

EXPERIMENTAL INVESTIGATIONS INTO THE SHEAR BEHAVIOR OF SELF-COMPACTING RC BEAMS WITH AND WITHOUT SHEAR REINFORCEMENT

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ABSTRACT

Self-compacting concrete (SCC) is a new generation of high-performance concrete, known for its excellent deformability and high resistance to segregation and bleeding. Nonetheless, SCC may be incapable of resisting shear because the shear resistance mechanisms of this concrete are uncertain, especially the aggregate interlock mechanism. This uncertainty is attributed to the fact that SCC contains a smaller amount of coarse aggregates than normal concrete (NC) does. This study focuses on the shear strength of self-compacting reinforced concrete (RC) beams with and without shear reinforcement. A total of 16 RC beam specimens was manufactured and tested in terms of shear span-to-depth ratio and flexural and shear reinforcement ratio. The test results were compared with those of the shear design equations developed by ACI, BS, CAN and NZ codes. Results show that an increase in web reinforcement enhanced cracking strength and ultimate load. Shear-tension failure was the control failure in all tested beams.

Keywords: self-compacting; concrete structure; shear strength; web reinforcement

REZUMAT

Betonul autocompactant (BAC) reprezintă o nouă generație de beton de înaltă performanță, cunoscut pentru excelența sa deformabilitate și rezistența ridicată la segregare și mustire. Totuși, BAC poate fi incapabil să preia forță tăietoare, deoarece mecanismele de rezistență la forță tăietoare ale acestui tip de beton sunt incerte, în special mecanismul de încleștare a agregatelor. Incertitudinea este atribuită faptului că BAC conține o cantitate mai mică de agregate mari decât betonul normal (BN). Studiul de față este focalizat asupra rezistenței la forță tăietoare a grinzilor din beton armat autocompactant (RC), cu și fără armare transversală. Un total de 16 specimene de grinzi RC au fost realizate și încercate în termeni de raport între deschiderea de forfecare și înălțimea secțiunii și de raport între ariile de armătură pentru încovoiere, respectiv forță tăietoare. Rezultatele încercărilor au fost comparate cu cele ale formulelor de calcul la forță tăietoare din codurile ACI, BS, CAN și NZ. Rezultatele arată că o creștere a armării pe inimă a mărit limita de fisurare și rezistența ultimă. Cedarea la întindere din forfecare a reprezentat criteriul de control al cedării pentru toate grinziile încercate.

Cuvinte cheie: autocompactant, structură de beton, rezistență la forfecare, armare pe inimă

1. INTRODUCTION

The shear behavior of reinforced concrete (RC) structures is not fully understood despite years of intensive study. To this end, researchers develop design methods and models to estimate the shear capacity of RC structures. The main parameters that generally influence shear behavior are dimensions, shear and flexural reinforcement, concrete compressive strength, load conditions, cross-

section shape, shear span/depth ratio, and concrete mix design. Many techniques have recently been proposed to improve the properties of concrete, such as self-compacting concrete (SCC). SCC can flow under its own weight and fills molds easily. Moreover, SCC is a dense and homogeneous material that does not require compaction in narrow areas, such as dense reinforcement [1,2]. Nonetheless, the mechanical properties of SCC, such as bond and shear behavior, are rarely studied in spite

of the extensive research on the fresh properties and durability behavior of this concrete. Given the lack of information regarding the structural performance of SCC members, this material is not confidently utilized by designers and engineers in the construction industry. However, SCC has many advantages, including increased productivity, reduced effort and improved structure quality [3].

Researchers [4–6] claim that SCC elements display a shear strength that is lower than that of normal concrete, as a result of the small aggregates in the former. This aggregate also affects the shear friction mechanism of these elements. By contrast, researchers such as [7] claim that SCC elements exhibit shear response behavior that is similar to that of elements manufactured from normal concrete. This claim is supported by the results obtained using SCC and normal concrete with the same aggregate size. When concrete samples with different granular structures are compared, shear behavior certainly varies [7].

This study demonstrates the results of an experimental study on the shear behavior of SCC beams with and without web reinforcements.

The shear failure mechanism of RC beams must be determined with and without web reinforcement to clarify the failure mechanisms in beams. Test parameters include concrete type (SCC), web and flexural reinforcement ratio, and shear span-to-depth ratio. The shear strength, crack patterns, and failure modes of the experimental SCC beams are also compared with those calculated according to the shear design equations presented by [8–11].

2. EXPERIMENTAL PROGRAM

A total of 16 RC beams were tested to investigate shear failure mechanism and concrete contribution to the overall shear resistance of SCC beams. These samples are designed only for adequate flexural reinforcements (with and without shear reinforcements).

Four concrete mixtures were used to cast 16 beams with different web reinforcements and shear span-to-depth ratios.

2.1. Beam geometry and reinforcement configuration

In this study, a total of 16 beam specimens were manufactured and tested. These beams were divided into four groups according to concrete mix design, as shown in Table 2.

The total length of each specimen was 1200 mm. The steel material properties are listed in Table 1.

The width of all beam specimens was constant at 180 mm, and the overall depth of all beam specimens was 250 mm.

The notation utilized to describe each group of test parameters is provided in Figure 1. The details of each specimen are listed in Table 2.

2.2. Proportions and properties of concrete mix

As mentioned previously, a total of four concrete mixtures was prepared to cast the concrete specimens.

The concrete mix proportions are detailed in Table 3. The cement contents in these four mixes were unequal, and each mix was designed to contain cement for developing concrete compressive strength.

Table 1. Properties of rebars

Bar type	Bar diameter (mm)	Sectional area (mm ²)	Tensile strength (MPa)	Modulus of elasticity (MPa)
Steel	16	201.0	420	200,000
Steel	8	50.26	340	200,000

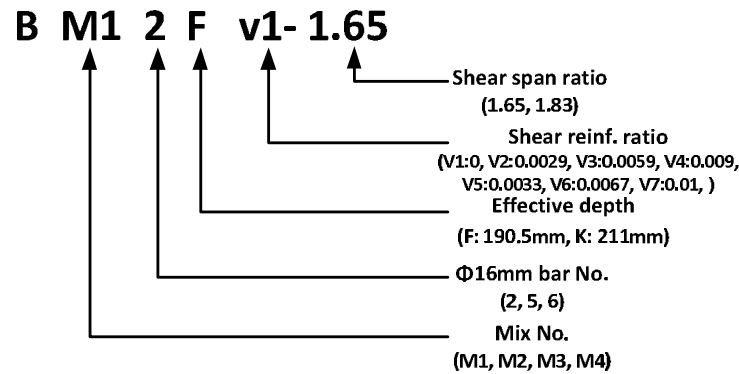


Fig.1 Notation to indicate the type of each specimen

Table 2. Specimen details

Specimen	d (mm)	a/d	Reinforcement ratio (%)	
			Pw	Pv
B M1 2 K v1-1.65	211	1.65	1.05	-
B M1 2 K v2-1.65	211	1.65	1.05	0.29
B M1 2 K v3-1.65	211	1.65	1.05	0.59
B M1 2 K v4-1.65	211	1.65	1.05	0.9
B M2 5 F v1-1.83	190.5	1.83	2.9	-
B M2 5 F v5-1.83	190.5	1.83	2.9	0.33
B M2 5 F v6-1.83	190.5	1.83	2.9	0.67
B M2 5 F v7-1.83	190.5	1.83	2.9	1
B M3 2 F v1-1.83	190.5	1.83	3.5	-
B M3 2 F v5-1.83	190.5	1.83	3.5	0.33
B M3 2 F v6-1.83	190.5	1.83	3.5	0.67
B M3 2 F v7-1.83	190.5	1.83	3.5	1
B M4 2 K v1-1.65	211	1.65	1.05	-
B M4 2 K v2-1.65	211	1.65	1.05	0.29
B M4 2 K v3-1.65	211	1.65	1.05	0.59
B M4 2 K v4-1.65	211	1.65	1.05	0.9

Table 3. Details of mixes

Mixture	Cement kg/m ³	Sand kg/m ³	Gravel kg/m ³	SP Kg/m ³	Water L/m ³	Total (cement+SP)	w/p	Dosage of SP (%) by weight of cement
MSCC20	270	780	850	250	187	520	0.35	1.35
MSCC50	500	785	850	85	173	585	0.29	7.5
MSCC60	550	825	850	65	150	615	0.24	8.25
MNC20	300	600	1100		180		0.60	

The physical properties of the ordinary Portland ASTM Type I cement used in this study are shown in Table 4. The fine aggregate utilized was local natural sand with a specific gravity of 2.6, water absorption of 0.75% and a sulfate content of 0.11%. Crushed gravel was used as coarse aggregate; the particles had a maximum size of 10 mm, a specific gravity of

2.6, water absorption of 0.75%, and a sulfate content of 0.061%. A polycarboxylic super plasticizer (SP) was also applied to the SCC mixtures. This plasticizer has a specific gravity of 1.21, a relative density of 1.1, and is known commercially as "GLENIUM51." This SP is free from chlorides and complies with ASTM C494 types A and F.

Table 4 summarizes the fresh properties of the SCC mixtures. The flow capability and flow characteristics of SCC were determined through slump flow [12], and L-Box [13] tests. The index values of slump flow, flow time and L-box satisfied the recommended values for SCC, as indicated in Table 5.

Table 4. Physical properties of cement

Physical properties	Test result
Specific surface area (Blaine Method), m^2/kg	332.9
Setting time (Yicale's method)	
Initial setting, hrs: min	2.0
Final setting, hrs: min	4.1
Compressive strength, MPa	
3 days	16.2
7 days	24.1
Autoclave expansion %	0.24

Both SCC and NC mixtures were mixed in a batch mixer. Tests were conducted on the fresh properties of the SCC mixtures immediately after mixing. The steps of the fresh test are detailed in Figure 2.

The monitoring results showed that SCC filled in the molds properly and effortlessly. Furthermore, the concrete flowed easily

around the reinforcing bars in each reinforcement configuration. The reduced casting time of SCC beams could shorten project construction time as well. The formworks were removed after one day of casting, and specimens were cured in a humidity chamber for approximately 24 days. These specimens were then removed from the chamber three days before testing.



Fig. 2. Schematics of experimental tests for fresh properties of SCC

Table 5. Fresh properties of SCC

Concrete mix	Slump flow		L-box		
	D (mm)	T ₅₀ (sec)	BR%	T ₂₀ (sec)	T ₄₀ (sec)
MSCC 20(A)	660	2.12	0.8	1.2	3.15
MSCC 50(B)	700	4.6	0.88	1.5	3.25
MSCC 60(C)	740	4.97	0.94	2.47	6.41
MNC 20(D)	400				

2.3. Experimental setup, instrumentation, and test observations

The instrumentation for the beam test program included a load cell, strain gauges and a linear variable displacement transducer (LVDT). A load cell with a capacity of 3000 kN was attached to the actuator to measure load, as illustrated in Figure 3.



Fig.3. Universal testing machine used to test the beams

Beam specimens were tested as simply supported beams under a four-point load condition. The schematic of the test setup is displayed in Figure 4. The initiation and development of cracks and cracking loads at various levels were recorded during loading time. The tests also obtained information on the overall behavior of beams, including failure modes and the influence of concrete characteristics. Loading was maintained until the beams failed.

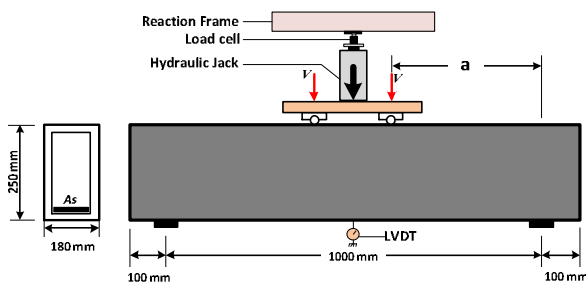


Fig. 4. Schematic diagram of experimental set-up

3. DISCUSSION OF RESULTS

3.1. Failure modes

All 16 beams tested under four-point loading were subject to perfect diagonal shear failure. Figure 5 shows the diagonal crack patterns and failure modes of the tested specimens. The numbers refer to the load at the point when the cracks reached the failure positions.

3.2. Cracking and ultimate shear strength

During loading, vertical flexural cracks were first initiated within the middle third span of all beams. In most cases, several small flexural cracks were observed within the zero shear span. The initial shear crack developed near the neutral axis in the shear span.

Table 6 presents the diagonal cracking loads on beams with and without stirrups, as well as the ultimate loads measured during testing.

Table 6. Details of diagonal cracking and ultimate loads for test beams

Specimens	f_c' MPa	a/d	ρ_w	ρ_v	V_{cr} kN	P_u kN	V_{cr}/P_u
B M1 2 K v1-1.65	19.87	1.89	0.0105	-	70	136	0.51
B M1 2 K v2-1.65	19.87	1.89	0.0105	0.0029	74	144	0.51
B M1 2 K v3-1.65	19.87	1.89	0.0105	0.0059	80	162	0.49
B M1 2 K v4-1.65	19.87	1.89	0.0105	0.009	98	172	0.56
B M2 5 F v1-1.83	49.49	2.09	0.029	-	100	218	0.45
B M2 5 F v5-1.83	49.49	2.09	0.029	0.0033	130	266	0.48
B M2 5 F v6-1.83	49.49	2.09	0.029	0.0067	142	320	0.44
B M2 5 F v7-1.83	49.49	2.09	0.029	0.01	150	336	0.44
B M3 2 F v1-1.83	60.10	2.09	0.035	-	126	222	0.56
B M3 2 F v5-1.83	60.10	2.09	0.035	0.0033	130	290	0.44
B M3 2 F v6-1.83	60.10	2.09	0.035	0.0067	140	340	0.41
B M3 2 F v7-1.83	60.10	2.09	0.035	0.01	146	344	0.42
B M4 2 K v1-1.65	23.21	1.89	0.0105	-	66	162	0.40
B M4 2 K v2-1.65	23.21	1.89	0.0105	0.0029	90	182	0.49
B M4 2 K v3-1.65	23.21	1.89	0.0105	0.0059	112	196	0.57
B M4 2 K v4-1.65	23.21	1.89	0.0105	0.009	118	242	0.49

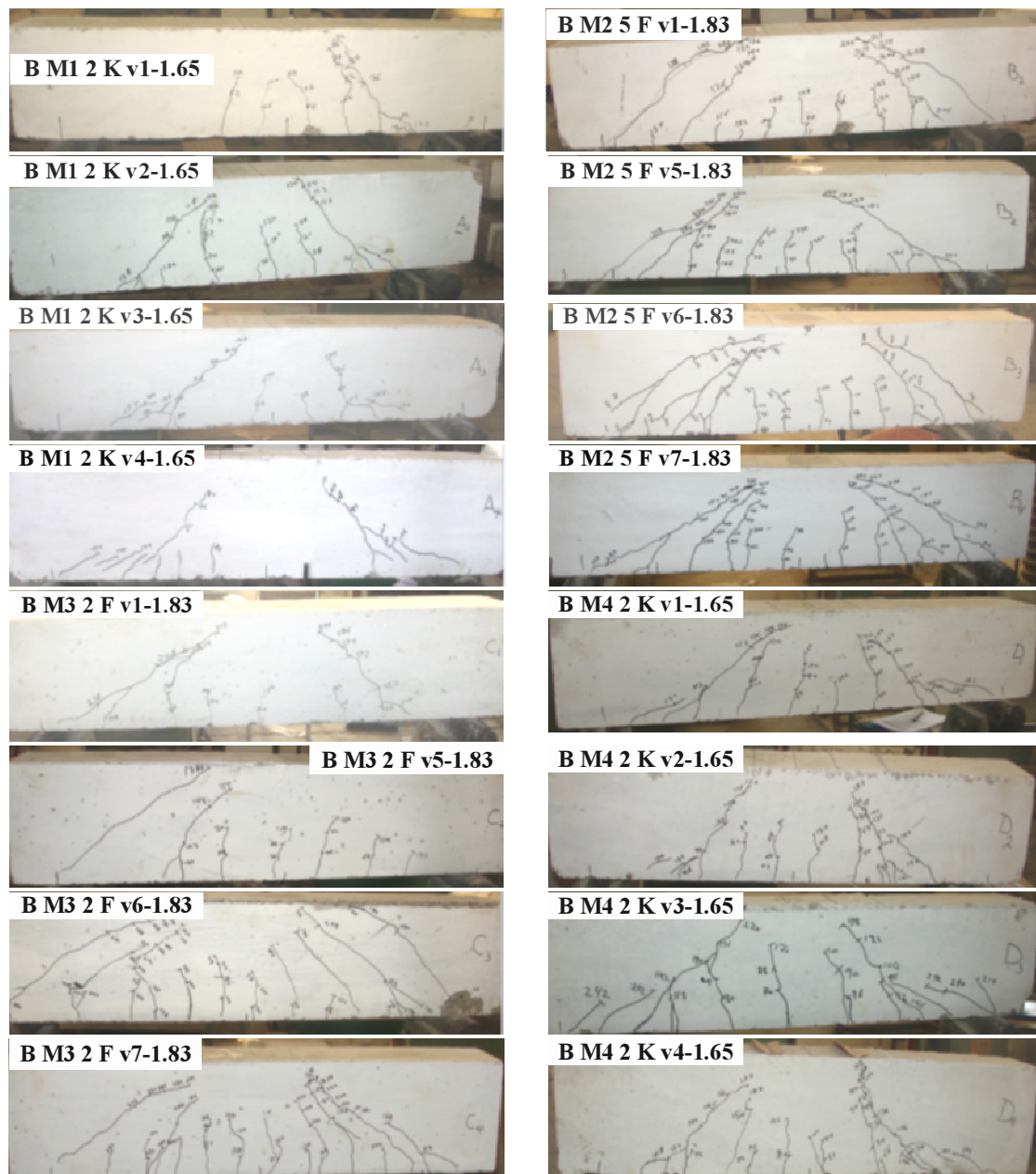


Fig. 5. Crack pattern for SCC beams.

3.3. Load-deflection response

The tested specimens were affixed with LVDTs to observe and record deflection during the test. The deflections of all four groups of beams were measured at the load points and mid-span of the beams using dial gauges for every 2 KN increment in load.

The results show that the deflection at the mid-span of the tested beams decreased with an increase in flexural reinforcement ratio.

No clear trend was observed with respect to overall deflection at failure because this

deflection depends on many parameters, including the flexural and shear reinforcement ratio, concrete compressive strength, and shear span-to-effective depth ratio.

As per the load-deflection curves depicted in Figure 7, all beam specimens exhibited an almost-bilinear response until failure. These specimens displayed similar stiffness up until the growth of the initial flexural crack, which reduced the stiffness in all specimens according to different trends. This variation in trends is ascribed to a difference in reinforcement ratios.

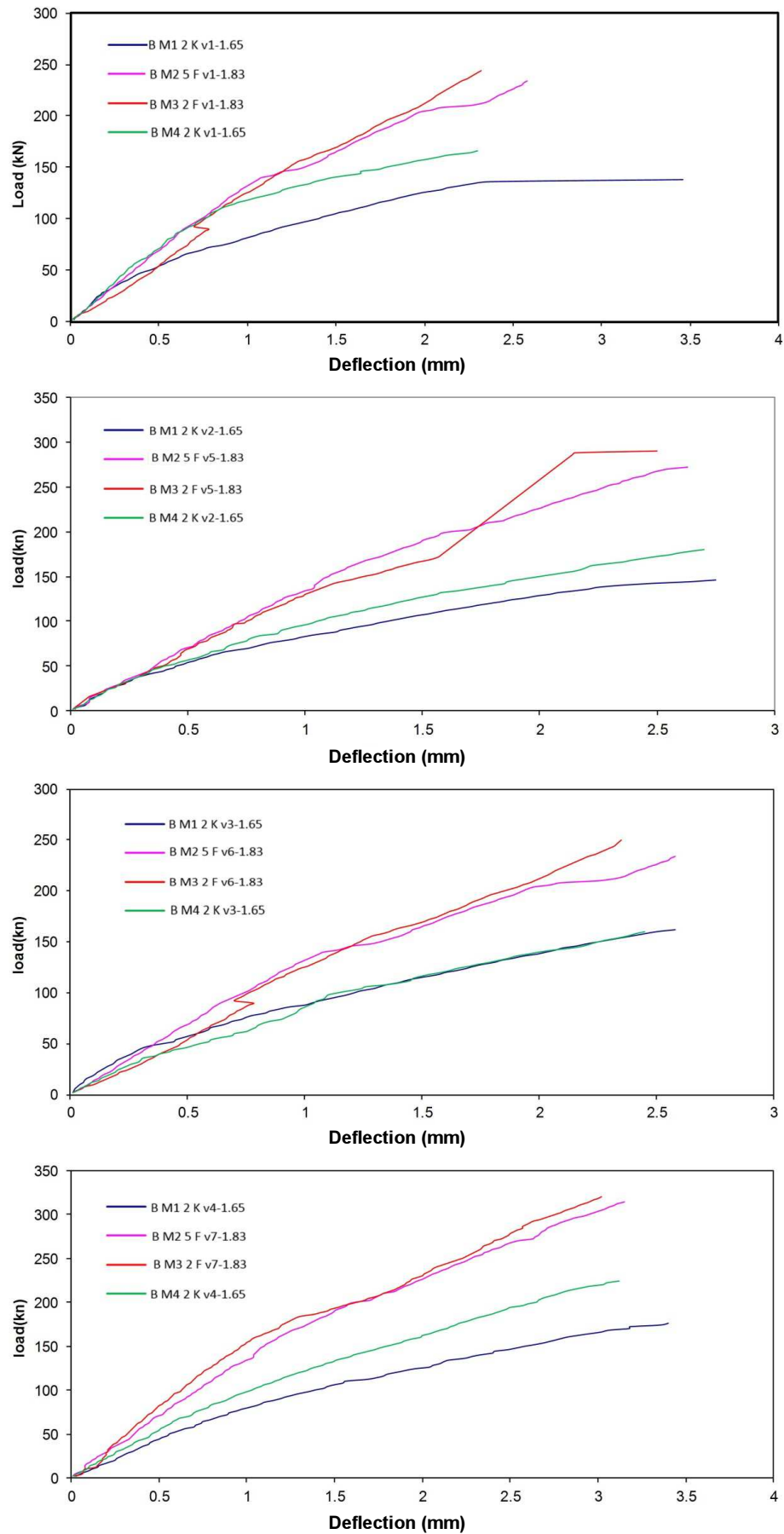


Fig. 6 Load-deflection curves

3.4 Comparison of code provisions

The ratios of experimental shear strength and of those evaluated using ACI, BS, CAN and NZ are compared in all of the tested specimens, as indicated in Table 7 and

Figure 7. Shear strength provisions for SCC beams are conservative, and the relative shear strength values of ACI and BS generate the lowest coefficient of variation values from among all of these references.

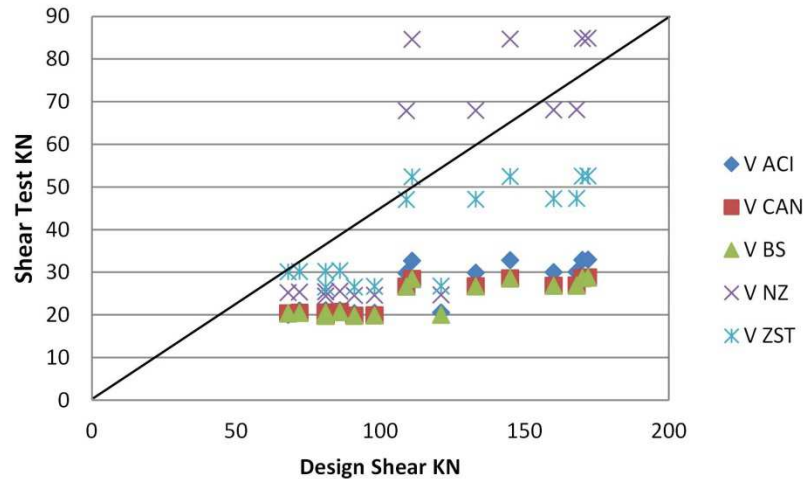


Fig. 7. The relative shear strength of tested SCC beam

Table 7. Comparison between the experimental data from the test results of this study and the predictions of five existing methods

Specimens	V_{test}/V_{ACI}	V_{test}/V_{CAN}	V_{test}/V_{BS}	V_{test}/V_{NZ}	V_{test}/V_{ZST}
B M1 2 K v1-1.65	3.4	3.34	2.38	27	2.26
B M1 2 K v2-1.65	3.44	3.52	2.52	2.84	2.39
B M1 2 K v3-1.65	3.85	3.94	2.82	3.19	2.68
B M1 2 K v4-1.65	4.09	4.17	2.98	3.37	2.84
B M2 5 F v1-1.83	3.66	4.1	2.29	1.61	2.32
B M2 5 F v5-1.83	4.45	4.98	2.79	1.96	2.82
B M2 5 F v6-1.83	5.34	5.97	3.34	2.35	3.39
B M2 5 F v7-1.83	5.59	6.25	3.50	2.47	3.55
B M3 2 F v1-1.83	3.4	3.90	2.09	1.31	2.12
B M3 2 F v5-1.83	4.42	5.08	2.73	1.71	2.77
B M3 2 F v6-1.83	5.17	5.94	3.19	2.01	3.24
B M3 2 F v7-1.83	5.22	5.99	3.23	2.03	3.27
B M4 2 K v1-1.65	3.99	4.11	2.9	3.32	3.06
B M4 2 K v2-1.65	4.47	4.60	3.24	3.71	3.43
B M4 2 K v3-1.65	4.79	4.93	3.48	3.99	3.68
B M4 2 K v4-1.65	5.89	6.06	4.28	4.90	4.53
Mean	4.45	4.81	2.99	2.72	3.02
Standard Deviation	0.82	0.99	0.55	0.98	0.63
Coefficient of Variation	0.18	0.21	0.18	0.36	0.21

4. CONCLUSIONS

A total of 16 SCC beams measuring 180 mm × 250 mm × 1200 mm were constructed and tested under four-point loading until

failure. The studied variables were flexural and shear reinforcement ratio, compressive strength, and shear span-to-effective depth ratio. Experiments were conducted to determine cracking, ultimate load, and

deflection response. Shear strength was also predicted according to the ACI, B.S., CAN and NZ provisions. On the basis of the experimental results and predictions, the following conclusions can be drawn from this research:

- All test specimens experienced brittle failure, and the failure mode was identified as diagonal shear failure.
- The beam specimens exhibited similar stiffness up until the initial flexural crack was initiated. Stiffness was then reduced in all beams at different tendencies according to reinforcement ratio, compressive strength, and shear span-to-depth ratios.
- Compressive strength affected cracking load for initial flexural or shear cracks. Specifically, cracking loads increased by approximately 42% and 60%. This increase strongly influenced the ultimate load capacity of beams.
- The shear strength provisions of ACI and B.S. for SCC beams were less conservative and more appropriate for SCC beams than those of the other references.

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