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Corrugated bamboo as reinforcement in concrete

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This study investigated improving bamboo–concrete bond by increasing mechanical interlock. Pull-out tests were used to measure the bond between bamboo and concrete. Corrugated and non-corrugated bamboo splints were tested, with four different patterns of corrugation. The effectiveness of using linseed oil for waterproofing corrugated and non-corrugated bamboo splints was also investigated. The bond stress and slip at the loaded and free ends were measured and recorded. The results show that the bamboo–concrete bond can be improved with the use of waterproofed corrugated bamboo splints. The bond achieved using waterproofed corrugated bamboo splints was comparable to the bond achieved using splints treated with expensive epoxy treatments. Although certain patterns were found to be more effective in achieving a strong bond with concrete, all the corrugation patterns with 2 mm projections achieved better results in comparison with non-corrugated splints. Linseed oil was found to be effective in improving the bond between corrugated splints and concrete.

Notation

A	width of concrete shear surface
B	width of bamboo shear surface
S_{fe}	slip at free end corresponding to maximum load
S_{le}	slip at loaded end corresponding to maximum load
T	theoretical bond strength
w	splint width
P	projection
t	splint thickness
τ	average bond
τ_b	bamboo longitudinal shear strength
τ_c	ultimate shear-friction stress
$\tau_{f\&c}$	maximum friction and chemical adhesion

1. Introduction

With exponentially increasing demands for materials by a growing world population, scientists around the globe are looking for affordable and sustainable materials to use in the construction industry. The construction industry is especially important because it consumes 50% of all raw materials (Pacheco-Torgal and Labrincha, 2013). Bamboo is cheap, rapidly renewable and has a high tensile strength, which has led to investigations of its use as reinforcement in concrete. This is especially pertinent in many developing countries where steel is less affordable and bamboo is readily available.

However, a fundamental problem in the use of bamboo as reinforcement is its weak bond with concrete. A strong bond is critical for the transfer of load between reinforcement and concrete. The bond between untreated bamboo splints and concrete has been found to be weak, as shown in Table 1. Bamboo-reinforced beams in previous research have failed, mainly due to the weak bamboo–concrete bond (Agarwal *et al.*, 2014; Ghavami, 2005). Ghavami (1995) attributed the weak bond to two reasons. (*a*) When concrete is cast, the bamboo splints absorb water from the concrete, causing the splints inside the concrete to expand. When the splints lose moisture, they shrink and lose contact with the concrete. (*b*) The smooth surface of the bamboo minimises friction and allows the splints to slip without the development of a strong bond. Another possible cause of the weak bamboo–concrete bond is bond degradation due to the alkalinity of concrete. Altalmas *et al.* (2015) found that alkaline solutions can degrade the bond of glass fibre and basalt fibre reinforced polymer bars to concrete.

A few researchers investigated waterproofing bamboo to limit the expansion and shrinkage due to moisture changes and also studied the effect of roughening the bamboo surface to increase friction. This resulted in a stronger bond (Table 1).

Table 1. Bamboo–concrete bond strengths

Treatment	Bond: MPa	Embedment length: mm	Concrete strength: MPa	Bond improvement relative to untreated specimen: %
Untreated[a]	0·404	152	28	—
Untreated[a]	0·208	305	28	—
Untreated[a]	0·202	457	28	—
Untreated[b]	0·73	150	20	—
Untreated[c]	0·127	100	20	—
Untreated[d]	0·52	100	19[e]	—
Untreated, node inside[b]	0·90	150	20	—
Untreated, notched, node inside[b]	0·92	150	20	2
Nailed[b]	0·90	150	20	23
Nailed, node inside[b]	1·09	150	20	21
Oil[b]	0·48	150	20	–34
Oil, node inside[b]	0·69	150	20	–23
Oil, with zeolite powder[b]	0·71	150	20	–3
Black Japan[b]	0·66	150	20	–10
Black Japan, node inside[b]	0·86	150	20	–4
Black Japan, with zeolite powder[b]	1·06	150	20	45
Araldite[c]	0·232	100	20	83
Araldite with wire[c]	0·539	100	20	324
Tapecrete P 151[c]	0·315	100	20	148
Sikadur 32 Gel[c]	0·588	100	20	363
Negrolin + fine sand[d]	0·73	100	19[e]	40
Negrolin + fine sand + wiring[d]	0·97	100	19[e]	87
Sikadur 32 Gel[f]	2·75	100	—	—

[a] Cox and McDonald (1970)
[b] Kute and Wakchaure (2013)
[c] Agarwal *et al.* (2014)
[d] Lightweight concrete (17 kN/m^3)
[e] Ghavami (1995): the researcher did not mention the existence of a node in the bonded area
[f] Ghavami (2005)

As shown in Table 1, the results obtained by different researchers varied significantly for the same treatment, which can be attributed to a number of reasons as follows.

- Different bamboo species have different mechanical properties and different shapes.
- Different testing procedures: some studies used an unbonded length near the loaded end (e.g. Ghavami, 1995) and some did not (e.g. Agarwal *et al*., 2014).
- Different embedment lengths.
- Possibly different rates of pull-out as these were not always reported by the researchers.
- Eccentricities in the splints' alignments: Agarwal *et al.* (2014) reported that some splints failed as a result of eccentricity in the experiment.
- The use of different concrete mixes.

So far, epoxies have been found to be the best materials for improving the bamboo–concrete bond (Agarwal *et al*., 2014; Ghavami, 2005), with a bond strength equal to 2·75 MPa achieved by treating bamboo with Sikadur 32 Gel (Table 1). However, epoxies are very expensive to use as bamboo treatments. Oil- and bitumen-based treatments have not been found to be effective in treating bamboo. Although these treatments can limit shrinkage due to moisture changes, they can also hamper the bamboo–concrete bond by decreasing friction and chemical adhesion, and can act as a lubricant between the bamboo and the concrete, especially when ample amounts are used. Compared with untreated splints, splints treated with oil and Black Japan were found to have 34% and 10% lower bond strengths respectively (Table 1).

Azadeh and Kazemi (2014) proposed corrugating bamboo as a way of improving bond. Studying the bond of corrugated bamboo splints theoretically, they hypothesised that corrugating bamboo would increase mechanical interlock and prevent splitting failure by limiting the concentration of load around the nodes.

Utilising mechanical interlock by corrugating bamboo could be an excellent alternative to the use of expensive treatments like epoxies. The shear strength of bamboo is much higher than the bond strengths reported by researchers to date. Richard (2013) tested Moso bamboo specimens and reported a shear strength of 14·2 MPa. Steel's excellent bond to concrete is mainly caused by mechanical interlock (Arel and Yazici, 2012), and mechanical interlock is the reason why splints with nodes in the embedded length had a 23% stronger bond relative to splints without nodes (Table 1).

2. Bond and pull-out testing

Pull-out tests are commonly used to test the bond between concrete and steel and fibre-reinforced polymer (FRP) rebars (ASTM, 2014; Wambeke and Shield, 2006). Although the pull-out test does not accurately estimate the bond between reinforcement and concrete in structural elements, it is useful for comparing the bond of different rebars and different treatments (ASTM, 2014; Wambeke and Shield, 2006). The pull-out test overestimates bond for the following reasons.

- The concrete in the pull-out test is under compression while in beams the concrete around the reinforcement is under tension.
- The concrete cover in a pull-out test is usually larger than in structural elements.
- The embedment lengths of rebars inside structural elements are much higher than those used in the pull-out test.

Bamboo's lower modulus of elasticity relative to steel's modulus of elasticity also contributes to its weaker bond with concrete. As shown in Table 1, the data reported by Cox and McDonald (1970) show a big discrepancy between the average bond results for different embedment lengths: the bond of splints with 152 mm embedment was double that of splints with 305 mm embedment. FRP rebars also show this discrepancy between bond strengths for different embedment lengths (Wambeke and Shield, 2006). Furthermore, in pull-out tests, FRP shows a high discrepancy between the slip at the loaded end relative to that at the free end, and this has been attributed to FRP's lower modulus of elasticity (Focacci *et al.*, 2000). Compared with FRP, bamboo has an even lower modulus of elasticity. This means that the difference between the slip at the loaded end relative to the slip at the free end is expected to be higher. In addition, the difference between slip at the loaded end relative to the free end is larger for greater embedment lengths. This is important because the bond at any point along the embedded length increases to a maximum value and then decreases (Figure 1). Varying slip along the embedded length causes consecutive debonding, beginning at the loaded end and moving towards the free end (Altalmas *et al.*, 2015), and this consecutive debonding results in an overall lower average bond strength.

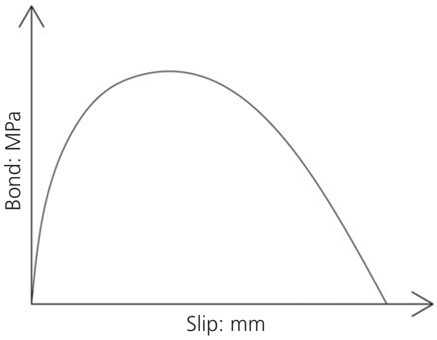

Figure 1. Modified Bertero–Eligehausen–Popov bond–slip relationship (Focacci *et al.*, 2000)

3. Experimental programme

The splints used in this study were taken from a single Moso bamboo culm of 3–4 years in age. The splints were cut to 850 mm lengths and were 20–30 mm wide. A total of 24 pull-out specimens were produced and tested. All the specimens had an embedment length of 100 mm and a debonded length of 100 mm near the loaded end. The purpose of the debonded length was to prevent splitting failure. A bitumen-based debonding compound was used to debond the splints (Figure 2). All the splints had no nodes in the bonded area. 18 splints out of the 24 were waterproofed with linseed oil.

A C35 concrete mix was used in the experiments. The mix ratio was 1: 1·7: 3 (cement: fine aggregate: coarse aggregate) with a water/cement ratio of 0·5. The compressive strength of the concrete cubes at the day of testing (28 d after casting) was determined to be in the range 40–48 MPa. This is equivalent to a cylinder compressive strength of 32–38 MPa (cylinder compressive strength = 0·8 × cube compressive strength) (McCormac and Brown, 2014). The concrete was cast in forms in three layers and was vibrated after the casting of each layer. Slump

Figure 2. Debonding of splints using a bitumen-based debonding compound

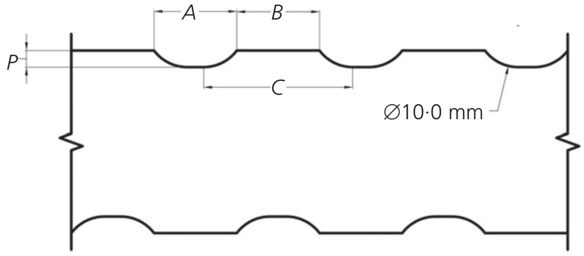

Figure 3. General pattern of corrugated splints

tests were performed to ensure that the consistency of the fresh concrete was within the necessary limits.

The use of three replicate specimens allowed the investigation of different patterns and the use of linseed oil as a treatment. Using three replicates is, however, a limitation on the confidence in the means and the standard deviation (SD) values. To limit the number of variables affecting the results, all the bamboo splints were taken from the same bamboo culm and all the concrete mixes had the same proportions. A univariate statistical analysis was performed to investigate the significance of the results.

To investigate the optimum bond with concrete, four different patterns of corrugation were investigated and a routing machine was used to produce the corrugations. Figure 3 shows the general pattern used for the corrugated splints. Two projections (*P*) (1 mm and 2 mm) and three *B*:*A* ratios (1:1, 1·5:1 and 1:1·5) were investigated. The grooves were staggered to limit their effect on the tensile strength of the splints. Using a router to fabricate the splints resulted in grooves of 10 mm diameter at the edges, as shown in Figure 3.

An Instron 8033 servo-hydraulic fatigue testing machine (which can be used for quasi-static tests) was used to test the specimens. The machine has a capacity of 250 kN. The tests were carried out at a rate of 1 mm/min. Two LVDTs (linear variable displacement transducers) were used to measure the displacements at the loaded and free ends (Figure 4). The bond was calculated by dividing the pull-out force by the bonded area. The widths and thicknesses of the splints were determined by averaging three measurements taken using a digital calibre with 0·01 mm precision.

4. Results

Figure 5 shows that the corrugated and treated bamboo splints achieved the strongest bond. The specimens with a *B*:*A* ratio of 1:1·5 ratio achieved, on average, a bond strength of 2·92 MPa, which is comparable to that achieved using Sikadur 32 Gel (2·75 MPa) (Table 1). All the corrugated splints achieved better bonds than the non-corrugated splints. Regarding the splints treated with linseed oil and with 2 mm projections, splints with *B*:*A* = 1:1·5 achieved, on average, 37% and 5% higher results relative to the splints with *B*:*A* = 1·5:1 and 1:1 respectively.

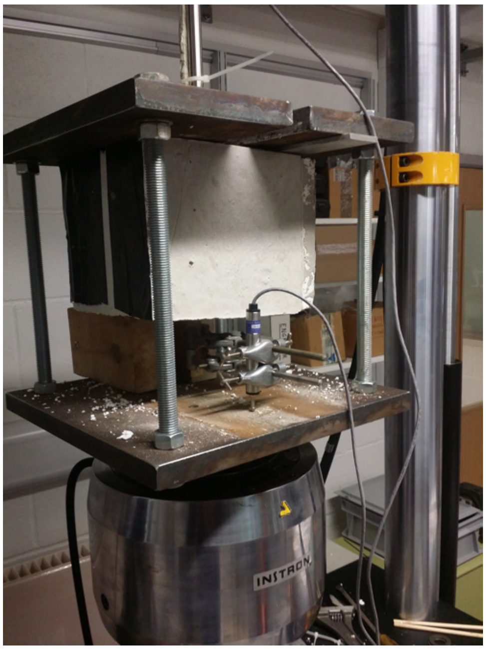

Figure 4. Pull-out testing of a bamboo splint

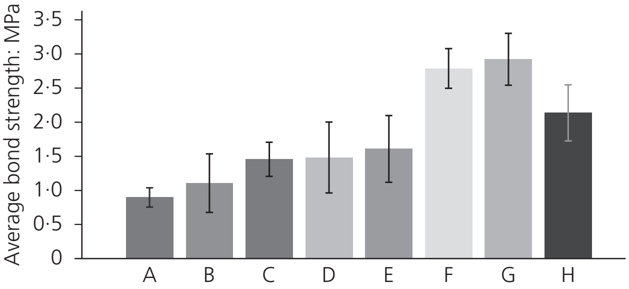

Figure 5. Average bond strengths (±1 SD) of different specimens without treatment and treated with linseed oil: A, non-corrugated; B, treated, non-corrugated; C, *P* = 1 mm, *B*:*A* = 1:1; D, treated, *P* = 1 mm, *B*:*A* = 1:1; E, *P* = 2 mm, *B*:*A* = 1:1; F, treated, *P* = 2 mm, *B*:*A* = 1:1; G, treated, *P* = 2 mm, *B*:*A* = 1:1·5; H, treated, *P* = 1 mm, *B*:*A* = 1·5:1

Linseed oil treated splints with 2 mm projections and *B*:*A* = 1:1 achieved, on average, 88% stronger bond than treated splints with 1 mm projections and the same *B*:*A* ratio. Untreated splints with 2 mm projections and *B*:*A* = 1:1 achieved 11% stronger bond relative to untreated splints with 1 mm projections and the same *B*:*A* ratio. While linseed oil improved the bond of the non-corrugated splints by 26%, it improved the bond of the corrugated splints with 2 mm projections and *B*:*A* = 1:1 by 73%. The linseed oil treatment improves the bond with concrete by limiting shrinkage, which prevents the diminishing of mechanical interlock between the corrugated splints

Table 2. Projection of multiple comparisons

				95% confidence interval	
Projection, *I*	**Projection, *J***	**Mean difference, *I* – *J***	**Significance**	Lower bound	Upper bound
0·00	1·00	−0·4468	0·388	−1·2927	0·3991
	2·00	−1·3024[a]	0·001	−2·0558	−0·5489
1·00	0·00	0·4468	0·388	−0·3991	1·2927
	2·00	−0·8556[a]	0·017	−1·5645	−0·1466
2·00	0·00	1·3024[a]	0·001	0·5489	2·0558
	1·00	0·8556[a]	0·017	0·1466	1·5645

Tukey's honest significant difference
Dependent variable: bond
[a] Mean difference significant at the 0·05 level

and the concrete. Using linseed oil may have also improved the bond by preventing bond degradation due to the alkalinity of the concrete.

To ensure that the results were significant, a univariate analysis of variance was carried. The results (Table 2) show that the mean bond of the splints with 2 mm projections was significantly higher than the mean bond of the splints with 1 mm projections and the non-corrugated splints at the 5% level of significance. The mean bond of the splints with 1 mm projections was not found to be significantly different from that of the non-corrugated splints. The mean bond of the treated splints with 2 mm projections was significantly higher than the mean bond of untreated splints with 2 mm projections: the *p*-value is equal to 2·9%. The linseed oil treatment did not improve the bond of the non-corrugated splints significantly and did not improve the bond of the splints with 1 mm projections. The use of a larger sample might prove the significance of the linseed oil treatment for non-corrugated splints and splints with1 mm projections. Statistically significant differences between the three *B*:*A* ratios (1:1, 1:1·5 and 1·5:1) were not found. The testing of more samples is needed to establish statistically significant differences between the different ratios. The normality of the distribution was checked using the Kolmogorov–Smirnov test and the distribution can be considered normal. The significance according to the Kolmogorov–Smirnov test was 13·8%, which is higher than 5%, so the null hypothesis cannot be rejected. The residuals were compatible with a normal distribution.

Failure between corrugated bamboo and concrete can be caused by shearing of the bamboo lugs, shearing of the concrete between bamboo lugs, diminishing mechanical interlock due to shrinkage and reduced mechanical interlock due to the mechanical properties of the bamboo in the direction perpendicular to fibres: bamboo is more easily compressible than steel or concrete.

Waterproofing bamboo with linseed oil prevents a reduction in mechanical interlock due to shrinkage. Higher projections can prevent a reduction in mechanical interlock due to the compressibility of bamboo in the direction perpendicular to fibres. However, using high projections reduces the splint's tensile strength. Thus, to achieve optimum behaviour, the projection should be equal to the smallest value that prevents the splint from slipping.

To avoid premature shear failure in the bamboo or in the concrete the *B*:*A* ratio should be such that the shear strength of the bamboo lugs and the shear strength of concrete between the lugs are equal. The concrete between the bamboo lugs fails by shear friction. Concrete shear-friction failure occurs when concrete pieces at the opposite sides of a crack are prevented from moving apart (McCormac and Brown, 2014). The concrete between the lugs is held in place by the bamboo on one side and the concrete on the opposite side. Richard (2013) performed bow-tie shear tests (ISO, 2004) on six specimens of Moso bamboo and found that the average shear strength in the longitudinal direction was 14·2 MPa.

Azadeh and Kazemi (2014) suggested that bamboo's longitudinal shear strength and concrete's shear strength are the main factors in the bamboo–concrete bond. They determined the internal stresses in bamboo and concrete as shown in Figure 6.

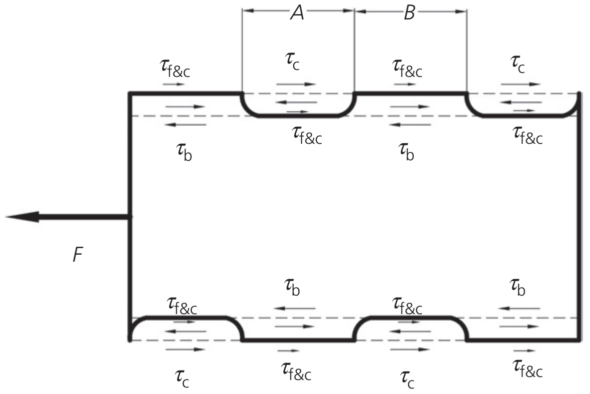

Figure 6. Internal stresses in bamboo and concrete

However, in addition to the concrete shear surface determined by Azadeh and Kazemi (2014), there are two concrete shearing surfaces that contribute to the shear strength (Figure 7). These two surfaces are parallel to the plane shown in Figure 6 with a width equal to the projection P and length equal to A.

Equation 1 was formulated based on the stresses shown in Figure 6 in addition to the stresses in the concrete surfaces parallel to the plane (Figure 7). The theoretical bond strengths of the corrugated splints were calculated using Equation 1, a bamboo shear strength of 14·2 MPa and a concrete shear-friction strength between the lugs equal to 20% of the average compressive strength (Table 3). As can be seen from Table 3, the treated non-corrugated splints reached their maximum bond at a lower slip relative to the corrugated splints. It was found that the average bond of the treated non-corrugated splints at a slip equal to the average slip of the corrugated splints at maximum bond was equal to 74% of the maximum bond. To account for the drop in bond after reaching the ultimate bond strength, only 74% of the friction and chemical

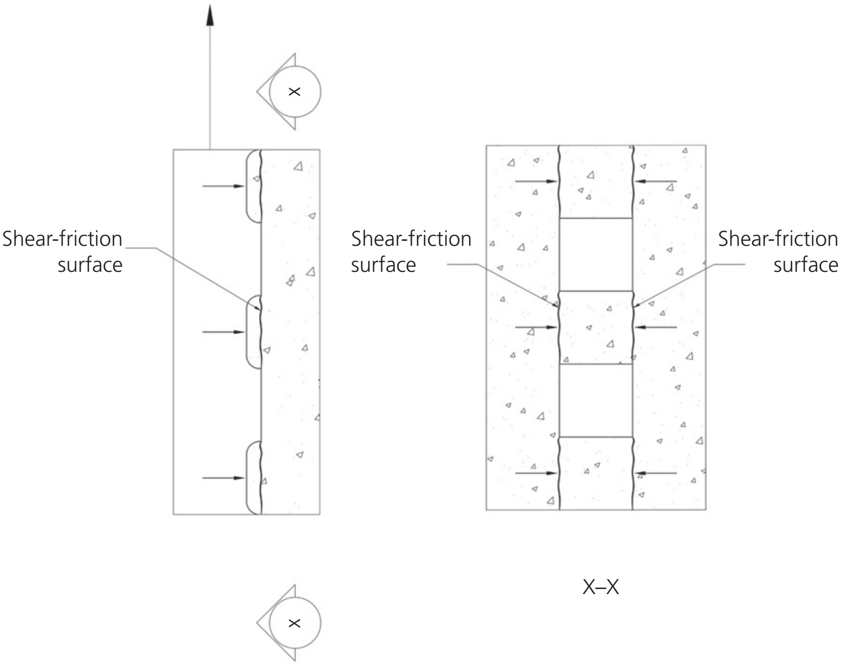

Figure 7. Shear-friction surfaces

Table 3. Results of pull-out tests on corrugated and non-corrugated bamboo without treatment (WT) and treated with linseed oil (TLO)

	Non-corrugated		Corrugated					
	WT	TLO	WT	TLO	WT	TLO	TLO	TLO
Specimen ID	A	B	C	D	E	F	G	H
B:A	—	—	1:1	1:1	1:1	1:1	1:1·5	1·5:1
Projection, P: mm	—	—	1	1	2	2	2	2
Average bond strength, τ: MPa	0·9	1·11	1·46	1·48	1·61	2·79	2·92	2·14
Number of specimens	2[a]	3	3	3	3	2[b]	3	3
SD: MPa	0·14	0·43	0·25	0·52	0·49	0·29	0·38	0·41
Bond improvement relative to specimen without treatment: %	—	26	66	69	84	220	235	145
Slip at loaded end corresponding to maximum load, S_{le}: mm	2·9	1·93	4·12	4·2	4·57	4·8	5·94	5·61
Slip at free end corresponding to maximum load, S_{fe}: mm	1·63	1·53	3·28	3·28	3·67	2·76	2·53	4·19
τ/S_{fe}: MPa/mm	0·55	0·73	0·44	0·45	0·44	1·01	1·16	0·51
Theoretical bond strength, T: MPa (T)	—	—	2·36	2·18	2·31	2·44	2·94	2·22
$(T-\tau)/\tau$: %	—	—	62·1	46·8	43·3	−12·5	0·5	4·0

[a] One specimen was ignored as a result of a technical error (setting the rate of pull-out to 10 mm/min instead of 1 mm/min)
[b] One specimen was ignored because it failed in tension

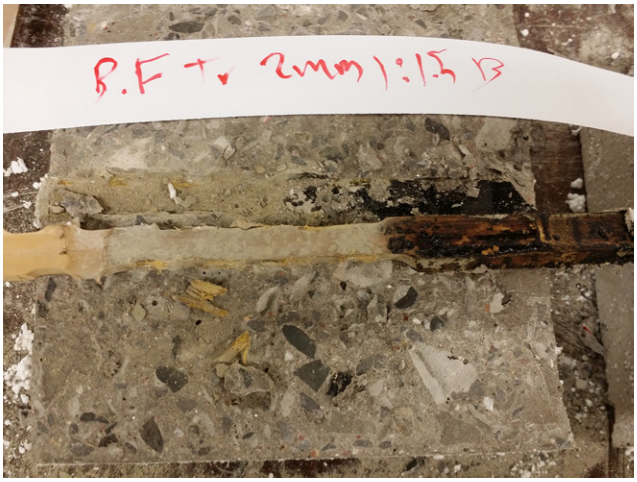

Figure 8. Bamboo–concrete surface after failure (treated, $P = 2$ mm, B:A = 1:1·5)

Figure 9. Bamboo–concrete surface after failure (treated, $P = 2$ mm, B:A = 1:1)

adhesion bond ($\tau_{f\&c}$) was used in Equation 1.

1.
$$\tau = \frac{\tau_b \times t \times B}{(A + B) \times (w + t)} + 0{\cdot}74\tau_{f\&c} \leq \frac{\tau_c A(t + 2P)}{(A + B) \times (w + t)} + 0{\cdot}74\tau_{f\&c}$$

where τ_c is the smallest value of $0{\cdot}2f'_c \leq 3{\cdot}31 + 0{\cdot}08f'_c \leq 11$ (ACI, 2008).

As shown in Table 3, the theoretical bond results of the treated splints with 2 mm projections are comparable to the experimental results. This proves that when the splints are treated with linseed oil, a 2 mm projection is large enough to develop full mechanical interlock between the bamboo and the concrete. The experimental results for the untreated splints with 2 mm projections and splints with 1 mm projections are much lower than the theoretical results. This means that, for these splints, the mechanical interlock was poor: bond is mainly due to friction and chemical adhesion and partial mechanical interlock. A 1 mm projection is thus smaller than required to develop full mechanical interlock. For the treated splints with 2 mm projections and B:A = 1:1·5, the theoretical mean bond strength was found to be 2·94 MPa and the experimental result was 2·92 MPa (0·5% difference).

Figure 8 shows the surface of a treated splint ($P = 2$ mm B:A = 1:1·5) after failure where the bamboo lugs were completely sheared off. Figure 9 shows the surface of a treated 2 mm B:A = 1:1 splint, which reveals that the damage in the bamboo was more pronounced in the area near the loaded end. Figure 10 shows the surface of an untreated splint ($P = 2$ mm B:A = 1:1): the bamboo splint was not damaged but shrinkage of the bamboo splint resulted in the loss of mechanical interlock.

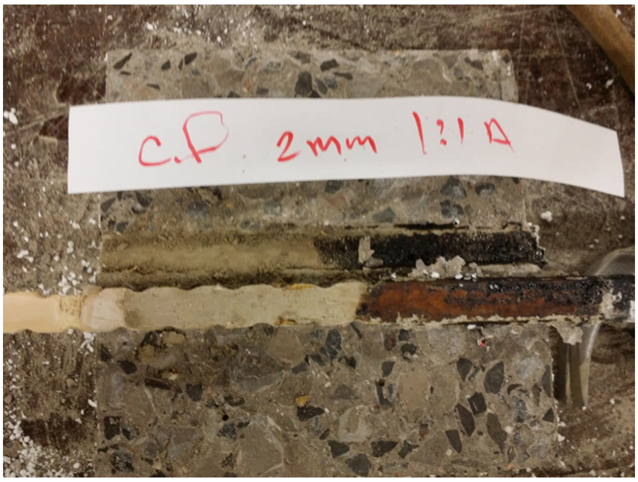

Figure 10. Bamboo–concrete surface after failure (untreated, $P = 2$ mm, B:A = 1:1)

The deflection of bamboo-reinforced beams can be reduced by using treated corrugated bamboo splints. The high deflection of bamboo-reinforced beams in comparison with steel-reinforced beams is due to (*a*) bamboo's low modulus of elasticity relative to that of steel and (*b*) slippage between the bamboo reinforcement and the concrete. As shown in Table 3, linseed oil treated corrugated splints with 2 mm projections and B:A = 1:1·5 achieved the highest bond–slip ratio of 1·16 MPa/mm. The untreated splints achieved the lowest bond–slip ratios of 0·55, 0·45 and 0·44 MPa/mm (non corrugated, corrugated 1 mm projection and corrugated 2 mm projection respectively).

5. Conclusions

This research investigated the use of mechanical interlock to solve a fundamental problem in using bamboo as reinforcement in concrete – the bamboo–concrete bond. It was found that corrugating bamboo is effective in improving the bond between bamboo and concrete. This contributes to a higher bending capacity of bamboo-reinforced concrete beams and limits the deflection of bamboo-reinforced concrete beams. It was found that a 2 mm projection in the corrugation was more effective than a 1 mm projection. In order to establish statistically significant differences between the different corrugation ratios (*B*/*A*), more specimens need to be tested. However, this research has shown that expensive epoxy materials can be replaced by inexpensive corrugation of bamboo while still achieving a strong bond. Corrugation patterns other than those investigated in this research should also be investigated. Linseed oil was found to be an effective treatment for bamboo splints. Sprinkling fine sand onto treated corrugated bamboo splints may also improve bond performance and this should be investigated.

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