PREDICTION OF SHEAR STRENGTH OF SLENDER RC BEAMS WITHOUT SHEAR REINFORCEMENT BY STANDARD CODES OF PRACTICE

Chidananda G.[1], Raviraj S.[2]

[1]Research Scholar, Department of Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysuru – 570 006, Karnataka, India.

[2]Professor, Department of Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysuru – 570 006, Karnataka, India.

ABSTRACT

This paper presents a discussion on shear strength of slender RC beams without shear reinforcement suggested by the standard codes of practice viz. ACI 318 (2014), BS 8110–1(1997), EC 2 (2004), IS 456 (2000) and JSCE 2007 (2010). Four hundred and fifty eight test beams selected from ACI–DAfStb database (2013) are considered for the study. The statistical analysis and demerit points classification indicate BS 8110–1(1997) to show better estimate of shear strength of the test beams. Also BS 8110–1(1997) captures well the influence of design parameters on shear capacity of RC beams.

Keywords : Shear strength, Standard codes of practice, ACI–DAfStb database (2013), Demerits points classification.

1. INTRODUCTION

Shear strength of RC beams is a debate subject of the century. Shear behaviour of RC beams is a complicated mechanism. Many investigators through experiments have proposed theories on shear mechanism of RC beams. The shear in RC beams without shear reinforcement is resisted by uncracked concrete, aggregate interlock across the cracks and the dowel action of longitudinal reinforcement. Percentage of reinforcement, compressive strength of concrete and effective depth of beam are important design parameters affecting the shear strength of RC beams. The expressions for shear strength in various standard codes of practice are empirical or semi empirical which consider the above parameters to predict the shear strength with appropriate safety and strength reduction factors.

2. SHEAR STRENGTH PREDICTION BY STANDARD CODES OF PRACTICE

Five standard codes of practice viz. ACI 318 (2014), BS 8110–1(1997), EC 2 (2004), IS 456 (2000) and JSCE 2007 (2010) are considered in the present study for predicting the shear strength of RC beams. The expressions for shear strength suggested in these codes of practice are given in Appendix A.

3. TEST BEAMS FOR EVALUATION OF STANDARD CODES OF PRACTICE

A total of 458 slender simply supported RC test beams without shear reinforcement are selected from ACI–DAfStb database (2013) [Reineck et al. (2013)] for the evaluation of five standard codes of practice. The selected beams satisfy the following criteria.

1. Rectangular in cross section having reinforcement only at the tension side.
2. Percentage of reinforcement p_t upto 3%.
3. Characteristic cylinder compressive strength of concrete f_{ck} in between 12 and 60 MPa.
4. Characteristic yield strength of reinforcing steel f_{syk} upto 1000 MPa.

Table 1 shows the list of investigators of 458 test beams selected from ACI–DAfStb database (2013).

Table 1 : List of Investigators of selected 458 test beams

Sl. No.	Investigators	Sl. No.	Investigators
1	Ahmad et al. (1986) (2)	29	Leonhardt and Walther (1962) (27)
2	Angelakos et al. (2001) (5)	30	Marti et al. (1977) (2)
3	Aster and Koch (1974) (5)	31	Mathey and Watstein (1963) (9)
4	Lubell et al. (2004) (9)	32	Moody et al. (1954) (21)
5	Bernander (1957) (6)	33	Morrow and Viest (1957) (9)
6	Bhal (1968) (8)	34	Mphonde and Frantz (1984) (1)
7	Bresler and Scordelis (1963) (3)	35	Niwa et al. (1987) (3)
8	Cladera and Mari (2002), Cladera (2002) (3)	36	Podgorniak-Stanik (1998) (3)
9	Chana (1981) (23)	37	Rajagopalan and Ferguson (1968) (5)
10	Chang and Kesler (1958) (15)	38	Regan (1971) (4)
11	Collins and Kuchma (1999) (5)	39	Rehm et al. (1978) (1)
12	Diaz de Cossio and Siess (1960) (2)	40	Rosenbusch and Teutsch (2002) (3)
13	Elzanaty et al. (1986) (6)	41	Rusch et al. (1962) (3)
14	Ferguson (1956) (1)	42	Salandra and Ahmad (1989) (2)
15	Ghannoum (1998) (10)	43	Taylor (1968) (8)
16	Hallgren (1994) (8)	44	Taylor (1972) (5)
17	Hamadi (1976) (4)	45	Walraven (1978) (3)
18	Hanson (1958) (3)	46	Xie et al. (1994) (1)
19	Hanson (1961) (4)	47	Lubell (2006) (7)
20	Hedmann and Losberg (1978) (4)	48	Sherwood (2008) (8)
21	Kani (1967) (41)	49	Thiele (2010) (5)
22	Kani et al. (1979) (63)	50	Winkler (2011) (5)
23	Kawano and Watanabe (1998) (2)	51	Tureyen (2001), Tureyen and Frosch (2002) (3)
24	Kim and Park (1994) (14)	52	Bentz and Buckley (2005) (9)
25	Krefeld and Thurston (1966) (28)	53	Krefeld and Thurston (1966) (12)
26	Kung (1985) (5)	54	Leonhardt and Walther (1962) (6)
27	Kulkarni and Shah (1998) (4)	55	Shioya (1989) (3)
28	Laupa et al. (1953) (2)	56	Iguro et al. (1985) (5)

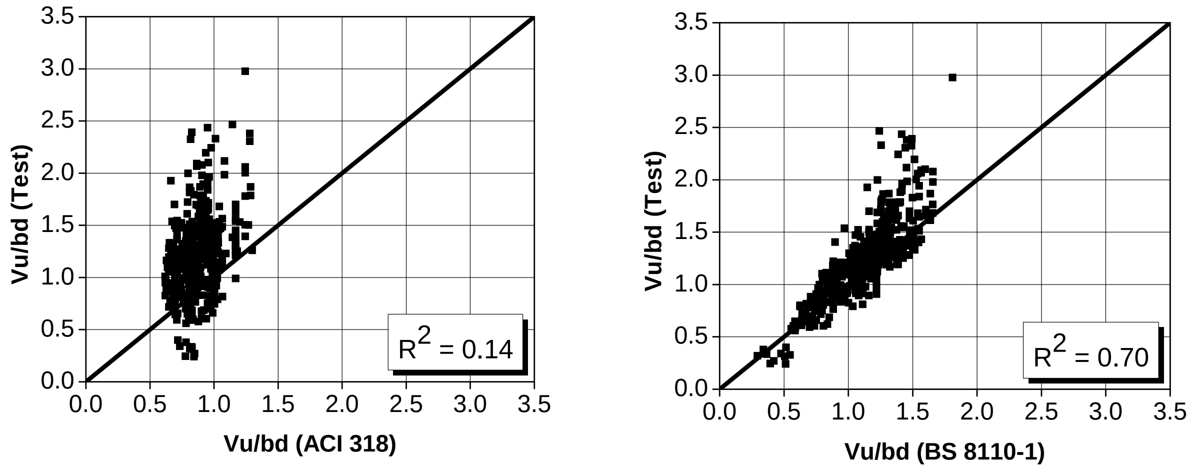
In Table 1, the values in the first and the second parentheses indicate the year of testing and the number of selected beams of the investigators respectively. Among the selected 458 test beams, 432 beams are subjected to either mid point or two point loadings and the remaining 26 beams, tested by the last four investigators (Sl. No. 53 to 56), are subjected to uniformly distributed loading. Table 2 shows the consolidated limits for various parameters of selected 458 test beams.

Table 2 : Consolidated limits for the parameters of selected 458 test beams

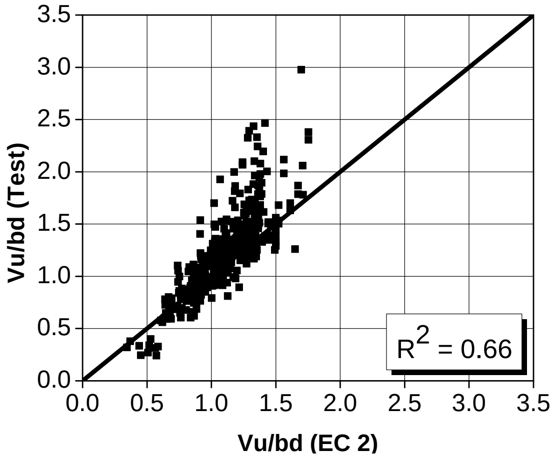
Sl. No.	Parameter	Unit	Minimum	Maximum
1	b	mm	50	3005
2	d	mm	65	3000
3	a/d	–	2.4	8.1
4	p_t	(%)	0.139	2.890
5	f_{ck}	MPa	12.27	59.45
6	f_{syk}	MPa	228.18	908.18

4. STATISTICAL ANALYSIS OF THE STANDARD CODES OF PRACTICE

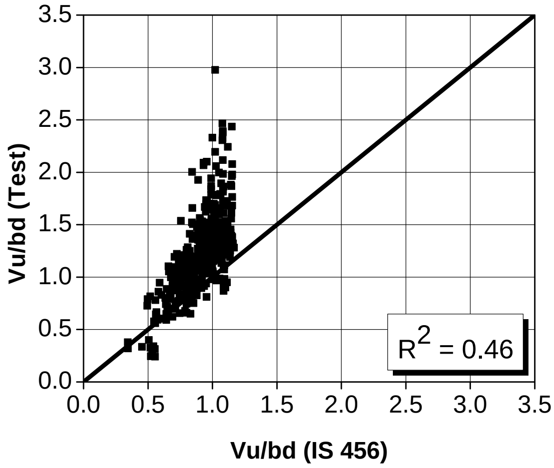
Unit partial safety factors, unit reduction factors and suitable conversion factors for concrete compressive strength given in Appendix B are applied to the expressions suggested in the five standard codes of practice to predict the shear strength (V_{pre}) of selected 458 test beams. The predicted shear strengths are compared with the corresponding experimental shear strength (V_{test}) results. The statistical results are summarized in Fig. 1 and Table 3.



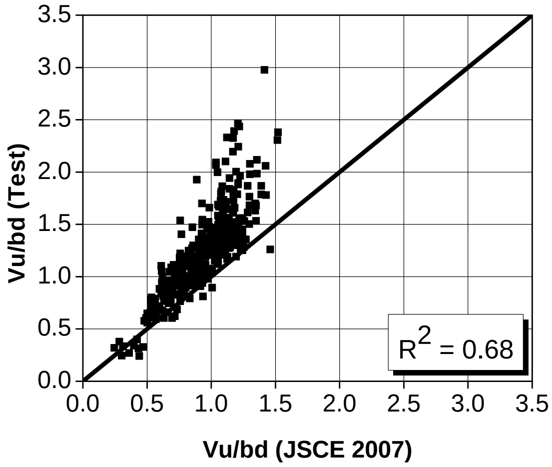
(a) (b)



(c)



(d)



(e)

Fig. 1 [(a) to (e)]: Correlation between the prediction from standard codes of practice and the test results of selected 458 test beams

Table 3 : Statistical results of the standard codes of practice

Sl. No.	Standard codes of practice	Statistical results		
		$\left(\frac{V_{test}}{V_{pre}}\right)_{Average}$	Standard deviation	Coefficient of Variation (CV) (%)
1	ACI 318 (2014)	1.41	0.41	29.08
2	BS 8110–1(1997)	1.10	0.18	16.36
3	EC 2 (2004)	1.10	0.20	18.18
4	IS 456 (2000)	1.34	0.30	22.39
5	JSCE 2007 (2010)	1.30	0.22	16.92

From Fig. 1 and Table 3, it is inferred that the shear predicted by BS 8110–1(1997) shows a better correlation with a correlation coefficient R^2 of 0.70, and an average (V_{test}/V_{pre}) ratio of 1.10 and a low CV of 16.36% in predicting the shear strength of selected 458 test beams than the other considered standard codes of practice.

5. DEMERIT POINTS CLASSIFICATION

The demerit points classification suggested by Collins (2001) measures agreement between V_{test} and V_{pre}. In this classification, the ratio $\frac{V_{test}}{V_{pre}}$ is calculated for each of the beam in the database. A demerit point value as given in Table 4 is assigned to each beam which depends on $\frac{V_{test}}{V_{pre}}$ ratio. The summation of the demerit points of all the beams shows the overall performance of the shear evaluation method. A smaller summation indicates the shear evaluation method to be more reliable in predicting the shear strength.

Table 4 : Collins (2001) demerit points classification

Sl. No.	Classification	$\frac{V_{test}}{V_{pre}}$	Demerit points
1	Extremely dangerous	<0.50	10
2	Dangerous	0.50 – 0.65	5
3	Low safety	0.65 – 0.85	2
4	Appropriate safety	0.85 – 1.30	0
5	Conservative	1.30 – 2.00	1
6	Extremely conservative	>2.00	2

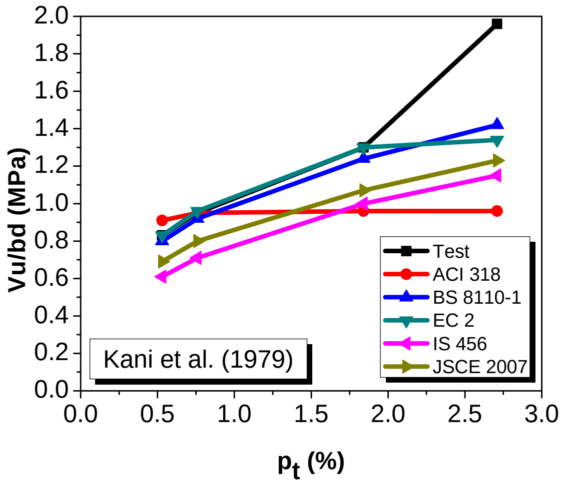
The demerit points classification is applied to evaluate the performance of five standard codes of practice in predicting the shear strength of selected 458 test beams. The demerit points value of the standard codes of practice for each classification are summarized in Table 5. A low value of 'Total demerit points' of BS 8110–1(1997) indicates that it performs well in predicting the shear strength than the other considered standard codes of practice.

Table 5 : Demerit points value of the standard codes of practice

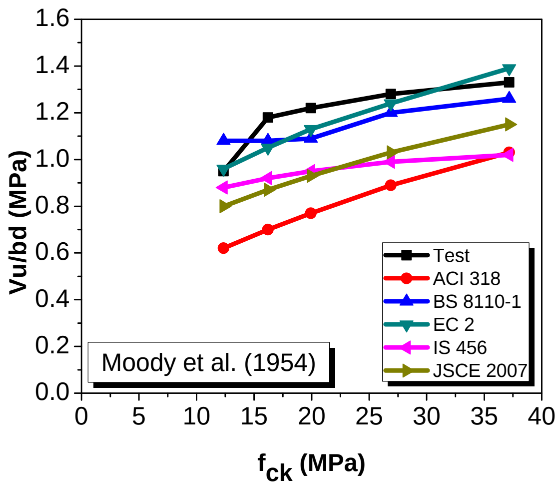
Sl. No.	Standard codes of practice	$\frac{V_{test}}{V_{pre}}$						Total demerit points
		<0.50	0.50 to 0.65	0.65 to 0.85	0.85 to 1.30	1.30 to 2.00	>2.00	
1	ACI 318 (2014)	9	2	24	141	248	34	464
2	BS 8110–1(1997)	1	4	17	391	45	0	109
3	EC 2 (2004)	1	4	21	379	53	0	125
4	IS 456 (2000)	2	4	9	218	210	15	298
5	JSCE 2007 (2010)	0	1	5	255	190	7	219

6. PARAMETRIC STUDIES

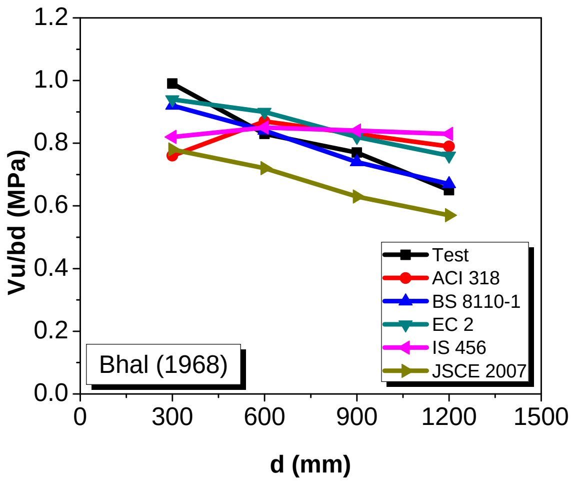
Parametric studies are carried out to study the influence of the design parameters viz. p_t, f_{ck} and d on shear strength of RC beams predicted by the standard codes of practice considering respectively a few beams tested Kani et al. (1979), Moody et al. (1954) and Bhal (1968). The details of the RC beams considered for the parametric study are tabulated in Appendix C. Comparison of shear predicted by the five standard codes of practice with the test results, for the three design parameters, are shown in Fig. 2. It is inferred that BS 8110–1(1997) shows better agreement with the test results of the above mentioned investigators than the other considered standard codes of practice.



(a)



(b)



(c)

Fig. 2 [(a) to (c)]: Comparison of shear predicted by the standard codes of practice with the test results of Kani et al. (1979), Moody et al. (1954) and Bhal (1968)

7. CONCLUSIONS

The prediction of shear strength of selected 458 slender RC beams without shear reinforcement by the five standard codes of practice viz. ACI 318 (2014), BS 8110–1(1997), EC 2 (2004), IS 456 (2000) and JSCE 2007 (2010) is presented. The following conclusions are drawn.

1. From statistical analysis and demerit points classification, the shear strength predicted by BS 8110–1(1997) predicts the test results fairly well than the other considered standard codes of practice.
2. The comparison with the test results of Kani et al. (1979), Moody et al. (1954) and Bhal (1968) shows that the influence of design parameters viz. p_t, f_{ck} and d on shear capacity is well captured by BS 8110–1(1997) than the other considered standard codes of practice.
3. It is suggested to consider BS 8110–1(1997) for evaluating the shear strength of RC beams without shear reinforcement among the five considered standard codes of practice.

NOTATION

a	Shear span
b	Width of beam
d	Effective depth of beam
a/d	Shear span to effective depth ratio
$f_{c,cu}$	Mean cube (150 mm) compressive strength of concrete
f_{ck}	Characteristic cylinder (150x300 mm) compressive strength of concrete
$f_{ck,cu}$	Characteristic cube (150 mm) compressive strength of concrete
f_{cm}	Mean cylinder (150x300 mm) compressive strength of concrete
$f_{lc,cu}$	Uniaxial compressive strength of concrete derived from $f_{c,cu}$
$f_{lc,cyl}$	Uniaxial compressive strength of concrete derived from f_{cm}
f_{sy}	Yield strength of reinforcing steel
f_{syk}	Characteristic yield strength of reinforcing steel (i.e. Grade of Steel)
p_t	Percentage of reinforcement
D	Overall depth of beam
V_{pre}	Predicted shear strength
V_{test}	Experimental shear strength

REFERENCES

1. Collins M.P. (2001), “Evaluation of Shear Design Procedures for Concrete Structures”, A Report Prepared for the CSA Technical Committee on Reinforced Concrete Design, Canada.
2. Reineck K.H., Kuchma D.A. and Fitik B. (2010), “Extended Databases with Shear Tests on Structural Concrete Beams without and with Stirrups for the Assessment of Shear Design Procedures–Research Report”, Institute for Lightweight Structures Conceptual and Structural Design (ILEK), University of Stuttgart and University of Illinois.
3. Reineck K.H., Bentz E.C., Fitik B., Kuchma D.A. and Bayrak O. (2013), “ACI–DAfStb Database of Shear Tests on Slender Reinforced Concrete Beams without Stirrups”, ACI Structural Journal, Vol. 110, No. 5, pp. 867–876.
4. ACI 318 (2014), “Building Code Requirements for Structural Concrete (ACI 318–14) and Commentary (ACI 318R–14)”, American Concrete Institute, Michigan, USA.
5. BS 5328–4 (1990), “Specification for the Procedures to be used in Sampling, Testing and Assessing Compliance of Concrete”, British Standards Institution, London, UK.
6. BS 8110–1 (1997), “Structural use of Concrete–Part 1 : Code of Practice for Design and Construction”, British Standards Institution, London, UK.

7. Eurocode 2 (2004), "Design of Concrete Structures–Part 1-1 : General Rules and Rules for Buildings (EN 1992–1–1)", European Committee for Standardization, Brussels, Belgium.
8. IS 456 (2000), "Plain and Reinforced Concrete–Code of Practice", Bureau of Indian Standards, New Delhi, India.
9. SP 24 (S&T) (1983), "Explanatory Handbook on Indian Standard Code of Practice for Plain and Reinforced Concrete (IS : 456–1978)", Bureau of Indian Standards, New Delhi, India.
10. JSCE Guidelines for Concrete No. 15, "Standard Specifications for Concrete Structures–2007 : Design" (2010), Japan Society of Civil Engineers, Tokyo, Japan.

Appendix A
Shear strength prediction by the standard codes of practice

1. ACI 318 (2014) (American Concrete Institute)

Clause 22.5.5 provides the shear strength of concrete for non prestressed members V_c which is given by

$$V_c = \left(1.9\lambda\sqrt{f_c'} + 2500\,\rho_w \frac{V_u d}{M_u}\right) b_w d \leq 3.5\lambda\sqrt{f_c'}\; b_w d \quad (1)$$

For most designs, the second term in the Eq. 1 is taken as $0.1\lambda\sqrt{f_c'}$. Therefore, Eq. 1 simplifies to

$$V_c = 2\,\lambda\sqrt{f_c'}\,b_w d \quad (2)$$

where,

λ is the modification factor which is equal to 1 for normal–weight concrete, 0.85 for sand–lightweight concrete and 0.75 for all–lightweight concrete .

$\sqrt{f_c'} \ngtr 100$ psi

A strength reduction factor of ϕ = 0.75 is applied to V_c to get the design strength.

(Remarks : In F.P.S. units)

2. BS 8110–1 (1997) (British Standards Institution)

Clause 3.4.5 suggests the design concrete shear stress v_c which is given by

$$v_c = \frac{0.79\left(\frac{100\,A_s}{b_v d}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}}{\gamma_m} \quad (3)$$

where,

$\frac{100\,A_s}{b_v d} \ngtr 3\%$

$\left(\frac{400}{d}\right)^{1/4} \nless 0.67$ for members without shear reinforcement.

For characteristic concrete cube strengths greater than 25 MPa, Eq. 3 for v_c may be multiplied by $\left(\frac{f_{ck,cu}}{25}\right)^{1/3}$.

$f_{ck,cu} \ngtr 40$ MPa

γ_m is a partial safety factor which is equal to 1.25.

(Remarks : In S.I. units)

3. EC 2 (2004) (Eurocode)

Clause 6.2.2 provides the design value of shear resistance $V_{Rd,c}$ which is given by

$$V_{Rd,c} = \left[C_{Rd,c}\, k(100\, \rho_l f_{ck})^{1/3} + k_1 \sigma_{cp}\right] b_w d \tag{4}$$

with a minimum value of

$$V_{Rd,c} = (V_{min} + k_1 \sigma_{cp}) b_w d$$

where,

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2$$

$$\rho_l = \frac{A_{sl}}{b_w d} \leq 0.02$$

$$\sigma_{cp} = \frac{N_{Ed}}{A_c} < 0.2\, f_{cd}$$

$$C_{Rd,c} = \frac{0.18}{\gamma_c}$$

γ_c = Partial factor for concrete which is 1.5 for persistent and transient design situations, and 1.2 for accidental design situations.

$$V_{min} = 0.035\, k^{3/2} f_{ck}^{1/2}$$

(Remarks : In S.I. units)

4. IS 456 (2000) and SP 24 (S&T) (1983) (Bureau of Indian Standards)

Clause 40.2 of IS 456 (2000) and Clause 39.2 of SP 24 (S&T) (1983) discuss the design shear strength τ_c of concrete in RC beams without shear reinforcement as

$$\tau_c = \frac{0.85\sqrt{0.8\, f_{ck,cu}}\left(\sqrt{1+5\beta} - 1\right)}{6\,\beta} \leq \tau_{c,max} \tag{5}$$

where,

$$\beta = \frac{0.8\, f_{ck,cu}}{6.89\, P_t} \nless 1$$

$$f_{ck,cu} \ngtr 40 \text{ MPa}$$

$$p_t \ngtr 3\%$$

$$\tau_{c,max} = 0.85\left[0.83\sqrt{0.8 f_{ck,cu}}\right]$$

The factor 0.8 in the formulae is for converting cylinder strength to cube strength and 0.85 is a reduction factor similar to partial safety factor γ_m for materials.

(Remarks : In S.I. units)

5. JSCE 2007 (2010) (Japan Society of Civil Engineers)

Clause 9.2.2.2 suggests the design shear capacity of linear members V_{cd} which is given by

$$V_{cd} = \frac{\beta_d \cdot \beta_p \cdot \beta_n \cdot f_{vcd} \cdot b_w d}{\gamma_b} \tag{6}$$

where,

$$\beta_d = \left(\frac{1000}{d}\right)^{\frac{1}{4}} \ngtr 1.5$$

$$\beta_p = (100 p_v)^{\frac{1}{3}} \ngtr 1.5$$

$$p_v = \frac{A_s}{b_w d}$$

If $N'_d \geq 0$

$$\beta_n = \left(1 + \frac{2M_o}{M_{ud}}\right) \ngtr 2$$

If $N'_d < 0$

$$\beta_n = \left(1 + \frac{4M_o}{M_{ud}}\right) \nless 0$$

$$f_{vcd} = 0.2(f'_{cd})^{\frac{1}{3}} \leq 0.72 \text{ MPa}$$

$$f'_{cd} = \frac{f'_{ck}}{\gamma_c}$$

$$\gamma_b = 1.3$$

$$\gamma_c = 1.3$$

If design axial compressive force N'_d is neglected,

$$V_{cd} = \frac{\beta_d \cdot \beta_p \cdot f_{vcd} \cdot b_w \cdot d}{\gamma_b} \quad (7)$$

(Remarks : In S.I. units)

Appendix B

Conversion factors for characteristic concrete compressive strength and characteristic yield strength of reinforcing steel

1. Concrete :

a. Cylinder compressive strength [Reineck et al. (2010)]

$f_{ck} = f_{cm} - \Delta f$, where $\Delta f = 4$ MPa (for laboratory conditions)

$f_{lc,cyl} = 0.95 f_{cm}$

$f'_c = \frac{f_{lc,cyl}}{0.95} - 2.4$ (in MPa, for ACI cylinder compressive strength)

b. Cube compressive strength [Reineck et al. (2010)]

$f_{lc,cu} = 0.79 f_{c,cu}$ if $f_{cm} \leq 54$ MPa

$f_{lc,cu} = 0.95 f_{c,cu} - 10.5$ if $f_{cm} > 54$ MPa

c. Relation between cube and cylinder compressive strengths are determined by equating uniaxial compressive strengths.

d. $f_{ck,cu} = f_{c,cu} - 3$ [from Clause 3.16.2 of BS 5328–4 (1990) and Clause 16.1 of IS 456 (2000) for compliance requirement]

2. Reinforcing steel :

$f_{syk} = \frac{f_{sy}}{1.1}$ [Reineck et al. (2010)]

Appendix C

Details of RC beams for the study of design parameters

Sl. No.	Specimen Nomenclature	b (mm)	d (mm)	a/d	p_t (%)	f_{sy} (MPa)	$f_{lc,cyl}$ (MPa)	V_{test} (kN)
Kani et al. (1979) – Influence of p_t								
1	179	153.2	264.2	2.57	0.526	400	30.73	33.58
2	163	156.0	272.5	2.49	0.756	378	33.61	40.48
3	197	150.4	273.6	2.48	1.835	376	34.20	53.38
4	214	153.4	271.8	2.50	2.708	412	34.20	81.84
Moody et al. (1954) – Influence of f_{ck}								
5	16	152.4	268.2	3.41	1.898	310	15.53	38.83
6	12	152.4	268.2	3.41	1.898	310	19.20	48.17
7	10	152.4	268.2	3.41	1.898	310	22.73	49.95
8	7	152.4	268.2	3.41	1.898	310	29.35	52.17
9	9	152.4	268.2	3.41	1.898	310	39.11	54.40
Bhal (1968) – Influence of d								
10	B1	240.0	300.0	2.94	1.257	426	22.02	70.99
11	B2	240.0	600.0	2.94	1.257	426	28.12	119.48
12	B3	240.0	900.0	2.94	1.257	426	26.11	166.38
13	B4	240.0	1200.0	2.94	1.257	426	23.95	187.10