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## CIVIL ENGINEERING | RESEARCH ARTICLE

# Bamboo reinforced self-compacting concrete one-way slabs for sustainable construction in rural areas

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**Abstract:** The paper presents an experimental study on the structural performance of the combined application of bamboo and self-compacting concrete (SCC) in the construction of reinforced concrete slabs, with the primary aim of helping to maintain a sustainable construction sector, particularly in developing region and rural localities. A total of 12 specimens were cast; six each of a normal concrete (NC) matrix and SCC were subjected to four-point bending test under monotonic action. The major design parameter was the percentage of bamboo reinforcing bars. Two specimens were made to have the same percentage of longitudinal reinforcement, that is, either 1%, 2% or 3%. Results indicated that the post-cracking stiffness of bamboo reinforced SCC slabs is lower than NC slabs. Moreover, varying the percentage of bamboo reinforcement from 1% to 3% in SCC slabs can double the corresponding increase in load and flexural deformation capacities. Finally, in the absence of any blind prediction, and for this limited study, the reliability of available partial factor of safeties for bamboo, should be

### ABOUT THE AUTHORS

Mark Adom-Asamoah obtained his PhD in Civil Engineering from Bristol University. He is a lecturer and the Provost of the College of Engineering, KNUST. His research evolves around performance-based earthquake engineering, reinforced concrete structures and several applications of finite element method in engineering.

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### PUBLIC INTEREST STATEMENT

The present study investigates the adequacy of bamboo as tensile reinforcement in Self-Compacting Concrete One-Way slabs. In a broader sense, it is envisioned by the authors that the use of bamboo may improve the sustainability and affordability of housing facilities, particularly in developing countries. Nevertheless, the performance of such structural components needs to be evaluated, in order to ascertain its feasibility. The paper reports experimental findings of twelve of such members when subject to static loads applied monotonically. A major finding of this study suggests that in the absence of any blind prediction, a reduction factor of 0.75 to the factored design tensile strength of bamboo, may allow for maximum utilisation of the flexural capacity of Bamboo-Reinforced Self-Compacting Concrete One-Way slabs. However, it is recommended that more experimental studies should be conducted to assert the reliability of the current estimate.

investigated and reviewed appropriately, since 75% of the anticipated flexural capacity of slabs were utilised experimentally.

**Subjects: Technology; Concrete and Cement; Structural Engineering**

**Keywords: self-consolidating concrete; beams; slab; bamboo**

### 1. Introduction

The provision of safe and affordable housing facilities, particularly in developing countries, still remains problematic for municipalities and governmental organisations (Moroz, Lissel, & Hagel, 2014). Also, as in 2014, global urban indicators of the United Nations Human Settlement Programme (UNHSP), estimate that 29.7% of the urban population in developing regions live in slums (Global Urban Indicators Database—UN-Habitat, 2014). Hence a crucial question that remains to be answered is “with rapid urbanisation in developing countries, what are the innovative technologies that will allow us to sustainably meet and improve the safety, affordability and durability of housing facilities?”

To date, several research efforts have investigated the use of bio-degradable and renewable materials that seemly present comparable performance in relation to conventional practices (Adewuyi, Otukoya, Olaniyi, & Olafusi, 2015; Adom-Asamoah, Tuffour, Afrifa, & Kankam, 2014; Agarwal, Nanda, & Maity, 2014; Javadian, Wielopolski, Smith, & Hebel, 2016; Kankam & Adom-Asamoah, 2006; Khare, 2007; Lima, Willrich, Barbosa, Rosa, & Cunha, 2007). Recently, it has been shown that the inclusion of greener materials, such as hemp fibre can significantly improve the ductility of masonry bricks (Formisano, Chiumiento, Junior Dessi, & Fabbrocino, 2017; Formisano, Dessi, & Landolfo, 2017). Another natural material that has received extensive research is bamboo. It has been shown that bamboo, a species of the grass family, possesses desirable properties, and hence can be used as reinforcement in concrete structures (Adom-Asamoah & Afrifa Owusu, 2010; Ghavami, 2005). Several attributes make bamboo a suitable and attractive alternative to conventional steel in reinforced concrete construction. For instance, the tensile strength of bamboo can be comparable to that of mild steel (Agarwal et al., 2014). Moreover, research has shown that the required amount of energy needed for engineered bamboo to be produced is about 50 times lesser than conventional steel (Ghavami, 1995; Janssen, 1981). Others (Ghavami, 1995; Ghavami & Hombeeck, 1981) have also shown that the self-weight of bamboo is six times lesser than steel at the same tensile strength level, thereby reducing the internal forces that are needed to counteract through member design. Comparatively, the additional load carrying capacity of bamboo reinforced beams can be five times that of plain concrete beams if effective chemical treatments is applied.

Self-compacted concrete (SCC), a new form of concrete technology, also present numerous advantages over conventional normal concrete (NC) economically. For SCC, there is no need for mechanical vibration, since the primary requirement in the design mix is to provide a highly fluid concrete matrix (Harkouss & Hamad, 2015; Hassan, Hossain, & Lachemi, 2008, 2010). In other words, the concrete matrix is made to flow under its own weight (Hassan et al., 2010). Hence, an economical advantage will be a reduction in the operating cost of a construction project in that, there is no need for mechanical vibrators. Consequently, this burgeoning concrete production technology, highly favours the use of unskilled labourers, which form a significant portion of the labour force in developing regions (Adom-Asamoah, Osei Banahene, Obeng, & Antwi Boasiako, 2017; Moavenzadeh, 1979; Moroz et al., 2014). Implicitly, the labour cost is expected to reduce in SCC construction. However, the structural performance particularly shear strength of SCC members may be compromised. This is due to the fact that the contribution of aggregate interlock capacity to the resistance of shear stresses is expected to decrease (Harkouss & Hamad, 2015; Hassan et al., 2008). The reduction is from replacing a significant portion of coarse aggregate with fine aggregate to achieve a highly flowable mix. In recent times, the shear performance of SCC beams has been heavily investigated. However, its application to other structural components such as slabs are limited.

Given the series of experimental works by the authors into structural materials that can promote sustainable construction in developing regions, the paper presents the behaviour of bamboo reinforced self-compacted concrete (BRSCC) slabs. The contributions of this research effort is to primarily study the impact of bamboo longitudinal reinforcement on the ultimate flexural capacities of BRSCC slabs, and secondarily recommend an empirical partial factor of safety for conservative design of such components.

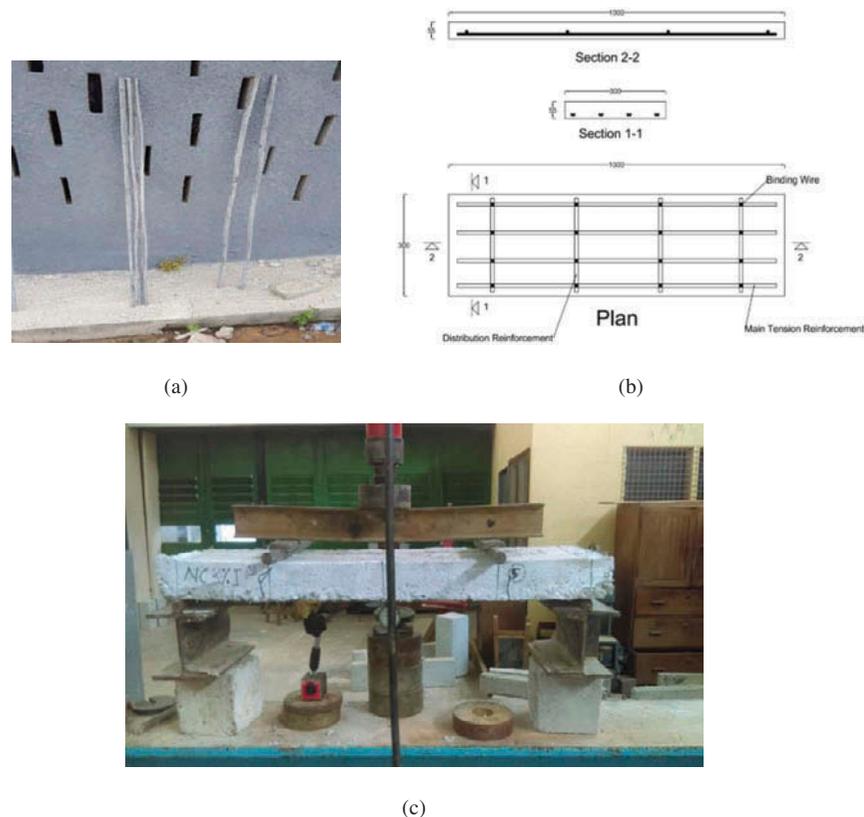
## 2. Experimental programme

### 2.1. Source and preparation of materials

Fine aggregates (river washed sand) and coarse aggregate (granite of sizes 10 and 20 mm) possessing specific gravities of 2.2 and 2.65, respectively, were locally acquired. Limestone Portland cement of strength grade 32.5R produced by Ghacem was the binder for concrete production. Bamboo culms of *Bambusa vulgaris* were obtained from the Kwame Nkrumah University of Science and Technology (KNUST) botanical gardens in Kumasi in the Ashanti Region of Ghana. Treated bamboo stripes (bituminous coating to a thickness of about 2 mm) were prepared for longitudinal reinforcements as replacement of steel to carry tensile stresses. This was necessary so as to minimise the water absorption capacity. However, to ensure that adequate bonding is achieved, the treated bamboo stripes were later smeared in sand (Figure 1a). Uniaxial tensile test was carried out for bamboo stripes with/without nodes (about 40 cm in length). The average tensile strength was 283 MPa and 235 MPa for bamboo stripes with nodes and without nodes, respectively. The beams were reinforced with three different flexural reinforcement ratios of 1%, 2% and 3%.

For SCC samples, a 1.2% by weight of cement superplasticiser free from chlorides and which meets ASTM C 494-92 requirements for Type A and F was used to enhance the flowability of concrete, without changing the water cement ratio.

Figure 1. Experimental setup.



**Table 1. Concrete mixture proportions**

Concrete Type	Binder (kg/m <sup>3</sup> )	Fine aggregate (kg/m <sup>3</sup> )	Coarse aggregate (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	Super-plasticiser mL/100kg per binder
NC	450	675	1350	225	0
SCC	450	1215	810	225	1.2

**Table 2. Physical properties of aggregates**

Property	Value	
	Fine aggregate	Coarse aggregate
Specific gravity	2.65	2.63
Water adsorption (%)	1.42	1.39
Fineness modulus	2.91	6.99

### 3. Concrete mix design, casting and curing procedure

A mix ratio of 1:1.5:3 being cement, fine and coarse aggregates, respectively, with a water to cement ratio of 0.5, was used for NC test specimens. This was redesigned to obtain an equivalent SCC mix ratio using coarse to fine aggregate ratios from the studies of Girish et al. (Girish, Ranganath, & Vengala, 2010), Ryan et al. (Ryan & O'Connor, 2016), Lachemi et al. (Lachemi, Hossain, & Lambros, 2005) and Hassan et al. (Hassan et al., 2008). The coarse aggregate content was reduced by 40% and replaced with an equivalent quantity of fine aggregates. The water cement ratio was maintained and a 0.0012l/kg of superplasticiser was added to obtain an adequate slump flow. This resulted in a mix ratio of 1:2.7:1.8 being cement, fine and coarse aggregates, respectively. The mix ratios of both NC and SCC are presented in Table 1. Other physical properties of aggregates are given in Table 2.

The required amount of water was measured and half of it was poured into the drum of the concrete mixer. The aggregates and the cement were measured and poured into the loader of the concrete mixer, which was then lifted into the drum. For the NC mix, concrete was allowed to mix for about a minute before the remaining water was added and then allowed to mix for about 3–5 min to achieve a uniform workable paste. For SCC mix, the superplasticiser was mixed with about half of the remaining water, and later added to the concrete. Finally, the remaining water was added to the concrete to obtain a homogenous and workable mixture. The mix was poured into a wheelbarrow and wheeled to the already fabricated formwork with their bamboo reinforcement for placement. Tests on the fresh properties of concrete were immediately carried out. Samples of concrete mixes were used to cast the 150 mm × 150 mm × 150 mm concrete cubes and the 100 mm × 100 mm × 500 mm unreinforced concrete beams (prisms) for the 28 days compressive and modulus of rupture (MoR) tests, respectively. The formwork for the slabs, cubes and prisms were struck after 24 h and cured for testing at 28 days. The beams and slabs were cured using damp jute sacks whereas the cubes and prisms were submerged in water tank. Before testing, the surface of the beams and slabs was given white painting to allow for easy detection and movement of cracks.

#### 3.1. Experimental setup and loading protocol

Twelve simply supported one-way slabs were cast and tested till ultimate failure under four-point bending in a monotonic fashion. An over-hang of 50 mm was provided beyond the support points to ensure adequate anchorage of the flexural reinforcement. Static loads were incrementally applied at a rate of 2 kN/min. A hydraulic steel jack supported on a rigid steel frame was used to produce loads

applied through an I-section steel spreader placed on two cylindrical steel bars. This facilitated the symmetrical transfer of loads to ensure pure bending in the mid-span of the specimen. The shear-span to depth ratio was set at 2.5 for all test specimens. A dial gauge reading to 0.001 mm accuracy was placed in the mid-span to record the central deflection of the slabs. The detection of cracks was done by visual inspection. A crack microscope of 0.02 mm was also used to measure the width of cracks on the surface of the slabs. The experimental setup is shown in Figure 1c.

The major design variables investigated were the percentage of bamboo reinforcement, and as such the slabs were designated as follows. “1”, “2” and “3” were used to denote the amount of tensile bamboo reinforcement present for a particular specimen. “NC” and “SCC” were used to denote whether the concrete matrix was from a NC or a SCC mix. Finally, “a” and “b” are used to emphasise the pair of samples having the same percentage of reinforcement and concrete matrix type. For instance, the slab referenced as 1NCa, as shown in Table 3, represents one with a 1% bamboo longitudinal reinforcement and from an NC matrix. 1NCb is the other sample with the same characteristic, which collectively makes up each pair.

#### 4. Theoretical flexural and shear capacities of slabs

For the slab setup instrumented for loading, the expected failure load that correspond to attaining full flexural and shear capacities is computed here under BS 8110 design guidelines. Considering load from the self-weight of the test specimen (Figure 1c), and the resistance offered by the flexural strength of concrete and the reinforcing material (bamboo), the limiting theoretical failure load that is expected to cause flexural damage is computed as

$$P_{ult} = \left[ M_{ult} + M_{cr} - \frac{\omega l^2}{8} \right] \cdot \frac{2}{a_v} \tag{1}$$

where  $M_{ult} = \eta f_y A_b z$ ;  $M_{cr} = f_r b h^2 / 6$ ;  $\eta$  is the material reduction factor (3.0 for bamboo (Kankam & Odum-Ewuakye, 2001));  $f_y$  is the yield strength of bamboo;  $A_b$  is the area of bamboo in the tension zone (fairly rectangular sections of about 10 mm by 12 mm);  $z$  is the internal level arm;  $f_r$  is the modulus of rupture;  $b$  is the width of section;  $h$  is the sectional height;  $\omega$  is the self-weight uniformly distributed load;  $l$  is the length of specimen and  $a_v$  is the shear span.

**Table 3. Test matrix**

Slab reference	Slab dimension			Shear-span to depth ratio	Reinforcement		Compressive strength
	Width (mm)	Depth (mm)	Length (mm)		Area	Percentage	
1NCa	300	55	1000	2.5	324	1.35	26.45
1SCCa	300	55	1000	2.5	324	1.35	26.21
1NCb	300	55	1000	2.5	314	1.31	26.45
1SCCb	300	55	1000	2.5	314	1.31	26.21
2NCa	300	55	1000	2.5	528	2.20	25.30
2SCCa	300	55	1000	2.5	528	2.20	25.10
2NCb	300	55	1000	2.5	558	2.33	25.30
2SCCb	300	55	1000	2.5	558	2.33	25.10
3NCa	300	55	1000	2.5	763	3.18	26.12
3SCCa	300	55	1000	2.5	763	3.18	26.00
3NCb	300	55	1000	2.5	729	3.04	26.12
3SCCb	300	55	1000	2.5	729	3.04	26.00

The primary shear resisting mechanisms for concrete beams without web reinforcement is governed by the dowel action of longitudinal reinforcement due to a friction (contributing 15–25% to the total), the aggregate interlock capacity (33–50% to the total) and contribution for the un-cracked section in the compression zone (20–40% to the total) (Kong & Evans, 1987). However, for concrete beams with shear stirrups, BS 8110 (BS 8110-1:1997—Structural use of concrete. Code of practice for design and construction, 1997) estimates the shear strength as an aggregated sum of the nominal contribution from concrete,  $V_c$ , and web reinforcement,  $V_s$ . For the loading protocol employed, the ultimate shear capacities can then be computed as

$$P_{shear} = 2.0 \left[ \frac{0.79}{1.25} \left( \frac{100A_b}{bd} \right)^{\frac{1}{3}} \left( \frac{400}{d} \right)^{\frac{1}{4}} \left( \frac{f_c}{25} \right)^{\frac{1}{5}} \right] .bd \tag{2}$$

where  $b$  is the width of slab section;  $d$  is the effective depth of slab;  $f_c$  is the characteristic compressive strength; and  $A_b$  is the area of bamboo in the tension zone.

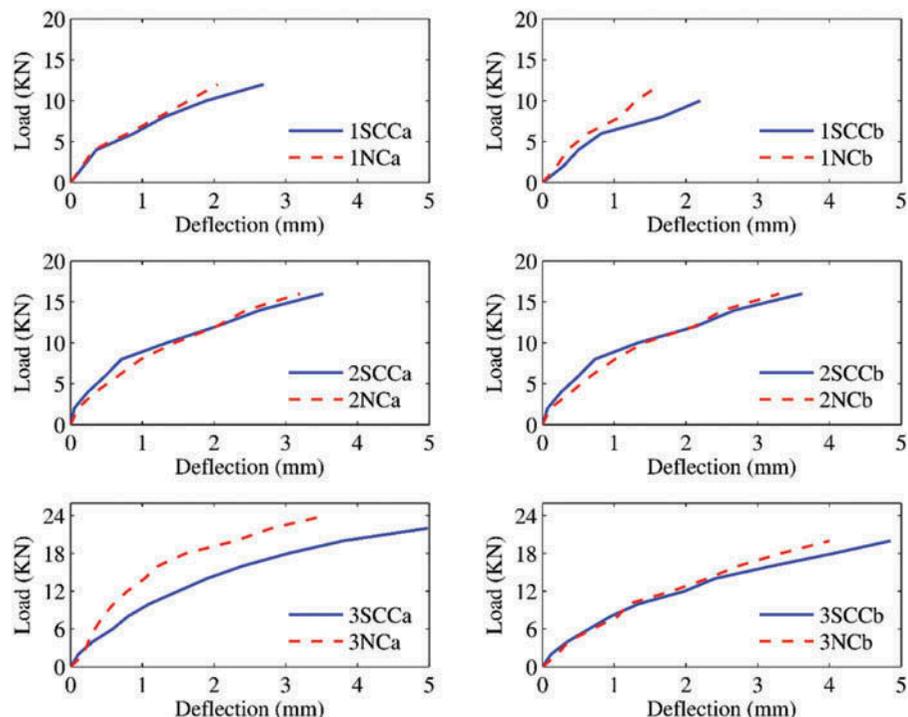
## 5. Results and discussion

### 5.1. Load-deformation and energy dissipation characteristics

Figure 2 presents the load–deflection curves of slab specimens. Behaviour of these slabs up until the formation of first flexural crack was fairly linear elastic. The post-cracking behaviour of SCC slabs in terms of stiffness were comparatively lower than their NC counterpart.

The reduction of the post-cracking stiffness in SCC slabs may primarily be due to the 40% reduction in coarse aggregate content; reduced aggregate interlocking mechanism. This finding is in agreement with the work of Hassan et al., (Hassan et al., 2010) who evaluated the shear strength performance of large-scale SCC beams. Nevertheless, the anticipated improved bond behaviour (larger quantity of fine aggregate and the high fluidity of SCC matrix) needed to enforce the strain compatibility assumption between the concrete and reinforcing material as noted by Helincks et al.,(Helincks, Boel, De Corte, De Schutter, & Desnerck, 2013) may not have been

Figure 2. Load-deflection curves.



**Table 4. Load, deflection and energy characteristics**

Slab Reference	Load, centre deflection and energy characteristics		
	Load (kN)	Deflection (mm)	Energy (kN mm)
1NCa	12	2.05	14.23
1SCCa	12	2.69	20.37
1NCb	12	1.65	11.03
1SCCb	10	2.20	13.26
2NCa	16	3.20	31.94
2SCCa	16	3.52	37.80
2NCb	16	3.30	33.02
2SCCb	16	3.62	38.88
3NCa	24	3.55	58.53
3SCCa	22	4.98	73.50
3NCb	20	4.00	48.66
3SCCb	20	4.85	62.07

adequately utilised when bamboo is used. Consequently, SCC slabs were characterised by higher ultimate deformations. Moreover, the ultimate load carrying capacities were slightly higher for NC than SCC slabs irrespective of the percentage of bamboo reinforcement. As expected, evaluating the effect of bamboo longitudinal reinforcement revealed that for a given load, the central deflection reduces as the reinforcement ratio increases. This implies an attainment of a relatively higher stiffness with increase in longitudinal reinforcement. The ultimate load capacities of SCC and NC slabs with 3.0% reinforcement ratio were 100% and 83% higher as those with 1.0% bamboo reinforcement respectively (see Table 4).

Analogous to bamboo reinforced concrete beams, Schnieder (Schneider, Pang, & Gu, 2014) reported a 26% increase in ultimate load flexural capacity of beams whose reinforcement ratio was increased from 1.6% to 2.4%. He also reported a gradual decline in the load carrying capacities when the reinforcement ratio was further increased to 3.0% and finally to 3.9%. The inexistence of strain hardening branch of his tested *Moso* bamboo strips may have caused this trend, and as such one can infer that for *B. vulgaris*, the bamboo species used for this experimental study, is ductile enough to resist applied loads. Similarly, the ultimate deformation capacity of tested slabs with 3.0% reinforcement ratio was as twice that of slabs with 1.0% bamboo reinforcement, irrespective of concrete type.

Generally, with respect to ultimate strain energy dissipation capacities, SCC slabs were able to absorb more energy than their corresponding NC slabs (25% more on average) (see Table 3). As expected, more energy (in the order of four) was dissipated as the longitudinal reinforcement ratio was gradually increased from 1% to 3% (Figure 3 and Table 4).

### 5.2. Failure and cracking behaviour

A comparison of the cracking and ultimate failure loads of the slabs considered is presented in Table 5.

The first flexural crack load ranges from 36% to 88% of the load at ultimate failure. On average, this cracking load corresponds to 63% of the ultimate failure load (Table 5 Column 6). However, a comparison of this experimental first crack load to that obtained from theoretical computations reveals that for such slabs the flexural strength of concrete is fully utilised and can be in excess of about 111% on average (Table 5, Column 7). These findings are comparable with the study on the flexural behaviour of *Babadua* reinforced one-way slabs (Kankam & Odum-Ewuakye, 2001).

Figure 3. Strain energy–deflection curves.

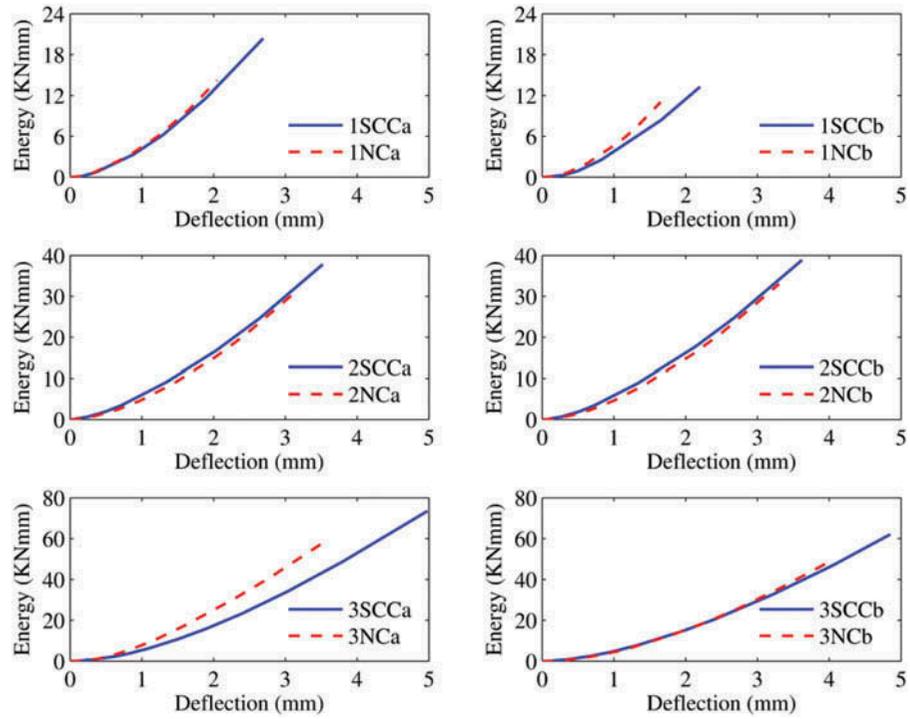


Table 5. Flexural crack and failure loads

Slab reference	Experimental loads (kN)		Theoretical loads (kN)		$\frac{P_{cr}}{P_{ult}}$	$\frac{P_{cr}L}{P_{cr}}$	$\frac{P_{ult}}{P_{ult}}$	$\frac{P_{ult}}{P_{cr}}$
	At first crack $P_{cr}$	At ultimate failure $P_{ult}$	At first crack $P'_{cr}$	At ultimate failure $P'_{ult}$				
1NCa	8	12	4.95	15.35	0.67	1.62	0.78	2.42
1SCCa	8	12	4.50	14.90	0.67	1.78	0.81	2.67
1NCb	8	12	4.95	15.03	0.67	1.62	0.80	2.42
1SCCb	8	10	4.50	14.57	0.80	1.78	0.69	2.22
2NCa	12	16	4.95	21.90	0.75	2.42	0.73	3.23
2SCCa	8	16	4.80	21.75	0.50	1.67	0.74	3.33
2NCb	14	16	4.95	22.86	0.88	2.83	0.70	3.23
2SCCb	8	16	4.80	22.71	0.50	1.67	0.70	3.33
3NCa	14	24	4.65	28.95	0.58	3.01	0.83	5.16
3SCCa	8	22	4.50	28.80	0.36	1.78	0.76	4.89
3NCb	14	20	4.65	27.93	0.70	3.01	0.72	4.30
3SCCb	10	20	4.50	27.78	0.50	2.22	0.72	4.45

Characterising the influence of SCC on the first crack load of tested slabs depicts a slightly lower performance when compared to their NC counterparts. This can be viewed as the cause for the larger deflections in SCC slabs.

In addition, we can also infer that the SCC matrix provides reduced bond deterioration between the bamboo and concrete during loading, thereby increasing its deformability as compared to NC slabs. On the other hand, all tested specimens were unable to fully utilise their expected flexural

load carrying capacities (75% of theoretically computed ultimate failure loads on the average). This therefore suggests that in the absence of any blind prediction, the reliability of the recommended empirical partial factor of safety of 3 for bamboo should be reviewed. However, the inability of the slabs to fully mobilise its flexural carrying capacities may be due to the interference from internal shear stress and minimal dowel action contribution from bamboo.

In evaluating the effect of longitudinal reinforcement ratio of the tested slabs under consideration, we observe that an increase in this parameter does not significantly impact the mobilisation of the ultimate flexural carrying capacity of slabs considered. Specifically, for slabs with 1% bamboo reinforcement, the average of  $P_{ult}/P'_{ult}$  was 77%. Increasing the bamboo longitudinal reinforcement to 2% and 3.0% yielded  $P_{ult}/P'_{ult}$  average values of 72% and 76%, respectively. With respect to experimentally observed loads at first crack  $P_{cr}$ , there was a slight reduction in the proportion of ultimate flexural load  $P_{ult}$  utilised before the initiation of first crack, as the longitudinal reinforcement ratio was increased. As seen in Table 5, the average decline in the  $P_{cr}/P_{ult}$  for the category of slabs whose reinforcement ratio was increased from 1.0% to 2.0% is approximately 5% on average. Further increase in bamboo reinforcement to 3.0% also caused an average reduction of approximately 12%. This trend implicitly and indirectly depicts an improvement in the post-cracking flexural resistance with increasing bamboo reinforcement, particularly larger in SCC than NC.

### 5.3. Shear strength and failure mode behaviour

The theoretical nominal and ultimate shear capacities of slabs investigated as per BS 8110 is given in Table 6. In order to evaluate whether the formation of cracks were flexure or shear controlled, the ratios  $P_{cr}/P_{s1}$  (first crack load to theoretical nominal shear load assuming only concrete section resist shear),  $P_{ult}/P_{s1}$  (ultimate failure load to theoretical nominal shear load assuming only concrete section resist shear) and  $P_{ult}/P_{s2}$ , which assumes that the contribution by dowel action between bamboo and concrete is paramount, are considered.

The first flexural crack loads ( $P_{cr}$ ) were significantly lesser than the estimated theoretical shear capacities of slab members that excludes the contribution longitudinal reinforcement ( $P_{s1}$ ) (an average  $P_{cr}/P_{s1}$  of 22%) (see Table 6).

Moreover, as given in Table 5, the observed first crack loads of tested slabs ( $P_{cr}$ ) were rather higher than the theoretical predicted flexural strength of concrete  $P'_{cr}$  (an average  $P_{cr}/P'_{cr}$  of 212%).

**Table 6. Shear capacities of tested slabs**

Slab reference	Theoretical shear strength (kN)		$\frac{P_{cr}}{P_{s1}}$	$\frac{P_{ult}}{P_{s1}}$	$\frac{P_{ult}}{P_{s2}}$
	Concrete section only $P_{s1}$	Including bamboo reinforcement $P_{s2}$			
1NCa	46.22	51.09	0.17	0.26	0.23
1SCCa	46.08	50.93	0.17	0.26	0.24
1NCb	46.22	50.56	0.17	0.26	0.24
1SCCb	46.08	50.40	0.17	0.22	0.20
2NCa	45.54	59.23	0.26	0.35	0.27
2SCCa	45.42	59.08	0.31	0.35	0.27
2NCb	45.54	60.33	0.18	0.35	0.27
2SCCb	45.42	60.18	0.18	0.35	0.27
3NCa	46.03	66.39	0.30	0.52	0.36
3SCCa	45.96	66.29	0.17	0.48	0.33
3NCb	46.03	66.39	0.30	0.43	0.30
3SCCb	45.96	66.29	0.22	0.44	0.30

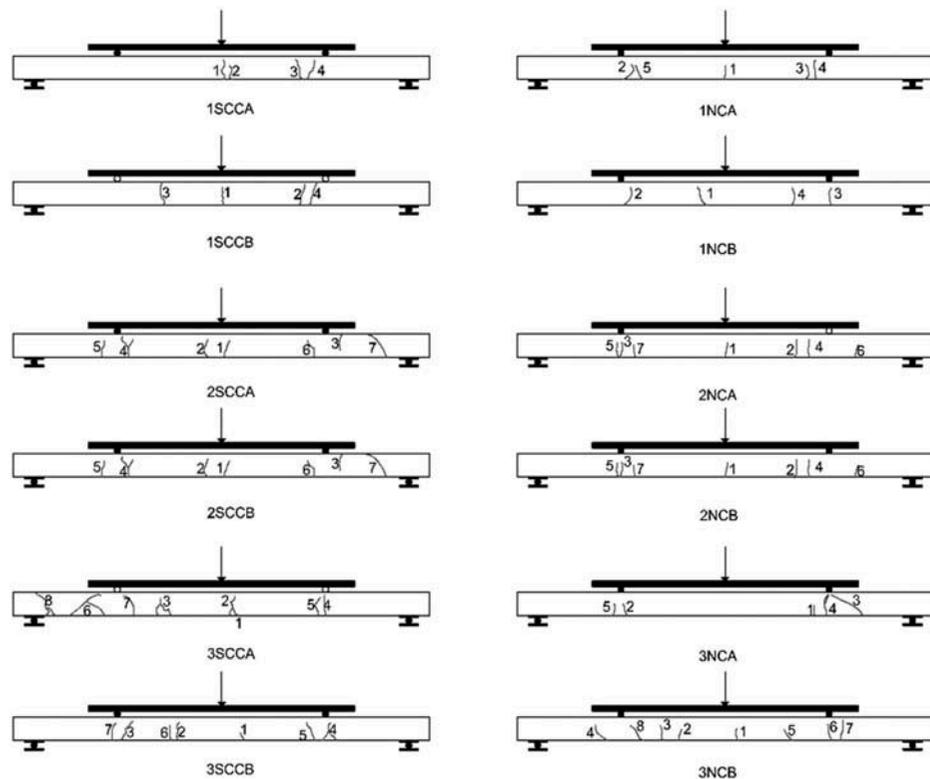
This implies that the development and propagation of cracks were flexure dominant as opposed to shear. By comparing the ultimate failure loads  $P_{ult}$  to the theoretical shear loads ( $P_{s1}$  or  $P_{s2}$ ), one can also infer that the dominating mode of failure is flexural, since it would have required extra loads of about 2.8 and 3.66 times the ultimate failure loads to mobilise the full utilisation of the theoretically estimated shear failure loads  $P_{s1}$  and  $P_{s2}$  respectively. Evidently, all tested slab specimen experience extensive flexural deformation and cracking till ultimate failure with the formation of diagonal shear cracks. A similar observation was reported in Kankam and Odum-Ewuakye (2001), which emphasised the role played by *Babadua* bars in contributing to shear resistance. It is worth noting that the effect of the reduced aggregate interlocking capacity in SCC slab was marginal and this could not significantly impact the rapid propagation of cracks to the compression zone as expected.

**5.4. Cracking behaviour**

A concrete crack width gauge was used to measure the width of cracks during testing. Crack width values were recorded at each load step upon the initiation of the first crack. The formation of flexural crack begun directly at the soffit of the centrally applied load. Upon further load, additional cracks were formed and propagated upwards and directed into the compression zone. The slab members developed adequate resistance to diagonal shear, since crack propagation was limited to a constant moment span of about 300 mm. The maximum crack width at near failure for each slab is outlined in Table 7. In addition, crack patterns and propagation is shown diagrammatically in Figure 4.

From a theoretical perspective, for structural members with constant ductility, one expects extensive deformation and flexural cracking for components with relatively higher amount of longitudinal

**Figure 4. Crack patterns of tested slabs**



reinforcement. Since there was no interference from shear failure for the slab tested, the number of flexural cracks for specimens with larger bamboo reinforcement was comparably higher than those with lower reinforcement (see Table 7). Another notable observation was that no SCC slab had more flexural cracks than their NC counterpart. However as previously discussed, SCC slabs experienced large deformation capacities than their NC counterpart. This observed phenomenon emphasises the impact of crack pattern in attaining improved deformation capacity of structural components.

Evaluating the distribution of maximum crack width at ultimate failure for each specimen, also revealed that making the concrete matrix self-compacting, significantly affect this parameter. With the exception of 3NCb and 3SCCb, all SCC specimens produced a much larger maximum crack width as compared to NC tested slabs. This may be partly due to the ease with which cracks are able to circumvent the aggregates and the global reduction in the aggregate interlocking capacity coming from the decrease in the proportion of coarse aggregate in the SCC mix. However, from Table 7, the correlation between the amount of bamboo reinforcement and the maximum crack width can be said to be statistically insignificant.

## 6. Conclusions

A total of 12 one-way simply supported slabs reinforced with *B. vulgaris* (bamboo species) were subjected to third-point line loads applied monotonically. Half of these slabs were design from a SCC mix, and the other half from a normally vibrated concrete matrix (NC). The design variables were primarily the amount of bamboo longitudinal reinforcement (1%, 2% and 3%) and secondarily the type of concrete matrix (SCC or NC). With the shear-span to depth ratio kept constant at 2.5, the following conclusions on the load-deflection relationships, ultimate failure loads, shear behaviour and crack patterns were drawn.

- Post-cracking stiffness of bamboo reinforced SCC slabs were lower than NC slabs, and this can be attributed to the fact that in the presence of a relatively lower coarse aggregate content, the needed aggregate interlocking mechanism to resist shear stress is reduced.
- The increase in ultimate load and deformation capacities of bamboo reinforced SCC and NC slabs can be about 91% on average if the percentage of longitudinal reinforcement is varied from 1% to 3%. However, for NC slabs, the average increase could be about 83% for this limited study.

**Table 7. Cracking behaviour**

Slab reference	Number of cracks	Maximum crack width (mm)
1NCa	5	0.14
1SCCa	4	0.30
1NCb	4	0.10
1SCCb	4	1.60
2NCa	7	0.12
2SCCa	7	4.00
2NCb	7	0.14
2SCCb	7	4.00
3NCa	5	0.08
3SCCa	8	0.40
3NCb	8	0.40
3SCCb	7	0.30

- The cracking performance of bamboo reinforced SCC slabs in terms of number of flexural cracks and maximum crack width is considerably better than those made from the conventional vibrated concrete.
- The use of *B. vulgaris* as structural reinforcing bars in rural construction of reinforced concrete slabs, coupled with the application of SCC mix can be an effective alternative for achieving and maintaining sustainability. From this limited study, an empirical partial factor of safety of 4.0 can be applied for conservative design.

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