Experimental Verification of Current Shear Design Equations for HSRC Beams

ATTAULLAH SHAH*, AND SAEED AHMAD**

RECEIVED ON 26.05.2009 ACCEPTED ON 08.06.2010

ABSTRACT

Experimental research on the shear capacity of HSRC (High Strength Reinforced Concrete) beams is relatively very limited as compared to the NSRC (Normal Strength Reinforced Concrete) beams. Most of the Building Codes determine the shear strength of HSRC with the help of empirical equations based on experimental work of NSRC beams and hence these equations are generally regarded as un-conservative for HSRC beams particularly at low level of longitudinal reinforcement.

In this paper, 42 beams have been tested in two sets, such that in 21 beams no transverse reinforcement has been used, whereas in the remaining 21 beams, minimum transverse reinforcement has been used as per ACI-318 (American Concrete Institute) provisions. Two values of compressive strength 52 and 61 MPa, three values of longitudinal steel ratio and seven values of shear span to depth ratio have been have been used. The beams were tested under concentrated load at the mid span.

The results are compared with the equations proposed by different international building codes like ACI, AASHTO LRFD, EC (Euro Code), Canadian Code and Japanese Code for shear strength of HSRC beams.From comparison, it has been observed that some codes are less conservative for shear design of HSRC beams and further research is required to rationalize these equations.

Key Words: **High Strength, Building Codes, Transverse Reinforcement, Shear Span, Beams.**

1. INTRODUCTION

1.1 Shear Strength of Reinforced Concrete Beams

The research on shear strength of concrete has shown that reinforced concrete beams without transverse reinforcement can resist the shear and flexure by means of beam and arch actions, also sometimes called concrete mechanisms [1]. These forces acting on the beam element in its shear span are shown in Fig. 1.

The joint committee ASCE-ACI-426 [2] in 1973 and later in 1998 reported the following five mechanisms for the shear in reinforced concrete sections:

(i) *Shear in the Un-Cracked Concrete Zone:* In cracked concrete member, the un-compression zone offers some resistance to the shear but for slender beams with no axial force, this part is very negligible due to small depth of compression zone.

* Project Director, Allama Iqbal Open University, Islamabad.

** Professor, Department of Civil Engineering, University of Engineering & Technology, Taxila.

(ii) *Residual Tensile Stresses:* When concrete is cracked and loaded in uni-axial tension, it can transmit tensile stresses until crack widths reach 0.06-0.16mm, which adds to the shear capacity of the concrete. When the crack opening is small, the resistance provided by residual tensile stresses is significant. However, in a large member, the contribution of crack tip tensile stresses to shear resistance is less significant due to the large crack widths that occur before failure in such members.

(iii) *Interface Shear Transfer:* The contribution of interface shear transfer to shear strength is a function of the crack width and aggregate size. Thus, the magnitude decreases as the crack width increases and as the aggregate size decreases. Consequently, this component is also called "aggregate interlock" denoted by V_a. However, it is now considered more appropriate to use the terminology "interface shear transfer" or "friction".

(iv) *Dowel Action:* When a crack forms across longitudinal bars, the dowelling action V_d, of the longitudinal bars provides a resisting shear force, which depends on the amount of concrete cover beneath the longitudinal bars and the degree to which vertical displacements of those bars at the inclined crack are restrained by transverse reinforcement.

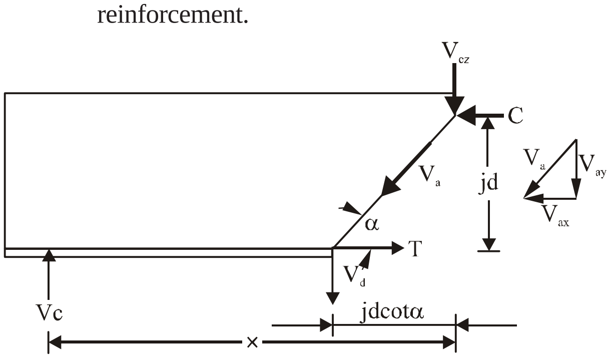

FIG. 1. FORCES ACTING IN A BEAM ELEMENT WITHIN THE SHEAR SPAN AND INTERNAL ARCHES IN A RC BEAM [1]

Currently, the shear design of the Reinforced Concrete beams is done with the help of empirical equations proposed by various building codes across the world. These equation have been based on experimental data of NSRC beams, with compressive cylinder strength of concrete as 40MPa or less. The most commonly used building codes are discussed as:

1.1.1 ACI Code 318-06

The ACI Building Code 318-06 [3] is no doubt the most widely applied Code for the shear design of concrete. The nominal shear capacity of reinforced concrete beam V_n, is given as the sum of Concrete contribution V_c, and contributions of stirrups V_s i.e.

$$V_n = V_c + V_s$$

Where V_c is nominal shear strength of concrete, and V_s nominal shear strength of beams due to stirrups.

For beams without shear reinforcement, the shear capacity is given as:

$$V_c = \left[\sqrt{f_c' + 120\rho \frac{V_u d}{M_u}}\right] b_w d / 7 \le 0.3\sqrt{f c'}\, b_w d \tag{1}$$

The ACI-ASCE Committee 462 has further assumed the following simplified Equation (1):

$$V_c = \left(0.167\sqrt{fc'}\right) bwd \tag{2}$$

The shear contribution of transverse steel is given as:

$$Vs = [Avfyd]/s \tag{3}$$

Where f_c' is cylinder compressive strength of concrete, ρ is Longitudinal steel ratio, V_u is Factored shear at the section, M_u is Factored Moment at the section, b_w is Width of beams web, d is Effective depth of beam, and s is Spacing of stirrups.

1.2.2 Canadian Standards for Design of Concrete Structures. CSA A-233-94

The General design method of Canadian code has been based on MCFT (Modified Compression Field Theory) and applies to concrete up to 81 MPa (16000 psi) [4].

According to CSA A- 23.3-94:

$$V_c = 0.2\sqrt{fc'}\,b_w \text{ if } dA_v \geq \frac{0.06\sqrt{fc'}\,b_w s}{f_y} \text{ for d} \leq 300\text{mm}$$

$$V_c = \left(\frac{260}{100+d}\right)\sqrt{fc'}\,b_w d \geq 0.1\sqrt{fc'}\,b_w d \text{ if } A_v \geq \frac{0.06\sqrt{fc'}\,b_w s}{f_y} \text{ d} \geq 300\text{mm} \quad (4)$$

$$V_s = [A_v f_y \mathrm{Cot}\theta]/s \quad (5)$$

Here A_v is Areas of the shear steel, f_y is Yield stress of longitudinal steel, and θ is Angle of crack defined under MCFT.

1.1.3 AASHTO LRFD (Load Reduction Factor Design) Bridge Design Specifications-2004 [5]

It is based on MCFT applicable to both non-pre stressed and pre-stressed concrete and gives:

$$V_S = 0.083\beta\sqrt{fc'}\,b_v d_v \leq 0.025 f'_c\, b_v d_v \quad (6)$$

$$V_s = A_v f_y \text{ dv Cot}\theta/s \quad (7)$$

1.1.4 European Code EC2-2003 [6]

For members without shear reinforcement:

$$V_c \left[\tau_R \kappa (1.2 + 40\rho)\right] b_w d \quad (8)$$

$\tau_R = 0.0525fc'$

Where κ is 1.6-d > 1.0, and ρ is $A_s/b_w d < 0.02$

For beams with shear reinforcement.

$$V_s = 0.9\,\rho_v f_{yv} b_w d \quad (9)$$

1.1.5 JSCE Code-1986 [7]

According to JSCE (Japanese Japan Society of Civil Engineers) Code, the shear capacity of linear reinforced members is given as [6]:

$$V_{cd} = \beta_d \beta_p \beta_n f_{vcd} b_w d/\gamma_b \quad (10)$$

Where γ is 1.3 for a/d > 2, f_{vcd} is $0.2f'_{cd}{}^{1/3} < 0.72$, β_d is $(1000/d)^{1/4} < 1.5$, β_p is [0.75 + 1.4 (a/d)], β_d is $(100\rho_w)^{1/3,}$ and β_n is [0.75 + 1.4 (a/d)].

For simply supported beams β_n=1.

Since we are comparing the test values directly with the code values therefore γ=1.0, no reduction factor shall be applied.

$$V_s = \rho_u f_w b_w d \quad (11)$$

A number of researchers have dealt with shear problem of HSRC beams in different ways and the experimental results vary from case to case. The results of Cornel University [8] tests and Perdue University [9] tests have given some important results for further verification. The findings of the earlier tests, describing the provisions of ACI Code for shear strength of HSRC as un-conservative by 10-30% are a significant outcome. Similarly the later findings at Perdue University require an increase in the minimum web reinforcement for compressive strength more than 10,000 psi (70MPa), to avoid brittle failure.

1.3 Evaluation of Shear Design Methods of Different Building Codes Based on Test Data Base [10]

The shear test database of 1359 beams of NSC was studied by NCHRP (National Cooperative Highway Research Program), USA which consisted of 878 RC beams and 481 pre-stressed concrete beams. In total of 1359, those containing shear reinforcement were 160 whereas 718 did not contain shear reinforcement. The test results V_{test} were compared with the code values V_{code} for the six different codes and the mean and CoV (Coefficient of Variation) were determined from the V_{test}/V_{code} values as shown in Table 1.

The following interesting results were reported in the study.

CSA and LRFD have given best results particularly for PC beams with shear reinforcement.

ACI provisions are poor predictor of shear for RC and PC beams with no transverse reinforcement but for beams with Av, these are reasonably good, hence Av is required where Vu>φVC/2 DIN is very poof predictor followed by JSCE.

1.3 The Shear Strength of High Strength Concrete Beams

The research data on the shear strength of high strength concrete beams is limited particularly for the compressive strength of 40 MPa and more. Following four challenges are pointed by Duthinh, et. al. [11] while dealing with the problem of shear design of high strength concrete.

(i) The current provision and empirical equations used for the shear design are mostly based on the research carried with concrete of 40 MPa or less. Again these equations proposed by researchers are both complex and difficult to understand. Hence there is a need to further simplify these equations for better understanding and easy application by the designers.

(ii) The minimum shear reinforcement for HSC beams needs to be rationalized to avoid brittle failure of the beams and adequate control of the shear cracks.

(iii) The relatively little role of the aggregate interlocking in HSC due to stronger matrix, the shear friction of HSC can be expected 30-35% less than the NSC.

TABLE 1. COMPARISON OF TEST VALUES AND CODES VALUES BASED ON SHEAR DATA BASE

Member Type With or Without Average		All	RC-Beams		
			Both	RC No Average	RC With Average
Code		1359	878	718	160
ACI	Mean	1.44	1.51	1.54	1.35
	Coefficient of Variation	0.37	0.40	0.418	0.277
LRFD	Mean	1.38	1.37	1.39	1.27
	Coefficient of Variation	0.26	0.26	0.266	0.224
CSA	Mean	1.31	1.25	1.27	1.19
	Coefficient of Variation	0.27	0.27	0.282	0.218
JSCE	Mean	1.51	1.36	1.35	1.38
	Coefficient of Variation	0.32	0.28	0.293	0.216
EC2	Mean	1.85	1.75	1.75	1.70
	Coefficient of Variation	0.40	0.32	0.328	0.373
DIN	Mean	2.05	2.10	2.10	1.25
	Coefficient of Variation	0.39	0.32	0.327	0.267

(iv) The compression capacity of the cracked web is reduced due transverse section, which is sometimes referred to as "Softening of concrete", which depends on the concrete strength.

Duthin, et. al. [11] further highlighted that most of the current shear design techniques either do not acknowledge the loss in the aggregate interlock mechanism in high strength concrete or simply do not account for the influence of adding shear reinforcement to other shear transfer mechanisms. Johnson, et. al. [10], reported that for a constant low shear reinforcement, the overall reserve shear strength after diagonal cracking diminishes with increase in the compressive strength of concrete.

Moinuddin, et. al. [12] applied the concept of FTM (Fracturing Truss Model) rather than MCFT and STM (Strut and Tie Model), to HSC concrete beams and compared the test results with the theoretical results. They observed that the assumption of FTM is more consistent with actual beam failure as compared to MCFT. They also examined the provisions of ACI-318 and recommended to include an alternate FTM (Fracturing Truss Model) in the future codes. They also observed that the concretes having different tensile stresses have significant effect on the shear capacity of beam, concrete stresses and steel strain. Hence biaxial tests must be conducted rather than split cylinder test for determining the exact concrete tensile stresses.

The share of the aggregates interlocking in the overall shear strength of HSRC beams is relatively lesser as compared to NSRC beams, mainly due the reason that the strength of concrete matrix in HSC is more than the strength of aggregates. The aggregates thus crush along smooth plane, thereby reducing the interlocking shear strength of aggregates [13].

From the above discussions and literature review on the shear strength of Normal and high strength beams, it has been deduced that more research is required to understand the behavior of HSRC beams and provisions of the International building codes.

Cladera, et. al., [13] developed an ANN (Artificial Neural Network) to predict the shear strength of RC beams, using a large database of experimental results and made the following important conclusions:

(1) The influence of the amount of web reinforcement is not linearly proportional to the amount of web reinforcement. i.e. the shear strength due to increase in shear reinforcement is not increasing in the same ratio. The effectiveness of stirrups decreases with their increase.

(2) Due to increase in size at low shear reinforcement, the shear strength has been reduced by 25% when the size of beam has been increased from 250-750mm.

(3) The influence of compressive strength of concrete also changes with the amount of web reinforcement.

(4) AASHTO LRFD design equation gives relatively good results as compared with the ACI-318 and EC-2.

Shehta, et. al. [14] developed theoretical models for the minimum flexural, shear and torsional for RC beams made with different compressive strengths of concrete. They reported that due to little test results available, there is great difference in the minimum values proposed by different Codes and hence more experimental research has been recommended by them.

Cladera, et. al. [15] worked on the HSRC beams failing in shear and reported a very brittle failure of the HSRC beams without shear reinforcement. The failure was observed as more sudden with further increase in the strength of concrete. However, the failure shear strength of beams was observed to increase with the increase in the compressive strength for such beams. They also proposed an expression for minimum web reinforcement of HSRC beams to avoid brittle failure of the beams. They also concluded that the limitation of 2% longitudinal steel for HSRC beams with web reinforcement is also not justified.

2. RESEARCH OBJECTIVES AND SIGNIFICANCE

The objectives of research can be summarized as:

(i) The research is mainly aimed at comparing the provisions of ACI-318, AASHTO-LRFD Code; Canadian Code, European Code and Japanese Code for shear design of HSRC beams with the actually observed experimental values and finally determining their relative degree of safety in the design.

(ii) To study the effect of various parameters like longitudinal steel and shear span to depth ratio on the shear strength of concrete and check how well, these are included in the mentioned codes.

(iii) To compare the relative degree of safety proposed by these codes for HSRC beams with the NSRC beams, based on the observed values.

3. TESTING DETAILS

To investigate the shear strength of HSRC, 42 beams in two sets of 21 beams each of size 9x12in (23x300cm) were cast. The values of shear span to effective depth ratios were used as: a/d = 3, 3.5, 4, 4.5, 5, 5.5, 6. For each value of shear span to effective depth ratio, three types of longitudinal steel ratios were used (ρ=1, 1.5 and 2%) to study the effect of longitudinal steel ratios. 60 grade steel (140MPa) was used for longitudinal steel.

For Series-I, 21 beams were used without transverse reinforcement where in Series-II, 21 beams having shear reinforcement with #2 bars of 40 grade (276MPa) @ 6 in c/c (#6@15cm c/c) were used, .i.e. ρv= 0.17%. The details of beams are shown in Table 2.

The 28 days compressive strength of the concrete mixes was observed as 52 MPa and 61 MPa. The details of mixed design are given in the Table 3.

4. RESULTS AND DISCUSSION

4.1 Shear Failure of Beams without Web Reinforcement

The beams were tested as simply supported beams at the Structural Laboratory of Engineering University Taxila-Pakistan. Deflection gauges were placed at the mid span

TABLE 2. DETAILS OF MAIN REINFORCEMENT AND TRANSVERSE REINFORCEMENT IN BEAMS

Main Steel		Transverse Steel		
Bars (A_w)	ρ_w (%)	Beams Series-I	Beams Series-II	
			A_v	ρ_v (%)
2#6	1	0	#2/@6in	0.17
(2#19)			(#6@15 cm)	
3#6	1.5	0	#3@6in	0.17
(3#19)			(#6@15 cm)	
2#7	2	0	#3@6in	0.17
(2#22)			(#6@15 cm)	

and critical section at d from of the supports as shown in Fig. 2.

When the monotonic load was applied at the centre of the beams and gradually increased, vertical flexural cracks appeared in the mid span region. When loads were increased, inclined cracks also developed in the region near the supports and their heights were typically equal to the heights of flexural cracks. With further increase in the loads, the second branch of the inclined crack initiates from the tip of the first crack at relatively flatter angle, which extended towards the point of load application. The racking of the compression zone, led to splitting of concrete which ultimately led to the failure of beams. The failure of HSRC beams without web reinforcement was observed to be relatively abrupt and sudden.

4.2 Shear Failure of Beams with Web Reinforcement

In beams with web reinforcement, the stirrups are brought into action after the formation of the secondary crack. With further increase in the width of cracks, the stirrups also start playing their role. The failure of the beams with web reinforcement is gradual and less abrupt as compared to the beams The values of the shear strength of beams have been shown in Tables 4-5 respectively for both sets of beams with and without web reinforcement respectively.

4.3 Comparison of the Provisions of the Codes for Shear Strength of HSRC Beams

The tests values were compared with the equations proposed by various building codes for the design of shear reinforcement of beams both with and without web reinforcement, shown in Tables 6-7.

The comparison of the V_{test}/V_{code} for NSRC beams given in the shear data base[10] are compared with the results obtained from the testing shown in Table 8.

5. CONCLUSIONS

From the comparison of specified Code values and actual test of results of the shear strength of HSRC beams, the following conclusions can be drawn:

(i) The shear design equations proposed by ACI-318 predict the shear strength of HSRC with reasonable accuracy for both sets of beams with

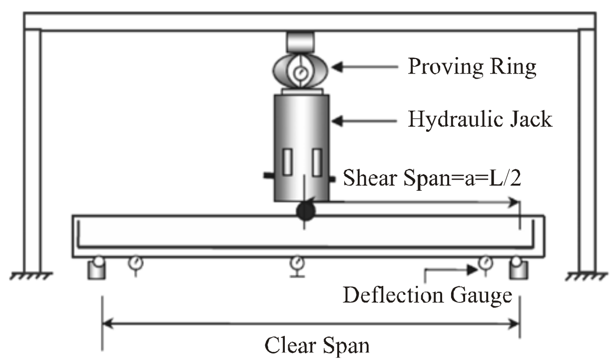

FIG. 2. CONCEPTUAL PLAN OF TEST SETUP USED

TABLE 3. MIX PROPORTIONING/ DESIGNING OF HIGH STRENGTH CONCRETE

Constituent	Mix-I	Mix-2
Type- I Cement	628 kg/m^3	640 kg/m^3
Fine Aggregates	484 kg/m^3	960 kg/m^3
Coarse Aggregates	1128 kg/m^3	1050 kg/m^3
HRWR @ by Weight of Cement	10.70 kg/m^3	12.58 kg/m^3
Water @ 0.25 w/c Ratio	157 kg/m^3	160 kg/m^3
Average Design Cylinder Compressive Strength (28 Days) fc’	52.0 M Pa	61.0 MPa

and without web reinforcement for longitudinal steel ratio of 1.5% and more. However for HSRC beam, the factor of safety has been reduced from 1.51-1.30, thereby recording a reduction of 21% in the shear strength of HSRC beams. However, the equations are still safe and conservatives for both types of beams. The equation for the shear strength of HSRC beams with web reinforcement is relatively safer.

(ii) The equations of CSA unlike for NSRC, overestimate the shear strength of HSRC beams, particularly for beams with no web reinforcement.

(iii) The equations of Euro-code EC2 are non conservative almost for all values of the longitudinal steel for beams with no web reinforcement; hence extra care is required in designing the HSRC beams with EC2 building code.

(iv) The Provisions of LRFD based on MCFT, appears best predictor of shear strength of HSRC beams for both types of beams with and without stirrups. However, simplification is required for application of the method for shear design of HSRC beams.

TABLE 4. VALUES OF TOTAL LOADS CORRESPONDING TO SHEAR CRACKS AND SHEAR STRENGTH OF BEAMS WITHOUT STIRRUPS

Beam	fc' (MPa)	ρ (%)	Span (cm)	a/d	Pcr (KN)	Failure Load (KN)	Shear Strength (KN)
B1	51	1.0	152	3.0	142	151	79
B2	51	1.0	178	3.5	122	132	68
B3	51	1.0	203	4.0	108	112	60
B4	51	1.0	229	4.5	103	107	57
B5	51	1.0	254	5.0	91	95	51
B6	51	1.0	279	5.5	89	100	50
B7	51	1.0	305	6.0	69	77	38
B8	51	1.5	152	3.0	208	216	116
B9	51	1.5	178	3.5	185	195	103
B10	51	1.5	203	4.0	161	169	90
B11	51	1.5	229	4.5	143	150	80
B12	51	1.5	254	5.0	125	132	70
B13	51	1.5	279	5.5	112	115	63
B14	62	1.5	305	6.0	99	105	55
B15	62	2.0	152	3.0	265	276	148
B16	62	2.0	178	3.5	223	236	124
B17	62	2.0	203	4.0	182	196	102
B18	62	2.0	229	4.5	172	179	96
B19	62	2.0	254	5.0	154	162	86
B20	62	2.0	279	5.5	138	145	77
B21	62	2.0	305	6.0	125	135	70

(v) The equations proposed by JSCE also predict the shear strength of HSRC beams very reasonably like NSRC beams, though the equations are 16% less conservative for HSRC beams than NSRC beams.

(vi) Based on equations proposed by the five codes, the ratio of V_{test}/V_{code} for HSRC beams with stirrups is less than the values for the beams without stirrups. Most of the Codes superimpose the individual contribution of concrete and steel to work out the total shear strength of beams with web reinforcement. However more research is required to prove this basic assumption, as the present results don't support it.

ACKNOWLEDGEMENTS

The authors are highly grateful to the staff of Structural and Concrete Laboratories, Department of Civil Engineering, University of Engineering & Technology, Taxila, Pakistan, and Higher Education Commission, Pakistan, for their assistance and funding of the work under faculty research project, jointly financed by UET, Taxila, and HEC.

TABLE 5. VALUES OF TOTAL LOADS CORRESPONDING TO SHEAR CRACKS AND SHEAR STRENGTH OF BEAMS WITH STIRRUPS

Title	fc' (MPa)	ρ (%)	Span (cm)	a/d	Pcr* (KN)	Failure Load (KN)	Shear Strength (KN)
Bs1	51	1.0	152	3.0	172	197	95.69
Bs2	51	1.0	178	3.5	152	179	84.81
Bs3	51	1.0	203	4.0	141	168	78.64
Bs4	51	1.0	229	4.5	139	161	77.53
Bs5	51	1.0	254	5.0	131	142	72.92
Bs6	51	1.0	279	5.5	126	124	70.31
Bs7	51	1.0	305	6.0	95	105	52.91
Bs8	51	1.5	152	3.0	271	235	150.58
Bs9	51	1.5	178	3.5	222	200	123.87
Bs10	51	1.5	203	4.0	194	178	107.79
Bs11	51	1.5	229	4.5	178	156	98.91
Bs12	51	1.5	254	5.0	156	138	87.16
Bs13	51	1.5	279	5.5	136	123	75.81
Bs14	62	1.5	305	6.0	123	115	68.41
Bs15	62	2.0	152	3.0	319	298	177.36
Bs16	62	2.0	178	3.5	278	245	136
Bs17	62	2.0	203	4.0	216	217	120
Bs18	62	2.0	229	4.5	207	208	116
Bs19	62	2.0	254	5.0	186	182	101
Bs20	62	2.0	279	5.5	169	181	100
Bs21	62	2.0	305	6.0	153	144	80

TABLE 6. COMPARISON OF V_{test}/V_{Code} VALUES FOR BEAMS WITHOUT WEB REINFORCEMENT

ρ (%)	fc'	a/d	ACI	Canadian Code	MCFT LRFD	Euro Code (EC-02)	JSCE
1	51	3	1.29	1.96	1.49	1.07	1.27
1	51	3.5	1.12	1.69	1.28	0.92	1.09
1	51	4	1	1.5	1.13	0.82	0.97
1	51	4.5	0.96	1.42	1.08	0.77	0.92
1	51	5	0.85	1.26	0.95	0.68	0.81
1	51	5.5	0.83	1.23	0.94	0.67	0.80
1	51	6	0.65	0.95	0.72	0.52	0.62
Mean			1.00	1.26	1.14	0.83	0.92
Standard Deviation			0.15	0.32	0.19	0.143	0.197
Coefficient of Variation			15	26	16	17	21
1.5	62	3	1.85	2.87	1.55	1.39	1.63
1.5	62	3.5	1.67	2.56	1.39	1.24	1.45
1.5	62	4	1.46	2.22	1.2	1.08	1.26
1.5	62	4.5	1.3	1.97	1.07	0.96	1.12
1.5	62	5	1.15	1.73	0.93	0.83	0.98
1.5	62	5.5	1.03	1.55	0.84	0.75	0.88
1.5	62	6	0.84	1.37	0.74	0.66	0.77
Mean			1.33	1.68	1.10	0.98	1.15
Standard Deviation			0.33	0.55	0.27	0.245	0.286
Coefficient of Variation			24	33	24	25	25
2	62	3	2.13	3.66	1.9	1.6	1.89
2	62	3.5	1.81	3.08	1.59	1.34	1.59
2	62	4	1.5	2.52	1.3	1.1	1.30
2	62	4.5	1.42	2.38	1.23	1.03	1.22
2	62	5	1.28	2.13	1.1	0.93	1.10
2	62	5.5	1.15	1.91	0.99	0.83	0.98
2	62	6	1.05	1.73	0.89	0.75	0.89
Mean			1.47	2.48	1.28	1.08	1.28
Standard Deviation				0.35	0.62	0.32	0.27 0.32
Coefficient of Variation			23	25	25	25	25
Mean of Means			1.27	1.80	1.17	0.96	1.12
Mean of Standard Deviation			0.26	0.49	0.26	0.22	0.26
Mean of Coefficient of Variation			0.20	0.28	0.21	0.22	0.23

REFERENCES

[1] Russo, G., Somma, G., and Angeli, P., "Design Shear Strength Formula for High Strength Concrete Beams", Material and Structures-RILEM, Volume 37, pp. 680-688, 2004.

[2] ASCE-ACI Committee 445, "Recent Approaches to Shear Design of Structural Concrete", Journal of Structural Engineering, Volume 124, No. 12, pp. 1375-1417, December, 1998.

TABLE 7. COMPARISON OF VTEST/VCODE VALUES FOR BEAMS WITH WEB REINFORCEMENT

ρ (%)	fc' (MPa)	a/d	ACI	Canadian Code	MCFT LRFD	Euro Code (EC-02)	JSCE
1	51	3	1.33	1.53	1.29	1.10	1.29
1	51	3.5	1.15	1.36	1.14	0.98	1.10
1	51	4	1.01	1.26	1.06	0.91	1.00
1	51	4.5	0.96	1.24	1.05	0.90	0.99
1	51	5	0.87	1.17	0.98	0.84	0.97
1	51	5.5	0.84	1.12	0.95	0.81	0.91
1	51	6	0.63	0.85	0.71	0.61	0.80
Mean			1.00	1.21	1.02	0.98	1.00
Standard Deviation				0.20	0.19	0.38	0.186 0.14
Coefficient of Variation			21	16	37	19	14
1.5	62	3	1.95	2.41	1.58	1.51	1.71
1.5	62	3.5	1.73	1.98	1.30	1.33	1.50
1.5	62	4	1.51	1.72	1.13	1.16	1.31
1.5	62	4.5	1.35	1.58	1.04	1.02	1.15
1.5	62	5	1.18	1.39	0.91	0.89	1.09
1.5	62	5.5	1.06	1.21	0.79	0.81	1.02
1.5	62	6	0.84	1.09	0.72	0.72	1.01
Mean			1.37	1.62	1.06	1.07	1.25
Standard Deviation				0.36	0.42	0.27	0.27 0.24
Coefficient of Variation			26	26	26	26	19
2	62	3	2.26	2.84	1.79	1.58	2.10
2	62	3.5	1.89	2.48	1.57	1.30	1.61
2	62	4	1.56	1.92	1.22	1.13	1.41
2	62	4.5	1.47	1.84	1.17	1.04	1.26
2	62	5	1.31	1.66	1.05	0.91	1.15
2	62	5.5	1.18	1.50	0.95	0.79	1.10
2	62	6	1.07	1.36	0.86	0.72	1.01
Mean			1.53	1.94	1.23	1.06	1.38
Standard Deviation				0.38	0.38	0.31	0.18 0.34
Coefficient of Variation			25	32	30	17	25
Mean of Means			1.30	1.58	1.36	1.03	1.27
Mean of Standard Deviation				0.31	0.33	0.21	0.21 0.24
Mean of Coefficient of Variation			0.24	0.24	0.31	0.2	0.19

[3] ACI Committee 318, "Building Code Requirements for Reinforced Concrete and Commentary", ACI318RM-06,ACI, Detroit, 2006.

[4] CSA A-233-94, Canadian Standards for Design of Concrete Structures, pp. 199, Rexdale Ontario Canada, December, 1994.

TABLE 8. COMPARISON OF THE SHEAR PROVISIONS OF DIFFERENT BUILDING CODES FROM DATA BASE OF NSRC BEAMS WITH THE HSRC BEAMS OF THE CURRENT TEST DATA

Code	NSRC Beams				HSRC Beams		
	Both		No Average	With Average	Both	No Average	With Average
ACI	Mean	1.51	1.54	1.35	1.30	1.27	1.34
	Coefficient of Variation	0.40	0.41	0.277	0.24	0.23	0.25
LRFD	Mean	1.30	1.39	1.27	1.13	1.17	1.10
	Coefficient of Variation	0.262	0.26	0.224	0.27	0.25	0.30
CSA	Mean	1.25	1.27	1.19	1.69	1.80	1.58
	Coefficient of Variation	0.27	0.28	0.218	0.43	0.502	0.369
EC2	Mean	1.75	1.75	1.70	0.97	0.96	1.03
	Coefficient of Variation	0.32	0.32	0.373	0.23	0.221	0.25
JSCE	Mean	1.36	1.35	1.38	1.20	1.12	1.27
	Coefficient of Variation	0.28	0.293	0.216	0.26	0.23	0.29

[5] AASHTO LRFD, “Bridge Design Specifications”, 2nd Edition, American Association for State Highway and Transportation Officials, Washington, DC, 1998.

[6] Euro Code-2, “Design of Concrete Structures Part-1: General Rules and Rules for Buildings”, Commission of the European Communities, ENV 1992-1-1, pp. 253, December, 1991.

[7] Japan Society of Civil Engineers, “Specification for Design and Construction of Concrete Structures”, Design, JSCE Standard, Part-1, Japan Society of Civil Engineers, Tokyo, 1986.

[8] Collins, M.P., and Mitchell, D., "Shear Design of Pre-Stressed and Non Pre-Stressed Concrete Beams", Journal of Pre-Stressed Concrete Institute, Volume 25, No. 5, pp. 32-100, 1980.

[9] Bazant, Z.P., and Kim, J.K., "The Size Effect in Shear Failure of Longitudinally Reinforced Beams", ACI Structural Journal, Volume 81, No. 5, pp. 456-468, 1984.

[10] NCHRP (National Cooperative Highway Research Program), Transport Research Board Washington DC-USA, 2005.

[11] Duthlin, D., and Carino, N.J., "Shear Design of High Strength Concrete Beams: A Review of State of the Art", Building and Fire Research Laboratory, NIST MD-USA, August, 1999.

[12] Mohiuddin, A.K., Edwin, R., and Shah, S., "Shear Design of High Strength Concrete Beams", Structural Journal, ASCE, 2000.

[13] Cladera, A., and Mari, A.R., "Shear Design Procedure for Reinforced Normal and High Strength Concrete Beams Using Artificial Neural Network-Part II Beams with Stirrups", Engineering Structures, Volume 26, pp. 927-936, Elsevier, 2004.

[14] Shehata, I., Shehata, L., and Garcia, S., "Minimum Steel Ratios in Reinforced Concrete Beams Made of Concrete with Different Strengths-Theoretical Approach", Materials and Structures-RILEM, Volume 36, pp. 3-11, 2003.

[15] Cladera, A., and Mari, A.R., "Experimental Study on High Strength Concrete Beams Failing in Shear", Engineering Structures, Volume 27, pp. 1519-1527, Elsevier, 2005.