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BAMBOO REINFORCED CONCRETE: LESSON LEARNED, PROHIBITIONS AND OPPORTUNITIES

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ABSTRACT

The use of small diameter whole-culm (bars) and/or split bamboo (a.k.a. splints or strips) has often been proposed as an alternative to reinforcing steel in reinforced concrete. The motivation for such replacement is typically cost and the drive to find more sustainable alternatives in the construction industry. Although bamboo is a material with extraordinary mechanical properties, this paper will summarise the reasons that for most load-bearing applications, bamboo-reinforced concrete is an ill-considered concept: having significant durability, strength and stiffness issues. Additionally, it is argued that bamboo-reinforced concrete does not possess the environmentally friendly credentials often attributed to it. Finally, the authors identify applications in which bamboo reinforcement may prove an acceptable alternative to steel provided durability concerns can be addressed.

KEYWORDS: bamboo, bamboo reinforcement, bamboo-reinforced concrete, durability, life cycle assessment

INTRODUCTION

The use of small diameter whole-culm (bars) and/or split bamboo (a.k.a. splints or strips) has often been proposed as an alternative to relatively expensive reinforcing steel in reinforced concrete. The motivation for such replacement is typically cost and the drive to find more sustainable alternatives in the construction industry. Although bamboo is a material with extraordinary mechanical properties, its use in bamboo-reinforced concrete is an ill-considered concept, having significant durability, strength and stiffness issues; additionally, it does not meet the environmentally friendly credentials often attributed to it [1].

BAMBOO REINFORCED CONCRETE

Published accounts indicate that the use of bamboo to reinforce concrete structures dates back a century in Southeast Asia. Early experimental studies of bamboo-reinforced concrete were conducted at MIT in 1914 [2], in Germany [3] and Italy [4] in the 1930's, the United States following the Second World War [5, 6], and Colombia [7]. These studies used either bamboo bars (whole-culms of small diameter) or splints (semi-round strips).

Much early interest in bamboo-reinforced concrete is attributed to the US Navy and their interest in rapid [re-]construction in Southeast Asia following the Second World War. Glenn [5] highlighted the relatively poor behaviour of bamboo reinforced concrete, identifying issues including: a) high deflection, low ductility, brittle failure, and reduced ultimate load capacity when compared to steel-reinforced elements; b) bonding issues associated with excessive cracking and swelling of bamboo; and, c) the need for using asphalt emulsions. Glenn prescribed 3 to 4% bamboo reinforcement ratio and an allowable bamboo stress of 20 to 28 MPa calibrated to control deflections. Brink and Rush [8] also promulgated an allowable stress approach for designing bamboo-reinforced concrete comparable to the contemporary approach [9] for steel-reinforced concrete; they recommended an allowable bamboo tensile stress of 28 MPa, a bond strength of 0.34 MPa, and for serviceability requirements, a bamboo modulus of 17.2 GPa. Geymayer and Cox [10] recommended a hybrid design approach in which a bamboo-reinforced concrete flexural element is designed as an unreinforced concrete member with a maximum tensile stress of $0.67\sqrt{f_c'}$ (MPa units). To this, 3 to 4% bamboo reinforcement is added resulting in, they claim, a factor of safety on the order of 2 to 2.5. Recognising the unique and limited bond behaviour of bamboo, bond strength was prescribed to be 44 N per mm of reinforcing 'bar' circumference and that the embedment must exceed 305 mm [10]. This is a maximum bond stress of about 0.15 MPa. Using either approach, bond capacity will always control design. As a basis of comparison, a 25 mm diameter bamboo reinforcing bar embedded 305 mm can develop only between 3.5 kN [10] and 8.4 kN [8]. By contrast, a 9.5 mm diameter steel reinforcing bar in the same conditions can develop 29.4 kN.

A number of research papers describing bamboo-reinforced flexural members confirm the basic premise of the design methodology proposed by Geymayer and Cox [10]. Optimal ratios of longitudinal bamboo reinforcement ratios range from 3 to 5% from which the capacity of an otherwise unreinforced concrete beam is increased at least 2.5 times [11-16]. Ghavami [17] demonstrated the importance of providing at least minimum bamboo reinforcement and appropriate surface treatment to enhance bond reporting that beams with a 3% ratio of treated split bamboo reinforcement had four times the ultimate capacity of comparable unreinforced concrete beams. By contrast, bamboo-reinforced concrete with approximately 1.4% splints having no bond enhancement provided no improvement over the behaviour of unreinforced concrete [18, 19]. Similarly, bamboo-reinforced slabs having a reinforcement ratio of only 0.5% developed a single large crack and exhibited significant reinforcement slip [20].

Agarawal et al. [18] showed the significant beneficial effects of 'treating' bamboo splints with commercial epoxy-based adhesives in order to enhance bond. They reported average bond stresses (from pull-out tests) on the order of 0.13 MPa for plain bamboo splints (a value echoing the recommendation of Geymayer and Cox [10]) and values as high as 0.59 MPa (350% increase) when epoxy adhesive was used to coat the splints. This behaviour translated to improved flexural response. Similarly, Ghavami [21] reports a 430% increase in the value of bond strength for epoxy-coated bamboo splints (2.75 MPa) embedded in concrete over uncoated splints (0.52 MPa). Ghavami also conducted tests with an asphalt and sand coating which resulted in a bond strength of 0.73 MPa. Agarawal et al. report that 8% untreated bamboo was necessary to result in flexural behaviour similar to that of a steel-reinforced concrete member having a reinforcing ratio 0.89% whereas epoxy-coated splints required a reinforcing ratio of only 1.4 % to achieve similar behaviour; implying a 470% improvement in behaviour when the splints were coated.

Pull-out bond tests of splints [10] and round culms [22] having varying embedment lengths are a more realistic manner of determining bond properties. Both [10] and [12] conclude that the average bond stress decreases as the embedment length increases, and that this decrease is significantly more pronounced than is observed in [isotropic] steel reinforcing bars. Such a reduction can be explained by the greater effects of shear lag and the poor transverse material characteristics of the anisotropic bamboo. Bamboo splints, which have no pronounced deformations (thus relying mostly on friction to transfer stress), exhibit a lower bond stress than round culms for which the nodal protrusions provide some degree of mechanical interlock with the surrounding concrete. Geymayer and Cox [10] concluded that bamboo splints had an effective bond length, beyond which further increases in embedded length had no effect on available capacity; from this they established their bond strength recommendation.

All known studies that address bond of bamboo in concrete identify shrinkage of untreated, green or pre-soaked bamboo, and swelling cycles resulting from variations in moisture in the concrete as being detrimental to bond. As a result, most studies recommend coating bamboo in a moisture barrier although sealing inadequately seasoned bamboo into a watertight environment has the potential to exacerbate decay.

There are few known studies specifically addressing the durability of bamboo embedded in concrete. Nonetheless, there is considerable literature addressing the durability and treatment of different biomass materials (occasionally including bamboo) in cementitious materials. Gram [23] represents perhaps the first significant study in this regard. Recent and very thorough reviews are provided by [24] and [25].

Portland cement concrete is a highly alkali environment which provides a passivating environment for embedded steel reinforcement. In contrast, alkali treatments are often used to break-down the cell structure of lignocellulosic materials such as wood, hemp, flax and bamboo [26] in order to retrieve, expose or treat their fibres. Such treatment may improve bond with polymeric resins in composite materials but are clearly undesirable in the case of bamboo bars used in bamboo-reinforced concrete. Hosoda [27] reports a 50% loss of bamboo tensile capacity following one-year conditioning in a high alkali water bath; after three years, the bamboo retained only 30% of its initial strength. Hemicellulose is reactive with calcium hydroxide ($Ca(OH)^2$) present in cement paste [28-31] leading to crystallisation of lime in the biomass pores. Lignin is soluble in hot alkali environments [23] as is the case during cement hydration, and potentially when the concrete is exposed to direct sunlight in a tropical environment. Reducing alkalinity whether using ternary cements [32] or through carbonation [33] were found to only partially mitigate the degradation of biomass. Lignocellulosic materials in hydrated cement are also embrittled by mineralisation associated with cations (primarily Ca^{2+}) in the concrete pore water [34]. Water absorption is a critical durability concern for biomass of any kind embedded in a cementitious matrix [25]. Water absorption and hygrothermal cycling result in volumetric change of the embedded biomass leading to interfacial damage and micro- and macro-cracking. These effects increase permeability, driving the deleterious processes described previously.

Biological attack is arguably the most critical concern for bamboo. Embedment in concrete is not believed to be sufficient to protect bamboo from insect – especially termite – attack. Termites can pass into cracks as small as 0.8 mm [35]. Bamboo-reinforced concrete is likely to exhibit such cracks from temperature, shrinkage and/or load effects. Thus, bamboo reinforcement requires chemical treatment through its entire wall thickness to mitigate insect attack [36, 37]. Fungal attack (rot) requires aerobic conditions and a moisture content typically exceeding 20% [38]. Bamboo that is fully or partially embedded in concrete is vulnerable to rot because concrete (or mortar) is porous and moisture is easily transported through capillary action [39] and through existing cracks. Surface or 'paint-on' treatments are generally not considered to provide sufficient protection against rot in timber [38, 40, 41] or bamboo [42]. Except in cases in which the concrete remains dry throughout its service life, decay is possible even when the bamboo is coated in a bituminous or epoxy coating.

ISSUES ASSOCIATED WITH BAMBOO REINFORCED CONCRETE

Concrete reinforced with bamboo, rather than conventional steel reinforcement exhibits a different behaviour and therefore needs to be designed using different paradigms. Fundamental differences between bamboo and conventional reinforcing steel are as follows [1]:

1. Bamboo is essentially an elastic brittle material; this limits the 'allowable' stress that may be utilised with bamboo based on the margin of safety desired.

2. The characteristic values of longitudinal tensile modulus and strength of bamboo are typically a tenth that of steel. As a result of the low modulus, serviceability considerations (i.e., deflections and crack control) are significant and typically govern design despite the low allowable strength.

3. The coefficient of thermal expansion of bamboo is: a) different from that of steel and concrete, which are, themselves, similar; and b) is almost an order of magnitude greater in the transverse direction than in the longitudinal direction affecting compatibility with the surrounding concrete, significantly impacting composite bond behaviour.

4. Unlike steel, bamboo is dimensionally unstable and requires some form of treatment to resist moisture transmission. Due to anisotropy, dimensional stability is not uniform in longitudinal and transverse directions, also potentially affecting bond behaviour.

5. Although not affected by corrosion, bamboo is susceptible to various degradation mechanisms associated with exposure to varying hygrothermic conditions and a high-alkali environment. There is no published or industry guidance that suggests that embedding bamboo into concrete will protect it against rot, even if it is coated with a water-proofing product.

One of the reasons steel reinforced concrete has been such a successful material is that its ductility allows engineers to safely design statically indeterminate structures by making use of the lower bound theory of plasticity. The absence of ductility in bamboo-reinforced concrete implies that not only is it inadequate for seismically active regions, it is inappropriate for statically indeterminate structures. In addition, there are other practical issues that hinder the use of bamboo as a reinforcing material in conventional construction. These include:

6. The anisotropic nature of bamboo makes hollow bars prone to crushing or splitting during

transportation, handling and erection; bamboo bars must be handled with additional care not required for steel bars.

7. There is no known research addressing methods of splicing or the behaviour of splices in bamboo reinforcing bars. Like steel, bamboo bars are practically limited to about 6 m in length; thus splicing will be necessary in some applications.

8. There is no known research addressing the anchorage (beyond bond development) of bamboo in concrete. Whereas steel bars are easily bent, it is not believed to be practical to bend bamboo bars in a manner appropriate to provide anchorage in concrete. Thus, the only practical anchorage for bamboo bars is straight bar development.

9. Utilising on the order of 4% reinforcement ratio, bamboo-reinforced concrete will have congested bar details. This congestion, and the variability in bamboo bars, leads to the recommendation that, in order to facilitate adequate consolidation of the concrete, bamboo bars should be placed with a spacing of at least 3 bar diameters. This limit may result in concrete sections being larger than is strictly required to satisfy strength design considerations. As a result, a greater amount of concrete will be necessary to meet the load carrying requirement of the functional unit, which compromises the environmentally friendly credentials often attributed to it.

10. Bamboo bars will float in concrete. This requires bars to be tied in place to resist uplift. With the larger number of bars present, this may be a cumbersome requirement.

11. In addition to through-thickness treatment for protection from insect and fungal attack, pre-treatment of bamboo with special coatings to enhance bond and/or the use of waterproof membranes in ground-supported slabs are laborious and require expensive and complex application systems. This is counter to claims that bamboo-reinforced concrete is a sustainable, local and low cost alterative in developing regions.

12. Unlike steel, that when properly confined can be relied upon to contribute as 'compression reinforcement', the poor transverse properties of bamboo make it ill-suited for use in compression zones, including columns.

13. Bamboo is known to creep under the effects of sustained loads limiting the sustained tensile force that can be practically resisted.

14. The behaviour of bamboo at elevated temperatures or in fire conditions is unknown. Bamboo properties degrade above 50°C [43]. The glass transition temperatures of lignin and hemicellulose (the primary components of the bamboo matrix) range from 97 – 171°C and 140 – 180°C, respectively [44]. It is likely that the behaviour of bamboo reinforcement under fire conditions is inferior to that of steel.

There is a common belief that bamboo reinforcement for concrete is a ''green'' or ''sustainable'' alternative to steel reinforcement. However, life cycle assessment (LCA) of both systems used as reinforcement of a prototype three-bay portal frame shows that the production of the bamboo reinforced structure will have emissions almost twice those resulting from the production of the same structure reinforced with steel [1]. This increase is attributed to the considerably greater amount of concrete necessary to meet the load carrying requirement of the prototype structure. The emissions savings achieved by replacing steel with bamboo reinforcement are surpassed by the emissions from the additional concrete and transportation [1, 45]

Bamboo reinforced concrete is an ill-considered concept. More importantly, bamboo reinforcement – if used safely – is not an environmentally friendly or sustainable alternative to steel. Bamboo-reinforced concrete must be designed to remain uncracked; the presence of bamboo reinforcing is intended to impart a degree of ductility to the section and may impart some post-cracking reserve capacity in the event of an overload that results in cracking. This post-cracking behaviour is only possible if there is sufficient bond between the bamboo and concrete. It has been shown that some bond-enhancing surface treatments are sufficient to impart the bond capacity required. Nonetheless, the required 'uncracked' design increases concrete member dimensions and has a 'knock on' effect resulting in increased formwork and foundation requirements. Additionally, the poor durability and bond characteristics of bamboo require through-thickness treatment and additional surface treatment of bamboo reinforcement, respectively. Such treatments, as described in the literature, are labour intensive, costly, and often utilise materials of known toxicity or which have handling restrictions associated with workplace health and safety. Vo and Navard [24] draw a very prescient conclusion in this regard: "*A large proportion of [the methods used to overcome issues of biomass durability when embedded in concrete] are effectively helpful in easing the concrete preparation and leading to better final materials. However, most of them, if not all, have little practical value since they are either impossible to be implemented because of the use of chemicals which are not environmentally-friendly or much too expensive.*"

POTENTIAL PRACTICAL USES OF BAMBOO AS REINFORCING MATERIAL

While bamboo-reinforced concrete is impractical in primary structural members [1], certain related applications may be practical provided issues of durability, dimensional stability and bond between bamboo and concrete are addressed.

1. Small cane or bamboo splints may be an alternative for crack control reinforcement for slabs on grade (slabs cast on the ground) provided at least 3% bamboo is used. Such slabs are designed to remain uncracked and/or are provided with control joints to facilitate controlled cracking. Slabs on grade are known to absorb moisture from the ground; thus this must be mitigated in order to avoid the potential for rot of the embedded bamboo.

2. Light cement bamboo frame (LCBF) panels, known colloquially as *bahareque* construction [46], are well established. LCBF construction is a modern technique utilising composite shear panels constituted of a wall matrix of bamboo or metal lath nailed onto a bamboo framing system, plastered with cement or lime mortar render. This method works well because the stresses in the wall matrix are very low. Provided the bamboo is treated against insect attack and kept dry through good design, the lifespan of the system is expected to exceed 30 years.

3. Small culm or bamboo splints have been proposed as reinforcement for hollow-core masonry construction in non-seismic environments [47]. Such bamboo-reinforced masonry may provide a means of strengthening otherwise unreinforced masonry. This requires further study and the application suffers from some of the same issues affecting bamboo-reinforced concrete described in this paper.

4. Javadian et al. [48] have proposed the use of a heat-treated, densified engineered bamboo composite for concrete reinforcement. The resulting composite strips have a reported tensile strength of 295 MPa and a modulus of 37 GPa. To be used as concrete reinforcing bars, the composite strips are coated with epoxy resin and sand is broadcast onto this as a means of enhancing bond. Bond capacities were reported to be about 80% of comparable steel reinforcement bond strength. Such engineered bamboo composite reinforcing bars hold promise for overcoming some of the obstacles associated with using bamboo as concrete reinforcement. To the authors' knowledge no LCA or similar comparison with steel has been made to document assertions of "sustainability". Nonetheless, it is clear that the additional processing, energy and the resins used on their production will have a significant impact on environmental impact and cost.

5. Finally, Bamboo-fibre reinforced concrete has been proposed and demonstrated by multiple researchers [49-51]. The nature of fibre reinforcement for concrete is quite different from conventional discrete bar reinforcement and beyond the scope of this summary.

CONCLUSION

Although widely proposed as a 'sustainable' alternative to the use of steel reinforcement in concrete, bamboo reinforced concrete is an ill-advised concept. Mechanically, bamboo is unable to contribute to reinforced concrete behaviour in a meaningful manner requiring bamboo-reinforced elements to remain essentially uncracked. This results in concrete member sizes considerably greater than required if conventionally reinforced and an effective prohibition on the design of indeterminate (continuous) structures (which itself results in design efficiency). Additionally, for a variety of reasons, bamboo – without considerable treatment to resist the alkali environment, rot and biological attack – is unlikely to be found to be durable in a concrete environment. Taken together, it is highly unlikely that any economy or sustainability benefit results from safely designed bamboo-reinforced concrete.

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