



# SHEAR PERFORMANCE OF BAMBOO REINFORCED SELF-COMPACTING CONCRETE BEAMS WITHOUT STIRRUPS

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## ABSTRACT

Experimental studies characterizing the structural performance of self-compacting concrete (SCC) are limited and this can be identified as one of the barriers to the widespread use and acceptance. The prime focus of this study is to characterize the behavior of bamboo reinforced SCC beams without stirrups. Twelve SCC and vibrated concrete (VC) beams were tested under four-point loading till ultimate failure. The major variables considered were the beam depth and the level of longitudinal reinforcement. Results indicated that the contribution from dowel action of bamboo to ultimate shear strength may be quite significant, and slightly higher in SCC beams than VC beams. The deformation capacities of tested SCC beams are comparatively higher. Shear provisions from four design standards were considered to evaluate their applicability to bamboo-reinforced self-compacting concrete beams without stirrups. From this limited study, estimated shear capacities from the Canadian standard, CSA-A23.3-14, were found to be conservative. Moreover, in order to achieve a conservative design, shear strength results revealed that a simple reduction factor of 2.5 is appropriate, adequate, and must be applied to the documented shear provisions of the standards being considered herein.

**Keywords:** bamboo, self-compacting concrete, aggregate interlock, dowel action, shear, code-based prediction.

## 1. INTRODUCTION

Effective concrete placement and consolidation are among several factors needed to be taken into consideration for ensuring durability of concrete structures [1–3]. Nevertheless, there is a high reliance on the consolidation technique employed during construction, and to a larger extent, the competence of the personnel involved in casting and placement of concrete. This is typical of conventional concrete construction practices. Nonetheless, the introduction of Self-Compacting Concrete (SCC) technology has allowed for effective concrete placement and consolidation.

SCC was developed in Japan to help reduce the excessive demand for vibrating heavily reinforced and congested sections. In order to facilitate placement with no mechanical consolidation, the concrete matrix is made to maintain a high slump flow value (about 500mm or above) to ensure easy filling ability in formwork, as well as reduced segregation and bleeding [1,4]. Notably economic gains in employing SCC in concrete construction include reduced labour cost, construction time and improved durability. Construction companies and countries have explored the use of SCC in real structures since its inception.

A large number of investigations on the performance of SCC has placed much emphasis on its fresh and hardened properties [2, 5-7]. However, studies characterizing the structural performance of SCC components are limited [8-10]. This has been identified as one of the barriers to the widespread use and acceptance of SCC [2]. Extensive experimental programs that sought to comparatively evaluate the performance of SCC and conventional vibrated concrete (VC), have reported significant difference between performances measures such as shear and ultimate moment capacities [11-13]. Such findings can only be applicable to reinforced concrete beams that use steel as reinforcement.

Bamboo has been shown to be a suitable alternative to conventional longitudinal steel [14-17]. Notable advantages of using bamboo as reinforcement include the reduced self-weight and lower energy demand in production when compared to steel [15, 18]. Even though its tensile strength may not be as high as steel, literature [17, 19] reports that the gain in ultimate moment capacity of VC beam sections reinforced with bamboo can go as far as five times as that of plain un-reinforced VC beam section.

The aim of the current study is to investigate the structural performance of bamboo reinforced SCC and VC beams without transverse reinforcements. Practically, engineers make provisions for at least minimum transverse reinforcement when designing RC beams. However, accurate estimation of the shear strength of concrete pre-informs the designer on the additional amount of transverse reinforcement required to counteract the expected internal shear forces to be resisted. Therefore, focusing on these members will be of interest to practicing engineers who wish to use bamboo reinforced SCC and VC beams in designing concrete structures. Conclusions from this work will help bridge the knowledge gap that exists in allowing the widespread acceptance of SCC in concrete construction, as well as its application to bamboo reinforced structures. In addition, the appropriateness of design shear provisions (ACI 318-R11, CSA A23.3-14, BS 8110-97 and EC2-2004) that were mainly developed using conventional vibrated concrete is also evaluated.

## 2. EXPERIMENTAL PROGRAM

A total of 12 bamboo reinforced concrete beams (six made from an SCC mix and the rest from VC mix) were cast and subjected to a four-point bending test. In order to ensure a shear failure mode, the shear-span to depth ratio was kept at 1.8 for all test specimens. The major variables considered were the cross-sectional height



of beams (150mm, 250mm and 275mm), the percentage of longitudinal reinforcement (1.5% and 3%) and the concrete type (SCC or VC) (see Table-1). The tested beams were coded using their percentages of longitudinal reinforcement, concrete type and beam height sequentially

as shown in the first column of Table-1. For instance, 3.0VC275 denotes a vibrated concrete (VC) beam with 3.0% bamboo longitudinal reinforcement and with a total cross-sectional height of 275mm.

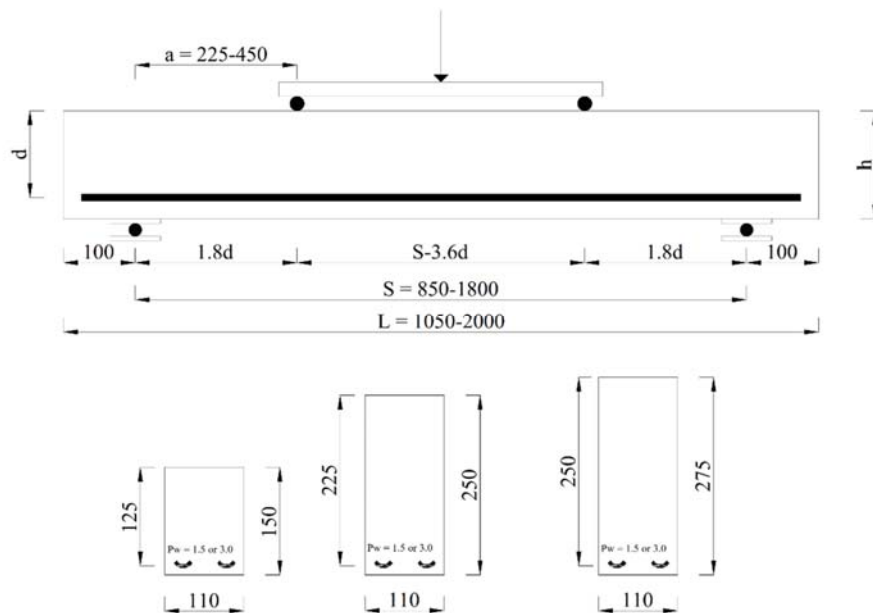
**Table-1.** Test matrix.

Beam reference	Height (mm)	Effective depth (mm)	Length (mm)	Effective span (mm)	Reinforcement ratio (%)	Compressive strength
1.5SCC150	150	125	1050	850	1.5	26.45
1.5VC150	150	125	1050	850	1.5	32.65
3.0SCC150	150	125	1050	850	3	26.45
3.0VC150	150	125	1050	850	3	32.65
1.5SCC250	250	225	1200	1000	1.5	26.45
1.5VC250	250	225	1200	1000	1.5	32.65
3.0SCC250	250	225	1200	1000	3	26.45
3.0VC250	250	225	1200	1000	3	32.65
1.5SCC275	275	250	2000	1800	1.5	26.45
1.5VC275	275	250	2000	1800	1.5	32.65
3.0SCC275	275	250	2000	1800	3	26.45
3.0VC275	275	250	2000	1800	3	32.65

Ordinary Portland cement of Grade 42.5 was used for all design mixes with a target 28-day average compressive strength of about 30MPa. River sand and granite aggregate with maximum size of 20mm was obtained and used for casting test specimens. Even though the relative proportions of fine and coarse aggregate were varied for the two concrete types (SCC and VC), the cement to total aggregate ratio of 1:4.5 was kept constant. The coarse to fine aggregate ratio was also kept at 200% and 66% for VC mix (1:1.5:3) and SCC mix (1:2.8:1.7) respectively. In order to ensure high fluidity (a requirement to allow for easy flow under its self-weight) in the concrete matrix of the SCC mix, super plasticizers were obtained locally and used for the experimental program. Three concrete cubes of dimensions 150mmx150mmx150mm were also casted and cured with portable water, alongside each beam to obtain compressive strength that is representative of the beams in each batch. The flexural strength of concrete was also obtained from companion unreinforced concrete prisms (modulus of rupture of beams) having a squared cross section of 100mmx100mm and total length of 500mm. Also three bamboo strips having average dimension of 300mm x 25mm x 4mm were procured for tensile test. For this particular bamboo specimen (*Bambusa Vulgaris*), the

average tensile strength and modulus of elasticity were 126.72MPa and 16.75GPa respectively. Standard deviations of tensile strength and elastic modulus were 7MPa and 2GPa for tested bamboo strips respectively. It is worth noting that even though the mechanical properties of bamboo is highly dependent on several factors, such as relative humidity, available moisture content and ambient temperature, a major determinant could be the age of the specimens procured for testing. Hence, it was imperative to give consideration to specimens that are between three to five years of age [20]. The treated (bituminous material with sand coating of thickness about 3-5mm) bamboo samples were used as main longitudinal reinforcement bars, placed at a distance of 25mm from the extreme fibres in the tension zone of tested beams. It is worth noting that no specific treatment was made to the joints of these bamboo strips. Bamboo strips had an average cross-section of 15mm x 10 mm.

The loading protocol consisted of incrementally applying a monotonic load of 2KN/min till ultimate failure is observed for each beam. An I-section steel spreader was placed on top of each beam, and with the help of two roller supports, these monotonically increasing loads were transmitted, as schematically presented in Figure-1.



**Figure-1.** Schematic diagram of experimental test setup.

The loads at first flexural cracking, first diagonal cracking and ultimate failure were recorded along with their respective mid-span deflections measured with a dial gauge beneath the soffit of the beam under test. The

maximum crack width and crack height were also taken, and crack patterns were marked on tested beams during loading. A typical diagram of the instrumented test setup after loading to failure is presented in Figure-2.



**Figure-2.** Experimental setup, loading and instrumentation protocol.

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Load-deflection behaviour

The load-deflection time history throughout testing for the various test specimens investigated is presented in Figure-3 below. These curves are quite similar for pairs of VC and SCC beams. It is evident from Figure-3 that the mid span deflections of SCC beams are greater than their corresponding VC counterparts irrespective of the influence of beam depth and percentage of bamboo longitudinal reinforcement ( $\rho_w$ ). Owing to the

fact that the modulus of elasticity of SCC is lower than VC [21, 22], one would expect slightly higher deflections in SCC beams than VC beams. The ultimate load carrying capacities for VC beams were slightly higher than their SCC counterpart, with a maximum absolute difference, greatest in the pair with 3%  $\rho_w$  and of beam depth of 275mm (3.0SCC275 and 3.0VC275). This can be mainly attributed to the variation in the compressive strength of the VC and SCC mixes (Table-1). The experimental loads at first flexural cracking, diagonal cracking and ultimate failure are also presented in Table-2.

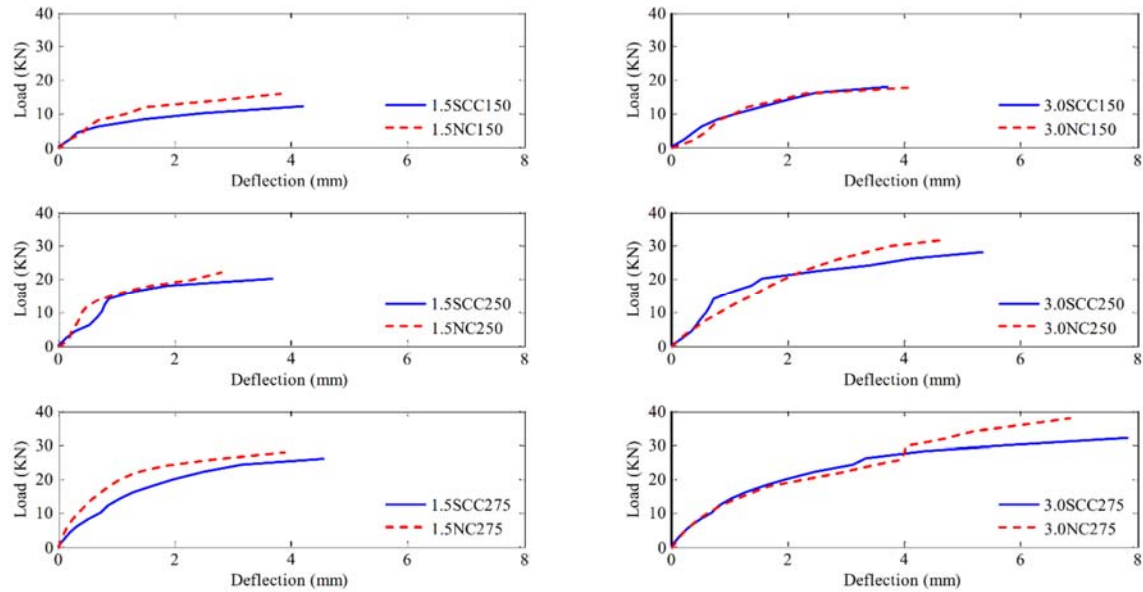


Figure-3. Load-deflection behaviour.

Table-2. Experimental response.

Beam reference	Load, deflection and energy characteristics						
	First flexural crack		First diagonal crack		Ultimate failure		
	$P_f$	$\Delta_f$	$P_d$	$\Delta_d$	$P_{ult}$	$\Delta_{ult}$	$E_{ult}$
1.5SCC150	8	1.50	10	2.49	12	4.22	36.34
1.5VC150	10	1.14	12	1.5	16	3.80	43.23
3.0SCC150	10	1.16	14	2.00	18	3.73	45.33
3.0VC150	14	1.80	16	2.28	18	4.05	51.74
1.5SCC250	14	0.89	18	1.90	20	3.70	56.20
1.5VC250	16	1.10	20	2.30	22	2.80	43.71
3.0SCC250	18	1.40	22	2.49	28	5.36	109.61
3.0VC250	20	1.92	26	2.86	32	4.67	96.43
1.5SCC275	20	2.01	24	3.16	26	4.58	85.80
1.5VC275	24	1.83	26	2.65	28	3.88	84.49
3.0SCC275	24	3.13	28	4.35	32	7.85	188.06
3.0VC275	28	4.00	34	5.18	38	6.84	167.52

$P_f$  = first flexural crack load (kN);  $P_d$  = first diagonal crack load (kN);  $P_{ult}$  = ultimate load (kN);  $\Delta_f$  = first flexural crack deflection (mm);  $\Delta_d$  = first diagonal crack deflection (mm);  $\Delta_{ult}$  = ultimate deflection (mm);  $E_{ult}$  = total energy absorbed (Nmm)

In evaluating the energy absorption capacity among each pair of beams (either SCC or VC with a particular beam depth and percentage reinforcement), it is observed from Table-2 and Figure-3 that the influence of beam depth and percentage of longitudinal reinforcement is found to be appreciably significant. Owing to the comparatively larger deformations in SCC beams (Figure-3), the rise in energy dissipation capacity of tested beams when the beam depth was increased from 150mm to

275mm, is significantly above VC beams, with a difference of about 41% for test specimens with 1.5%  $\rho_w$  and 91% for those with 3.0%  $\rho_w$ .

### 3.2 Post-cracking behaviour

The major shear resisting mechanisms in reinforced concrete beams without transverse reinforcement is widely governed by aggregate interlock,



dowel action of tensile reinforcement and contribution across the compression zone of the member [23]. An extensive evaluation of the independent contribution from these mechanisms has been performed [24] for conventional reinforced concrete members, of which 50-75% of their ultimate shear strength can be attributed to the combined effect of dowel action and aggregate interlock [25]. This range of values suggest that when adequate bond strength is maintained (adequate frictional force to sustain the dowel action) and the interlocking effect of aggregate on opposite sides of the crack becomes effective, the applied forces can be adequately resisted after the initiation of diagonal cracks. In order to assess the post-cracking shear behaviour of tested specimens, two normalized quantities, defined as  $P_{ult}/P_d$  and  $\Delta_{ult}/\Delta_d$  as presented in Table-3 are employed. These ratios reflect the additional gain in strength and deformation after the formation of diagonal shear cracks.

From Table-3, it is observed that there is a minimal resistance to shear strength after diagonal cracking ( $P_{ult}/P_d$ ), ranges from 108% to 129% and 108% to 133% for SCC and VC beams respectively. The post diagonal cracking resistance ( $P_{ult}/P_d$ ) reduced from 120%

to 108% as the beam depth was increased from 150mm to 275mm for SCC beams with  $\rho_w$  of 1.5%, and 129% to 114% for those with  $\rho_w$  of 3.0% accordingly. A similar observation was found for VC beams with  $\rho_w$  at 1.5% ( $P_{ult}/P_d$  reducing from 133% to 108% as beam depth increased), but inconclusive for those VC test specimens with 3.0%  $\rho_w$ . Irrespective of longitudinal reinforcement ratio and beam depth,  $P_{ult}/P_d$  for SCC were slighter higher than their VC counterpart (see Table-3). From the observation made in the current research work, it could be suggested that the theoretical assertion of loss of aggregate interlock capacity in SCC beams (Hossain, & Lachemi, 2008b, 2010a; Lachemi, Hossain, & Lambros, 2005), may be counteracted by an enhanced SCC matrix quality that ensures a much improved interfacial transition zone. A similar work was made by others who worked on SCC and VC beams [12]. Nevertheless, the contribution of dowel action to shear resistance from bamboo reinforcement, particularly in tested SCC beams, increased the post diagonal cracking shear resistance ( $P_{ult}/P_d$ ) to about 10.33% on the average, when the percentage of bamboo reinforcement was increased from 1.5% to 3.0% (see Table-3).

**Table-3.** Shear strength characteristics.

Beam reference	$P_d$	$\Delta_d$	$P_{ult}$	$\Delta_{ult}$	$P_{ult}/P_d$	$\Delta_{ult}/\Delta_d$
1.SCC150	10	2.49	12	4.22	1.20	1.69
1.5VC150	12	1.5	16	3.8	1.33	2.53
3.0SCC150	14	2	18	3.73	1.29	1.87
3.0VC150	16	2.28	18	4.05	1.13	1.78
1.SCC250	18	1.9	20	3.7	1.11	1.95
1.5VC250	20	2.3	22	2.8	1.10	1.22
3.0SCC250	22	2.49	28	5.36	1.27	2.15
3.0VC250	26	2.86	32	4.67	1.23	1.63
1.SCC275	24	3.16	26	4.58	1.08	1.45
1.5VC275	26	2.65	28	3.88	1.08	1.46
3.0SCC275	28	4.35	32	7.85	1.14	1.80
3.0VC275	34	5.18	38	6.84	1.12	1.32

$P_d$  = first diagonal crack load (kN);  $P_{ult}$  = ultimate load (kN);  $\Delta_d$  = first diagonal crack deflection (mm);  $\Delta_{ult}$  = ultimate deflection (mm)

In terms of post-cracking shear ductility,  $\Delta_{ult}/\Delta_d$ , the SCC beams ranged from 154% to 215% and 122% to 253% in VC beams, regardless of the influence of beam depth and amount of longitudinal reinforcement. Considering the effect of longitudinal reinforcement on post cracking shear ductility, there was a 15% increase when  $\rho_w$  was increased from 1.5% to 3.0% in tested SCC beams. Same cannot be said for VC beams, as Table-3 shows a remarkable decrease in  $\Delta_{ult}/\Delta_d$  when  $\rho_w$  increased from 1.5% to 3.0% (1.5VC150-3.0VC150 and 1.5VC275-3.0VC275 pairs). A physical reason for this observation

may be partly attributed to the anticipated and slightly higher modulus of elasticity of VC, and the fact the overall VC beam section may be over-reinforced at that level of bamboo reinforcement. This trend shows the role and contribution of SCC in maintaining adequate ductility when the amount of bamboo reinforcement is increased in shear critical beams. At the other end, there is the need for effective treatment of bamboo strips in order to make their water absorption capacity as minimal as possible; in traditional construction practices which uses vibrated concrete (VC).

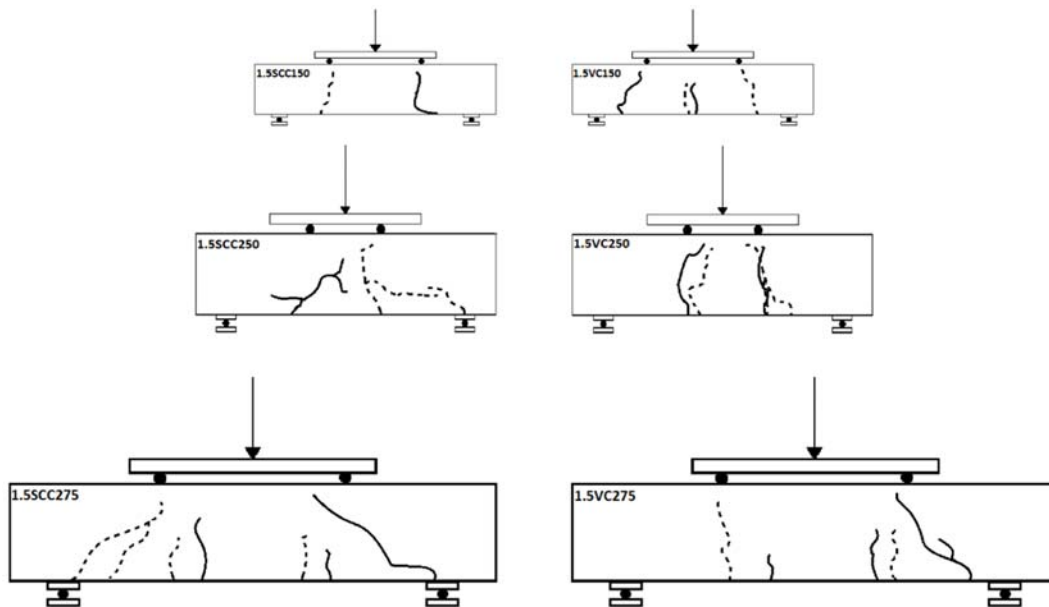




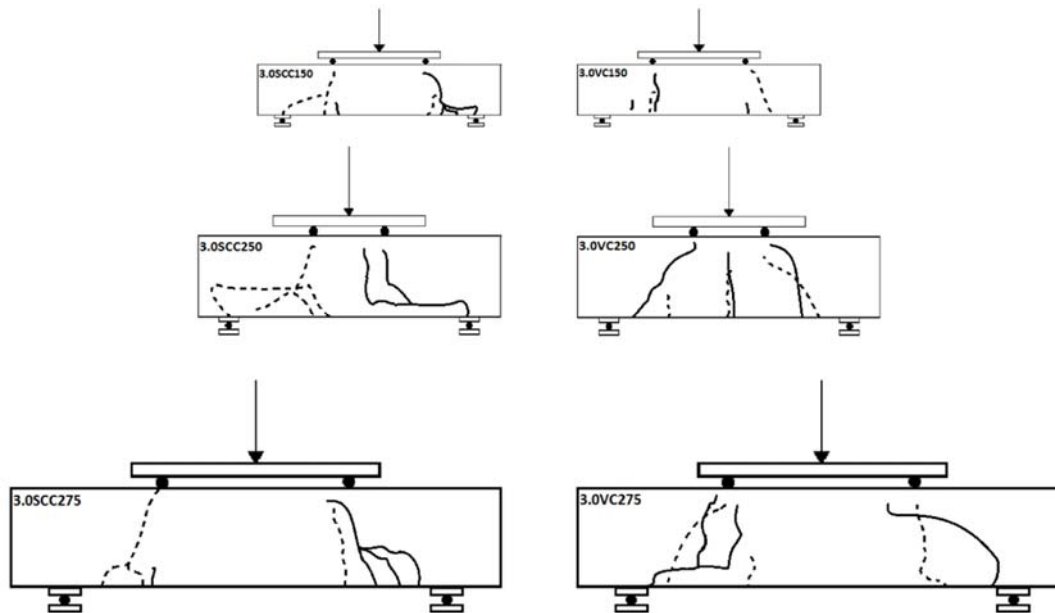
#### 4. FAILURE CRACKING BEHAVIOUR

The crack patterns at failure of tested beams with 1.5% and 3.0% bamboo reinforcement are shown in Figures 4 and 5 below. The maximum crack width, height and number of cracks present at ultimate failure are discussed. During loading, flexural cracks initially appeared primarily within the middle region of the beam's span with first crack loads averaging 70% of the loads corresponding to ultimate failure. Upon further loading, formation of diagonal shear cracks which were seen to be directed towards the loading point, appeared at loads of about 86% of that at ultimate failure, averagely. In some cases, the bond failure resulted in the formation of secondary crack which normally preceded the initiation of diagonal cracks. Even though the test specimens were designed to fail in shear, Table-4 outlines the observed

failure mode. Cracks that fell within the shear span, inclined and beginning at the support, were predominantly considered as diagonal shear cracks, whereas those that fell the middle-third of the beam's effective length were considered as flexural cracks. Generally the maximum crack width for beams with higher reinforcement is expected to be lesser than those with lower reinforcements [29]. However as seen in Table-4, this may not hold for bamboo reinforced concrete beams. Nevertheless, the maximum crack width is highly positively correlated with beam depth (see Table-4). This adversely affects the ultimate shear strength of beams since the aggregate interlock capacity is weakened [29] and may have been one of the reasons for the small post cracking shear resistance as discussed in Section 3.2.



**Figure-4.** Crack patterns for beams with 1.5% bamboo reinforcement (solid line for front view and hidden line for back view)



**Figure-5.** Crack patterns for beams with 3.0% bamboo reinforcement (solid line for front view and hidden line for back view)

**Table-4.** Cracking behaviour.

Beam reference	Crack features at ultimate failure			Failure mode
	Width (mm)	Height (mm)	Number	
1.5SCC150	0.2	125	3	Flexure
1.5VC150	0.2	138	4	Flexure-Shear
3.0SCC150	0.3	127	6	Bond Failure
3.0VC150	0.2	122	5	Shear Failure
1.5SCC250	0.4	212	4	Bond Failure
1.5VC250	0.2	215	4	Flexure-Shear
3.0SCC250	0.3	205	5	Bond Failure
3.0VC250	0.2	221	6	Shear
1.5SCC275	0.5	268	6	Shear
1.5VC275	0.5	255	7	Shear
3.0SCC275	0.5	270	7	Bond Failure
3.0VC275	0.5	255	7	Bond Failure

## 5. THEORETICAL FORMULATION OF CODE-BASED SHEAR STRENGTH PREDICTION

Reliable quantification of the shear strength of structural components has ever since been a crucial task, due to the inadequate identification of all influential parameters which results in shear transfer, and the fact that the design of experimental studies are unable to account for all these parameters simultaneously [30, 31]. Notable approaches recommended for design purposes are either based on Richter-Morsh truss analogy [32-35] or fracture mechanics [36, 37] formulations. The evaluation of the application of current code-compliant predictive models

for the estimation of bamboo reinforced concrete beams is presented below.

The shear capacity of reinforced concrete structural members without transverse reinforcement, as per the British Standard BS 8110 [33] can be computed as;

$$V_{u-BS8110} = \left[ \frac{0.79 \left( \frac{100A_b}{bd} \right)^{\frac{1}{3}} \left( \frac{400}{d} \right)^{\frac{1}{4}} \left( \frac{f_c}{25} \right)^{\frac{1}{3}}}{1.25} \right] bd \quad (1)$$



where  $V_{u-BSS110}$  is the ultimate shear capacity;  $b$  is the breadth of the member's cross section,  $d$  is the effective depth of the member's cross section,  $A_b$  is the area of longitudinal reinforcement,  $f_c$  is the characteristic cube strength of concrete.

According to European Standards, Eurocode 2 [32] provides estimate of the nominal ultimate shear capacity as;

$$V_{u-EC2} = 0.18 \left[ \left( 1 + \sqrt{\frac{200}{d}} \right) \left( 100 \cdot \frac{A_b}{bd} \cdot f_c' \right)^{\frac{1}{3}} \right] bd \quad (2)$$

where  $V_{u-EC2}$  is the ultimate shear capacity as per EC2;  $b$  is the breadth of the member's cross section,  $d$  is the effective depth of the member's cross section,  $A_b$  is the area of longitudinal reinforcement,  $f_c'$  is the cylinder compressive strength of concrete (assumed to 80% of the cube strength).

Canadian Standards [34] estimate the nominal concrete shear strength of structural members without stirrups using the generalised method (CSA 11.3.6.4) as;

$$V_{u-CSA} = \left[ \left( \frac{0.4}{(1+1500\varepsilon_x)} \right) \left( \frac{1300}{1000+S_{ze}} \right) \sqrt{f_c'} \right] bd_v \quad (3.1)$$

$$\varepsilon_x = \frac{M_f/d_v + V_f}{2(E_s A_s)} \quad (3.2)$$

$$S_{ze} = \frac{35S_z}{15+a_g} \geq 0.85S_z \quad (3.3)$$

where  $V_{u-CSA}$  is the shear capacity;  $b$  is the breadth of the member cross section;  $d_v$  is the effective shear depth (the greater of either 90% of the effective depth or 72% of the beam height);  $\varepsilon_x$  is the longitudinal strain, derived with  $M_f$  and  $V_f$  as factored moment and shear loads respectively,  $E_s$  as the modulus of elasticity of the provided longitudinal reinforcement and  $A_s$  as the cross

sectional area of provided longitudinal reinforcement;  $S_{ze}$  is the equivalent crack spacing parameter, with  $a_g$  as the maximum nominal aggregate size and  $S_z$  is conservatively taken as  $d_v$ ;  $f_c'$  is the specified compressive strength.

Finally, as per American Standards, ACI 318-R11 [35] provides an estimate for the nominal shear capacity for structural members without transverse reinforcement as;

$$V_{u-ACI} = \left[ \lambda \sqrt{f_c'} + 120 \left( \frac{A_b}{bd} \right) \left( \frac{V_f d}{M_f} \right) \right] \frac{bd}{7} \quad (4)$$

where  $V_{u-ACI}$  is the corresponding nominal shear capacity;  $\lambda$  accounts for the effect of lightweight concrete on shear strength;  $M_f$  and  $V_f$  as factored moment and shear loads respectively;  $b$  is the breadth of the member's cross section,  $d$  is the effective depth of the member's cross section,  $A_b$  is the area of longitudinal reinforcement,  $f_c'$  is the cylindrical compressive strength of concrete.

A review of the four design codes considered reveals the importance of the influence of compressive strength on shear capacity of reinforced concrete members. However, explicit consideration of the effect of the shear-span to depth ratio, a dominant influential parameter [29], is implicitly accounted for in both Canadian and American Standards through the use of the factored loads in their mathematical representation. More so, the generalised method of the Canadian Standard provides a means of quantifying the modulus of elasticity of the reinforcing bar.

### 5.1 Comparison between experimental and predicted responses

Table-5 presents the experimental and predicted ultimate shear loads among the tested beams for the four design codes considered above. The ratios, that is, experimental to predicted loads, are also computed for comparison. Figure-6 also seeks to investigate the correlation between experimental and predicted estimates, and how these values are affected by beam depth and percentages of longitudinal reinforcement for four identified categories.



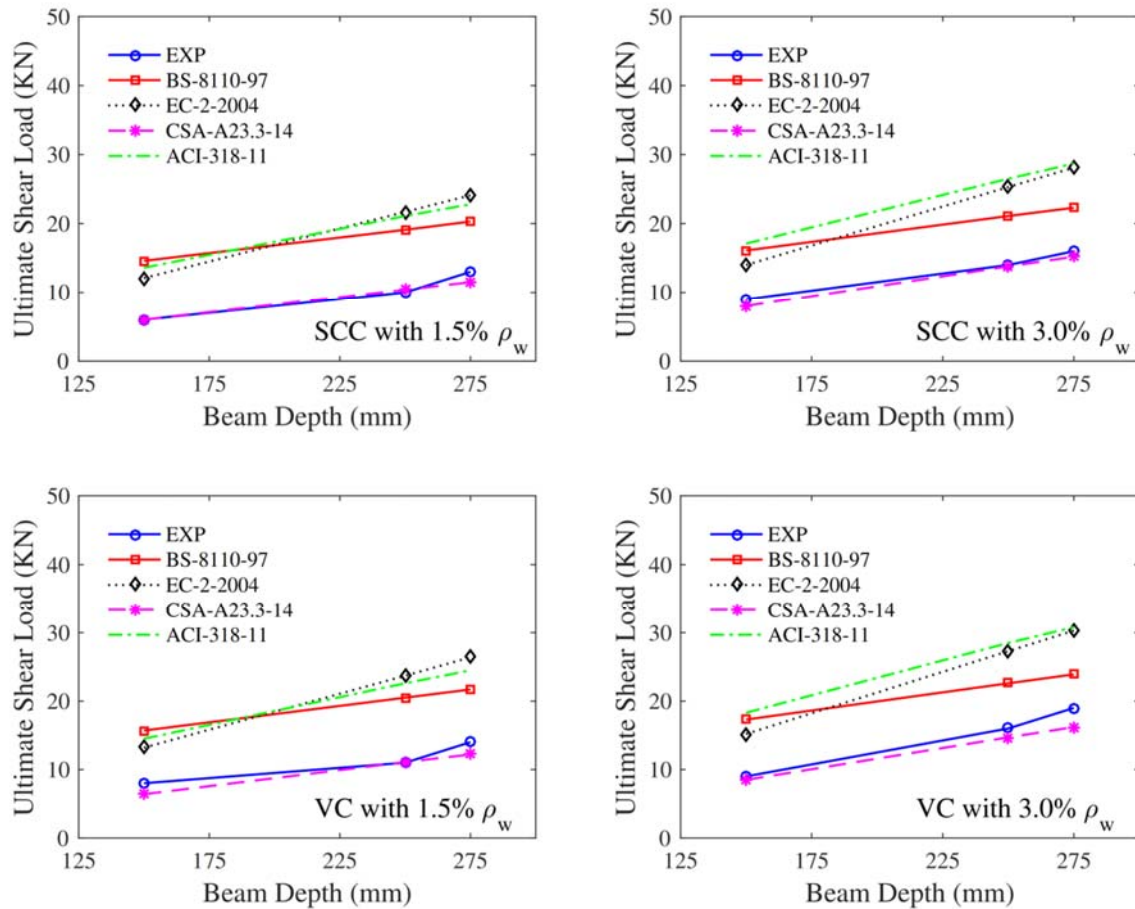


Figure-6. Parametric correlation between experimental and predicted shear loads.

Table-5. Design code- based shear performance.

Beam reference	Ultimate shear load (KN)					Comparison (ratio)			
	EXP	BS	EC	CSA	ACI	BS/EXP	EC/EXP	CSA/EXP	BS/EXP
1.5SCC150	6	14.6	12.1	6.0	13.6	2.44	2.01	1.01	2.26
1.5VC150	8	15.7	13.2	6.4	14.5	1.96	1.65	0.80	1.82
3.0SCC150	9	16.1	14.0	8.0	17.1	1.79	1.56	0.89	1.9
3.0VC150	9	17.3	15.2	8.5	18.3	1.92	1.68	0.95	2.04
1.5SCC250	10	19.1	21.7	10.4	21.1	1.91	2.17	1.04	2.11
1.5VC250	11	20.5	23.7	11.1	22.6	1.87	2.16	1.01	2.05
3.0SCC250	14	21.1	25.3	13.8	26.5	1.50	1.80	0.98	1.9
3.0VC250	16	22.6	27.3	14.7	28.5	1.41	1.70	0.92	1.78
1.5SCC275	13	20.3	24.1	11.5	22.8	1.56	1.86	0.88	1.75
1.5VC275	14	21.7	26.4	12.2	24.5	1.55	1.88	0.87	1.75
3.0SCC275	16	22.3	28.1	15.2	28.7	1.39	1.75	0.95	1.8
3.0VC275	19	23.9	30.3	16.2	30.8	1.26	1.60	0.85	1.62

As seen in Figure-6, the Canadian Standard, [34] produced ultimate shear load estimates that were closest to observed experimental values, irrespective of the influence

of beams depth, concrete type and percentage of bamboo longitudinal reinforcement. However, their predicted values seem to slightly underestimate the true shear



strength, noticeably, for VC beams than SCC beams. This implies that the, CSA-A23.3-14 may be appropriate for design of bamboo reinforced beams. The other design codes (BS-8110-97, EC-2-2004 and ACI-318-11) provided estimates that were significantly above the experimental values (Figure-6). However, it becomes evident from Figure-6 that, EC-2-2004 approximates the experimental shear load with a decrease in beam depth. Contrary, for BS-8110-97, the ultimate shear strength of bamboo reinforced concrete beams without shear reinforcement can efficiently approximate the true strength, as the beam depth increase. The strength of this prediction (BS-8110-97), seemed to be stronger in beams with higher bamboo reinforcement ( $\rho_w$  of 3.0%) (see

Figure-6). It is recommended that large-scale tests be performed for validation of these assertions. Generally, ACI-318-11 overestimated the ultimate shear load, and the impact of beams depth on predicted values was insignificant.

At an aggregated level, Figure-7 evaluates the relative comparison of predicted and experimental shear load for the four design codes. The predicted estimates ( $y$ ) are shown on the y-axis (ordinates) and observed experimental responses ( $x$ ) on the x-axis. The mean value of  $y/x$  and its corresponding coefficient of variation, COV, (ratio of standard deviation to mean) are reported accordingly, for the four design codes considered.

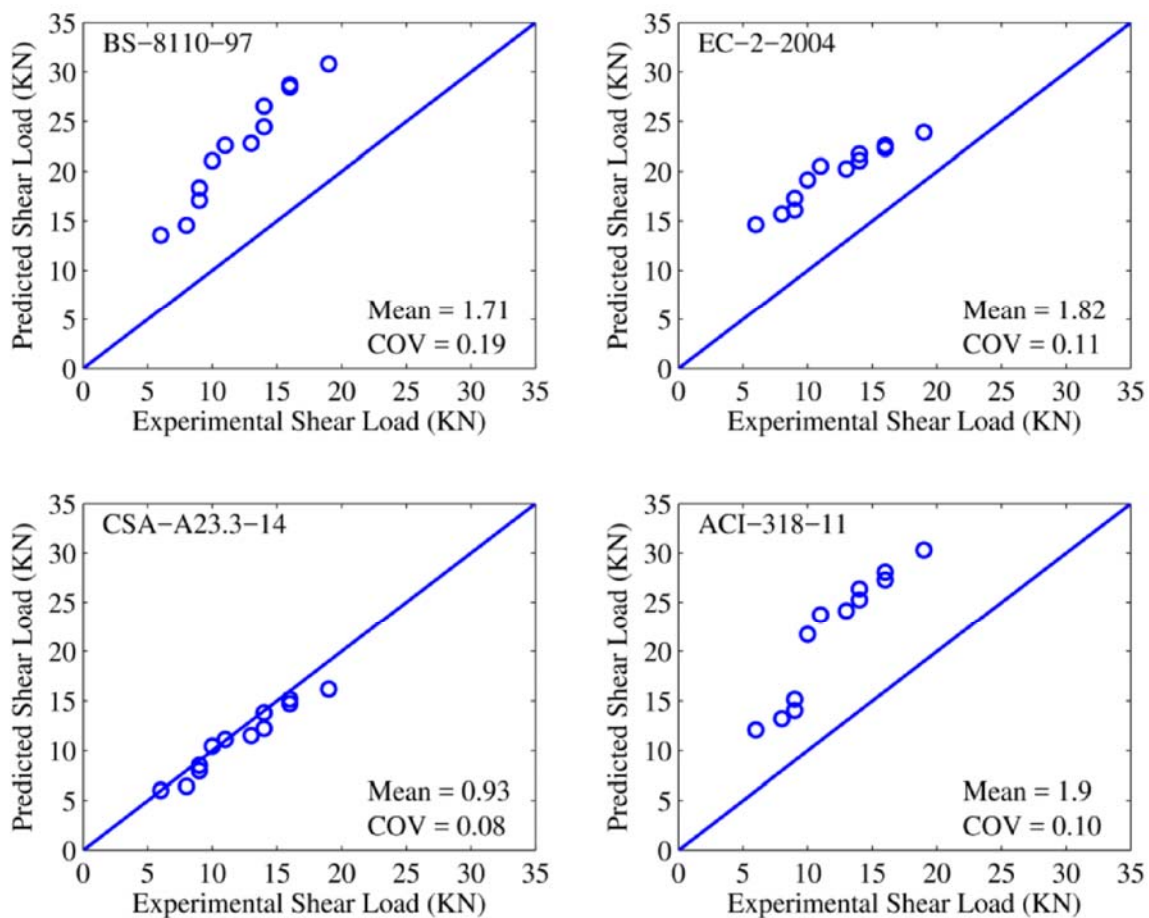


Figure-7. Code-base shear performance of tested beams.

As indicated in Figure-7, CSA-A23.3-14 is slightly conservative in estimating the shear strength of bamboo reinforced concrete beams without shear reinforcement, with mean of 0.93 and a COV of 0.08. The actual values of  $y/x$  ranged from 0.80-1.04, and hence can be safely used for estimation of their shear strengths. The other three design codes were un-conservative in quantifying the shear strength of bamboo reinforced concrete beams. The relatively lower uncertainty for CSA

shear provision can be due to the fact that it explicitly accounts for maximum aggregate size in the concrete matrix, as well as the modulus of elasticity of the longitudinal reinforcement. This is highly advantageous, particularly in reference to the bamboo reinforcement, since most of the shear provisions in various standards were obtained either empirically or analytically from large databases of steel reinforced conventionally vibrated concrete beams.



## 6. CONCLUSIONS

Characterization of the behaviour of bamboo reinforced self-compacting concrete beams without stirrups is performed. A total of 12 beams without transverse reinforcement; six of them from an SCC mix with coarse to fine aggregate ratio of 66% and the remaining from an VC mix. The major variables investigated were the beam depth (150-275mm) and the percentage of longitudinal reinforcement (1.5% and 3.0%). Discussions on the crack patterns, the post cracking shear resistance, load-deformation response envelopes and evaluation of the application of existing code-based shear predictive equations, were drawn. After a comprehensive assessment and evaluation of the results, the following conclusions are made.

- The deformation capacity of bamboo reinforced SCC beams is higher than VC beams, with comparable amount of bamboo reinforcement. This results in a larger amount of dissipated energy (load-deflection curve) for SCC beams, which is largely dependent on the amount of bamboo reinforcement present.
- The contribution from dowel action of bamboo reinforcement and surrounding concrete to ultimate shear capacity may be quite significant, and slightly higher in SCC beams than VC beams. Improvement in the post diagonal cracking shear resistance, were evident in tested SCC beams, when the amount of longitudinal reinforcement increased from 1.5% to 3.0% (10.3% increase on the average).
- The post-diagonal cracking shear resistance, particularly in SCC beams, is strongly influenced by beam depth. The resistance to shear failure beyond the formation of diagonal crack reduces as the beam depth increases (13% decline on average when beam depth was increased from 150mm to 275mm).
- The generalised methods for estimating shear strength of RC beams in the Canadian standard, CSA-A23.3-14, is seen to be reliable and suitable for application to bamboo reinforced self-compacted and vibrated concrete beams. On the other hand, BS-8110-97, EC-2-2004 and ACI-318-11 shear prediction equations are un-conservative and would require a strength reduction of about 2.25, 2.15 and 2.21 respectively. For a holistic assessment, a simple reduction factor of 2.5 is recommended for design of such members in reference to the four design standards considered herein. However, from this limited study which suggests that the difference between SCC and VC beams may not be significant, further experimental studies should be carried out to improve upon the estimated reduction factors recommended herein.

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