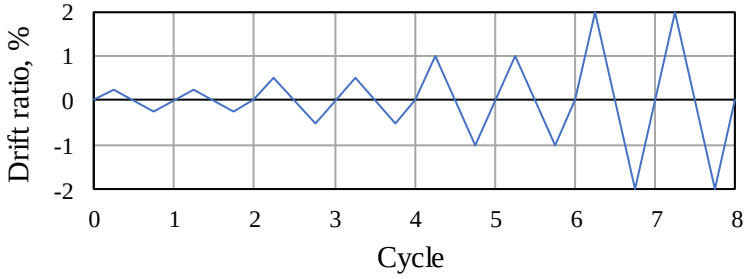

Fig. 5 – Displacement control lateral loading history

3.2 Observations

During the loading, the shear cracks of the columns are checked for each cycle. Diagonal cracks are observed in all the columns since all of them failed in shear. The horizontal load is plotted against the drift ratio for Test setup 1 and Teat setup 2 specimens in Fig. 6 and Fig. 7.

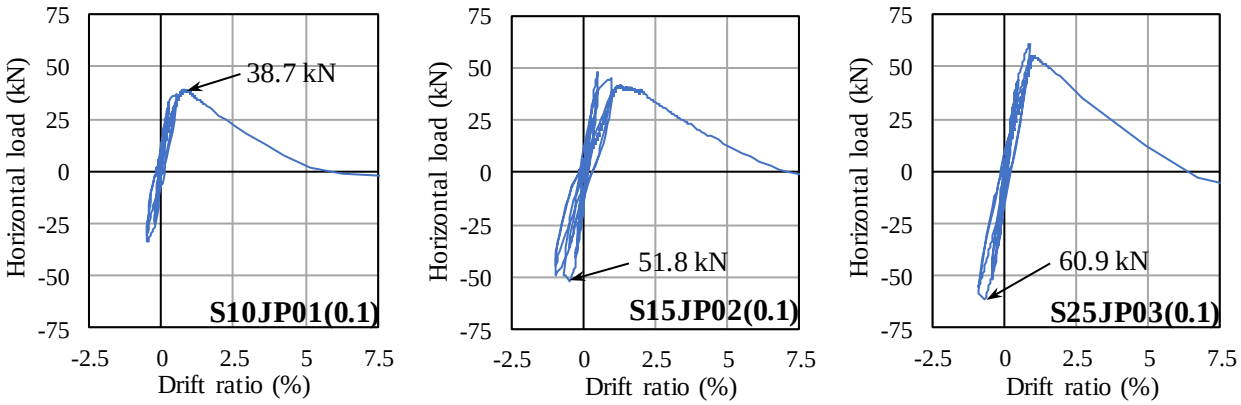

Fig. 6 – Horizontal load–drift ratio relationship of the specimens tested in Test setup 1 (continued)

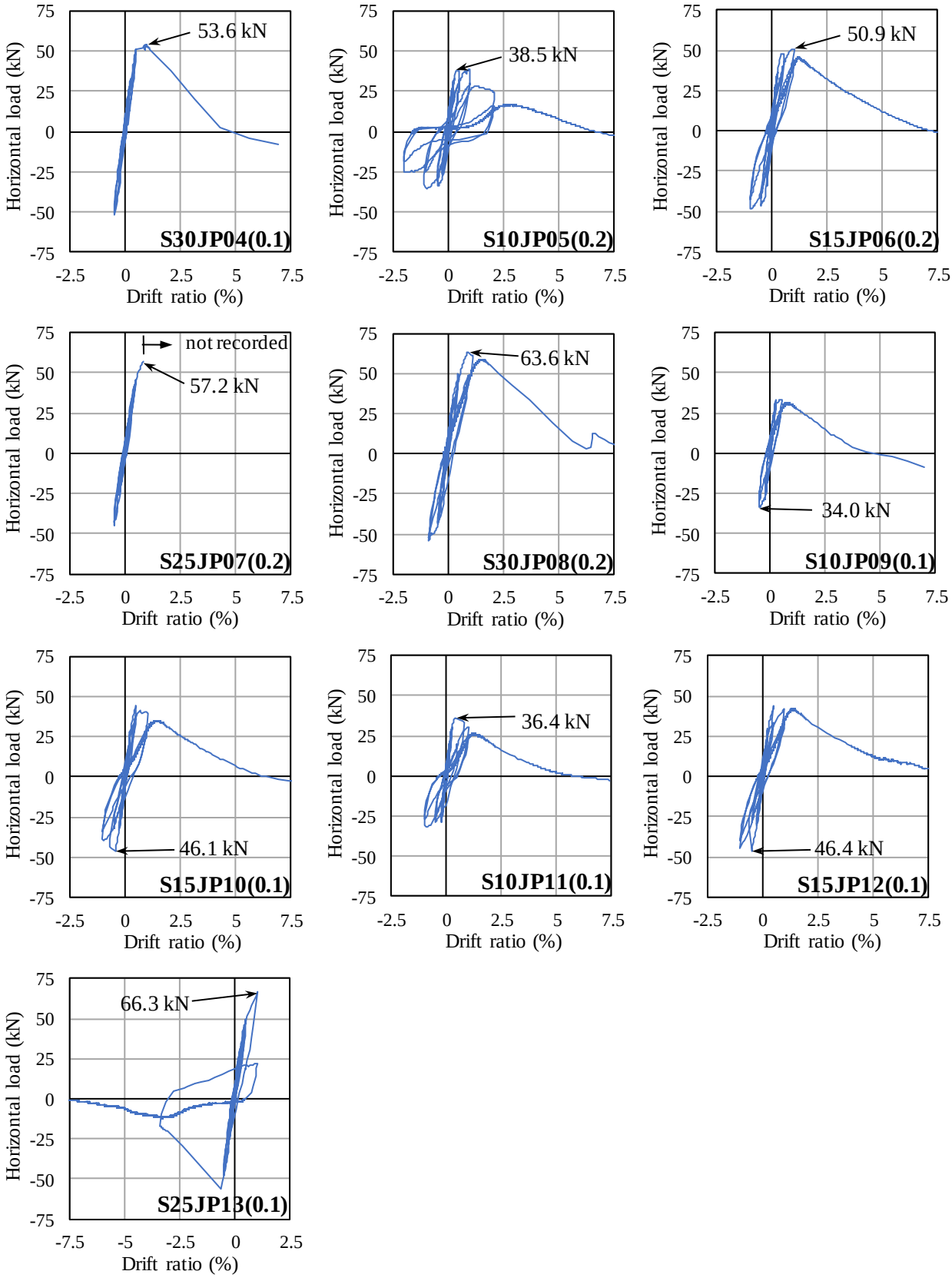

Fig. 6 – Horizontal load–drift ratio relationship of the specimens tested in Test setup 1

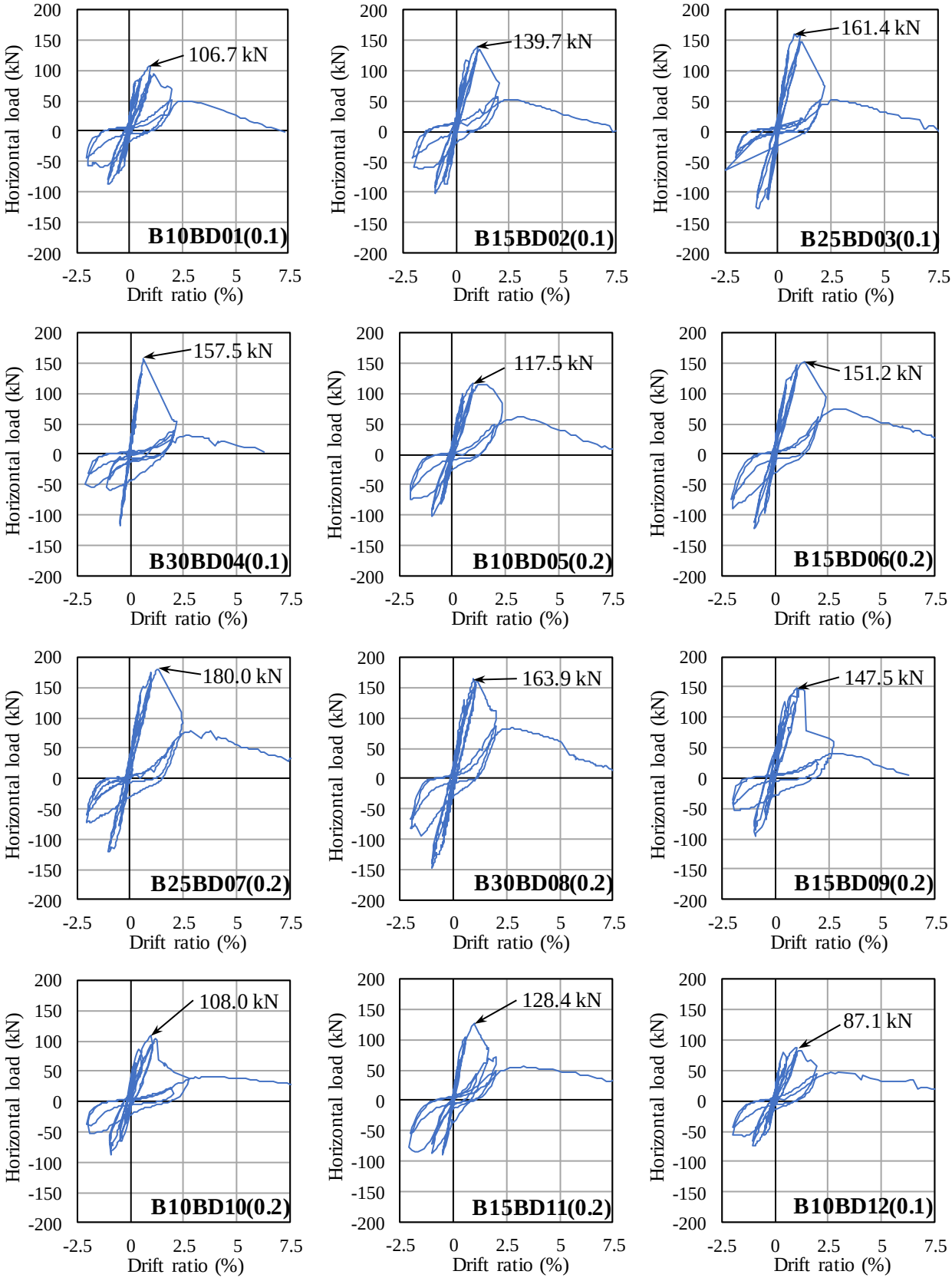

Fig. 7 – Horizontal load–drift ratio relationship of the specimens tested in Test setup 2 (continued)

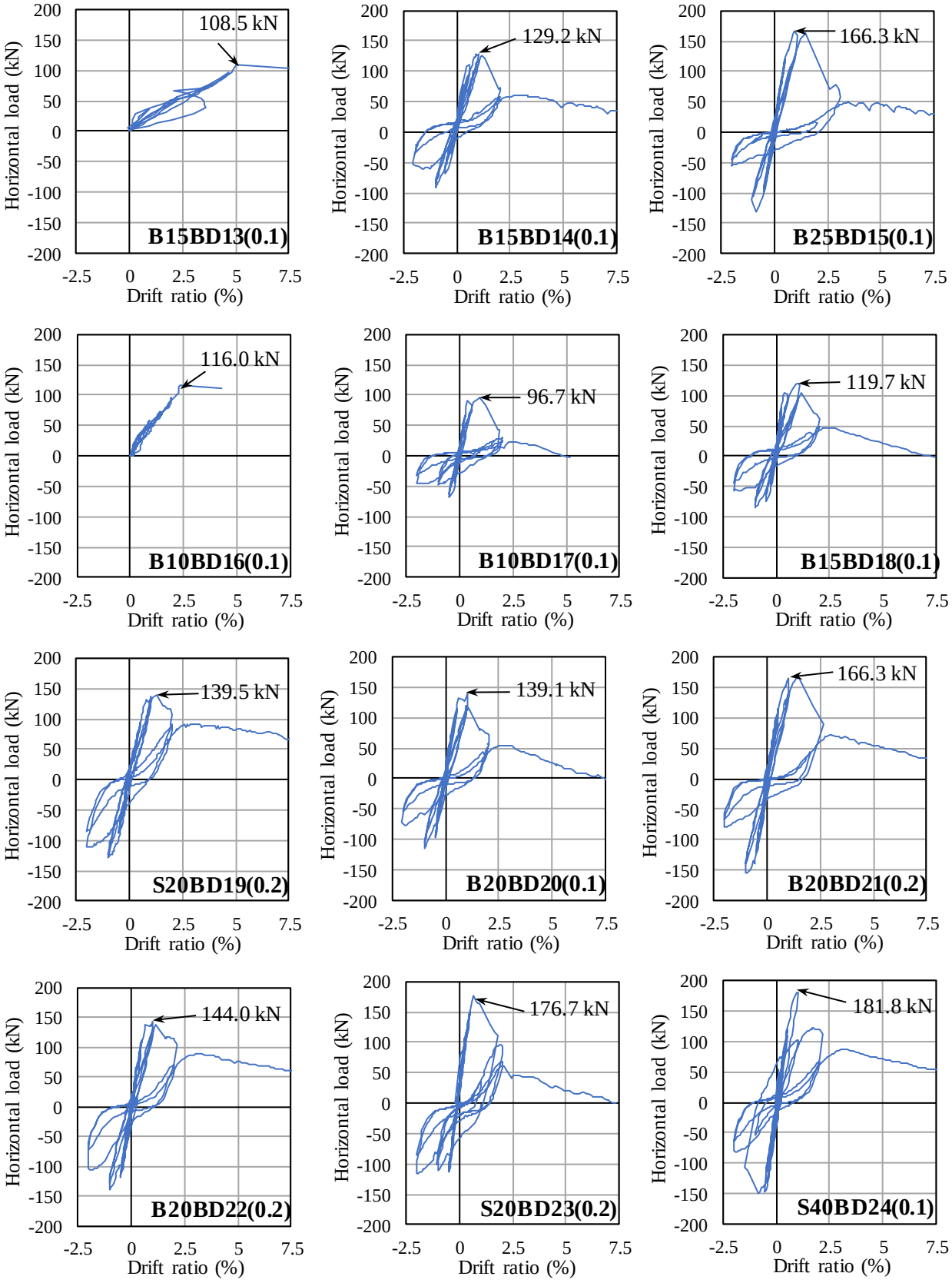

Fig. 7 – Horizontal load–drift ratio relationship of the specimens tested in Test setup 2 (continued)

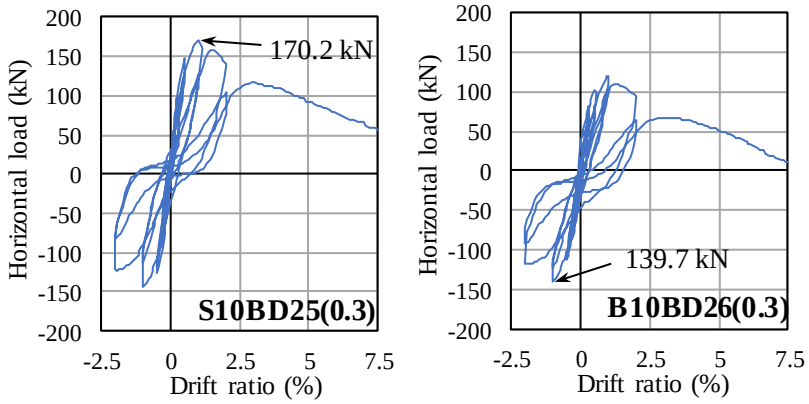

Fig. 7 – Horizontal load–drift ratio relationship of the specimens tested in Test setup 2

3.3 Application of existing standards

The main objective of this study is to compare two different ultimate shear strength evaluation methods of RC columns and find their applicability to the columns with low strength concrete, where the concrete having compressive strength, F_c below 13.5 MPa is defined as low strength concrete in [9]. Eighty specimens are considered for the comparison. Among them, 41 specimens that were made with stone aggregate and tested by other researchers, can be found in references [10-19].

In the first method, the shear strength of each specimen is estimated from Eq. (1) according to the JBDPA standard [5], which is adopted from Arakawa et al. [6] by allowing up to 5% of non-exceedance as a lower bound. This equation is proposed to predict the lower bound of test results for RC columns with medium to high strength concrete, but it is not applicable for the columns with low strength concrete. The relationship between the ratio of experimental value to the estimated value of shear strength, $Q_{exp}/Q_{su,}$ and F_c is shown in Fig. 8(a), where an overestimation is observed in the low strength concrete zone.

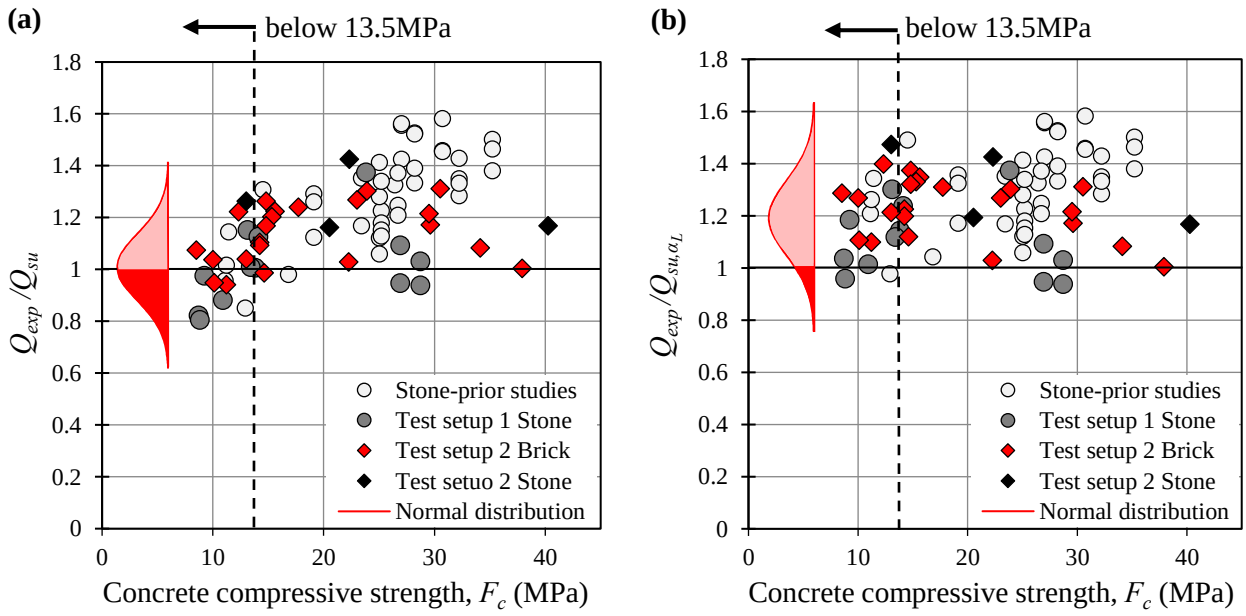

Fig. 8 – Relation between the ratio of experimental value to the estimated value of shear strength and concrete compressive strength; (a) JBDPA standard, (b) Yasojima's equation with reduction factor, α_L

Assuming a normal distribution of shear strength ratios, Q_{exp}/Q_{su} of specimens having F_c below 13.5 MPa, 47.3% of the ratios lie below the estimation by Eq. (1), as shown in Fig. 8(a).

$$Q_{su} = \left\{ \frac{0.053\, p_t^{0.23}\,(F_c + 18)}{M/(Qd) + 0.12} + 0.85\sqrt{p_w \sigma_{wy}} + 0.1\sigma_0 \right\} bj \tag{1}$$

Where, Q_{su} is the shear strength of column (MPa), p_t is the tensile reinforcement ratio (%), F_c is the concrete compressive strength (MPa), M/Qd is the shear span length to depth ratio, p_w is the transverse reinforcement ratio, σ_{wy} is the yield strength of shear reinforcing bars in columns (MPa), σ_0 is the axial stress in column (MPa), b is the width of column (mm), and j is the distance between centroids of tension and compression forces (mm), with an assumed value of $0.8D$ (where D is the depth of column).

The second method follows an equation proposed by Yasojima et al. to predict the shear strength of columns that have F_c below 22.0 MPa using a reduction factor, α_L as shown in Eq. (2).

$$Q_{su,\alpha_L} = \left\{ \frac{0.053\, p_t^{0.23}\,(F_c + 18)}{M/(Qd) + 0.12} + \alpha_L\sqrt{p_w \sigma_{wy}} + 0.1\sigma_0 \right\} bj \tag{2}$$

where $\alpha_L = 0.038 \times F_c \leq 0.85$

The reduction factor, α_L is multiplied with $\sqrt{p_w \sigma_{wy}}$ to account for the lower strain in columns of low strength concrete. The ratio of experimental value to the estimated value of shear strength, $Q_{exp}/Q_{su,\alpha_L}$ is plotted against the F_c in Fig. 8(b).

Assuming a normal distribution of the shear strength ratios as was studied earlier, $Q_{exp}/Q_{su,\alpha_L}$ of specimens having F_c below 13.5 MPa, 9.3% of the specimens lie below the estimation by adopting Eq. (2). Fig. 8 clearly shows that Eq. (2) gives a better prediction for the lower bound of shear strength of columns with low strength concrete.

4. Conclusion

In this study, the static cyclic lateral loading test of RC columns is conducted under constant axial load. Experimental studies are carried out to find a proper shear strength evaluation method for low strength concrete columns. Specimens are designed considering several parameters, e.g., concrete compressive strength, transverse reinforcement ratio, hoop details, axial load ratio, and coarse aggregate. This paper mainly focuses on the effect of concrete compressive strength, transverse reinforcement ratio, and axial load ratio on the shear strength of columns.

Two different methods suggested by JBDPA standard and Yasojima et al. are compared with experimental results. It is found that using the proposed reduction factor, α_L proposed by Yasojima et al. can evaluate the shear strength of columns that have concrete compressive strength below 13.5 MPa and brick chips coarse aggregate by allowing 9.3% of the specimens to fall below the expected estimation.

5. Acknowledgments

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