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Bamboo Reinforcement – A Sustainable Alternative to Steel

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Abstract: *Researchers at the Future Cities Laboratory Singapore/ETH Zurich achieved the liaison of both the superior physical properties of the bamboo fiber and the extraordinary mechanical properties of polymer resins in a new green and sustainable material technology. The team investigates the potential of high-performance bamboo fiber composite materials to replace steel reinforcements in structural concrete applications. The technology as such is to be considered low-tech with injected high-tech knowledge and components in order to up-scale and install it in developing territories. With their fast growing urbanization rates, these areas overlap with the global natural habitat of bamboo, rendering bamboo an affordable and locally available natural resource for a future construction industry. The herein presented newly developed fiber composite materials might revolutionize this industry. In this sense, the research at the Future Cities Laboratory Singapore/ETH Zurich aims to offer a local solution on urban sustainability within a global frame.*

Bamboo, Concrete, Reinforcement, Composite Materials

Introduction

According to the UN Population Division Report 2013([i]) the world's population will increase by 1.8 billion people until 2050. Regarding the question, which parts of the world will have to cope with the highest growth rates, the UN predicts the utmost population increase for developing territories – mainly in Africa and South East Asia. What's more, these territories will not only gain inhabitants but simultaneously experience a rise of urban population. Such ever-growing urbanization, on the other hand, comes along with a huge demand for building materials. Due to traditional construction ideologies, it is in particular cement, steel, glass and aluminum consumption, which shoots up in parallel with urbanization rates. Hence, growing economies within the developing nations entail a huge demand for these materials, which must mainly be imported due to the lack of resources, production knowledge or the necessary industry. Not surprisingly, nearly 90 % of the worldwide shares for concrete demand are ascribed to emerging and developing countries.([ii]) For Ethiopia, for instance, which according to the Economist is the fastest growing nation in Africa today([iii]), cement, steel, glass and machinery add up to the majority of its trade deficit. Such dependence on trade markets, which are mainly dictated by the developed world results in an exploitative north-south relationship and puts entire nations into huge trading shortfalls. In this regard, we ask ourselves what are the possible solutions to the problematic issues, which emerge from an exponentially growing population with an ever-increasing demand for building materials. The answer to this question requires the reshaping of traditional western ideologies imposed on

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the construction sector in the developing world to more innovative and local resources-oriented approaches.

Hence, considering that most developing countries are located within the tropical climate zone and this coincides to be the natural habitat of bamboo – one of the strongest naturally growing materials – it is not far fetched to contemplate its potential for the local building and construction sector. Therefore, we aim to benefit from bamboo's fast growth, its unrivaled capability to store CO_2, its superior mechanical strength and renewability and activate all these features in a new innovative material technology that delivers a lighter, stronger and cheaper material alternative to steel that does not corrode. However, above all, bamboo is growing exactly there, where it can substantially unfold its potential by far more than simply as a building material. Providing these territories a technology to produce an alternative construction material and with it liberate themselves from the current conditions of heavy steel import creates social equity. Even more: the usual one-way directions of global material flows could be reversed into a South-North relationship. A high-performance bamboo-based material helps to establish local value chains, which could in turn strengthen rural-urban linkages and establish alternative technologies based on renewable resources as their key industries. All these factors drive our motivation for the development of this new material technology. As of now, we are able to produce a fibrous material, in which the inherent mechanical properties of certain bamboo species are retained, and then process it into a high-strength composite material. In this publication, we describe the fabrication and mechanical properties of the composite material as well as its performance in reinforcing concrete applications.

Mechanical Properties of Gigantochloa Apus Bamboo
Due to local availability and proximity to Singapore we chose the Indonesian bamboo genus *Gigantochloa Apus* or *Tali Putih*([iv]) as the raw material for the production of our composite. After five to six years, the *Tali Putih* species reaches its full strength capacity, which makes it suitable for high load capacity applications. For this study, we chose 5-year-old bamboos which represent an average distribution of the bottom and middle parts of the entire culm. Tensile specimens out of raw bamboo have been prepared and tested to verify its inherent tensile strength. With an average tensile capacity of the entire culm including nodes – in contrast to solely single fibers – of 363 MPa this bamboo species is particularly suitable for reinforcing applications. Another important material property for building and construction applications is the modulus of elasticity (MOE), which has been determined to values between 19.4 and 22.6 GPa and is higher than many other bamboo species.([v]) No significant variation of both the tensile strength and MOE could be found for the different parts of the culm which points to a rather homogenous distribution of the fibers. The density of *Gigantochloa Apus* is 0.6 g/cm^3.([vi])

Bamboo Composite Material – Fabrication and Properties
In order to exploit these remarkable mechanical properties for building and construction applications it is crucial to preserve the inherent natural strength of the bamboo fibers and

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protect these from environmental impacts such as moisture, fungi and insects. One way to achieve this goal is to process the raw bamboo with the help of thermoset polymer resins and pressure into a composite material with controlled and durable properties.

Our approach involves a processing method for raw bamboo, which entirely relinquishes chemical substances and purely mechanically delivers long bamboo fiber bundles. Thereby, the inherent material properties of the natural bamboo fibers are preserved, which has been proven by achieving equal tensile strengths of the processed fiber bundles as for the natural raw material. After obtaining the raw material, it is dried to reduce the moisture content. The dried bamboo fiber bundles are then bewetted with the resin and placed in the mold of a press. In particular, we look into resin compositions, which utilize naturally sourced ingredients obtained from waste industry. Together with the environmental benefits of bamboo as a raw material and the relatively low operating temperatures of our hot press the production of our composite material (Figure 1) turns out to be CO_2 negative.

Figure 1. Left – High-tensile strength composite material as produced at the Future Cities Laboratory in Singapore. Right – Tensile test specimens after failure.

The obtained composite samples are subsequently prepared into various shapes in accordance with the corresponding standards (ASTM) for testing their mechanical properties. By creating a closed feedback loop between fabrication, analysis and modification we are able to quickly react on the parameters which control the mechanical properties of our composite – the raw material processing, the production process, the resin composition – and control them to achieve optimal material features with respect to the application in concrete. Hence, presently the tensile strength of our prototype surpasses 400 MPa with a MOE of nearly 50 GPa. The compressive strength is in the range of 100 to 120 MPa and the bending strength nearly 200 MPa. Our method protects the bamboo from moisture absorption, fungi and insect attacks as well as renders the material corrosion-free, which is due to the distinct synergy between resin and fibers (Figure 2).

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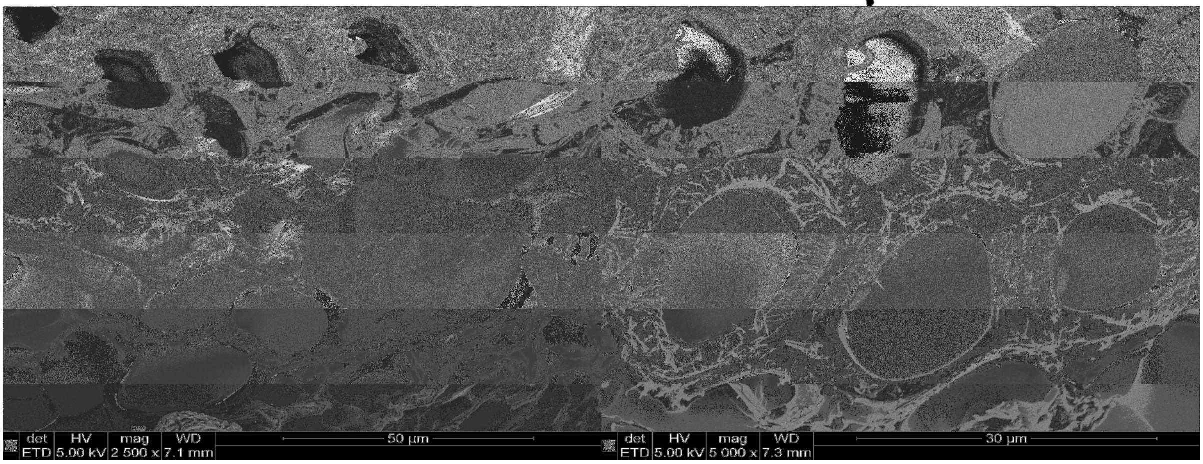

Figure 2. Scanning electron microscopy images of the resin-filled vascular bundles of the bamboo composite material. The smooth surfaced structures represent the resin.

Bamboo Reinforced Concrete – Application and Analysis
After the fabrication of the first proof-of-concept high-tensile specimens of our bamboo composite material the next logical step was the analysis of the reinforcing qualities for concrete applications. Similar approaches have already been attempted decades ago. Early applications of raw bamboo as concrete reinforcement go back to 1914 when when Prof. Chow tested small diameter bamboo culms and splits as a reinforcement material for concrete applications at the MIT in Boston([vii]). Later on, during the 1950s Prof. Glenn conducted major extensive research on natural bamboo as reinforcement in concrete structures at the Clemson Agricultural College of South Carolina([7]). The tensile capacity of bamboo made its application in concrete in principle feasible but drawbacks such as water absorption, low modulus of elasiticity and thermal expansion obstructed a longterm usage. With time, the exposure of bamboo – a natural material – to the concrete matrix results in water absorption from the concrete, leading to a progressive degradation and excessive swelling. The swelling causes internal pressure that builds up inside the concrete and ultimately leads to internal cracks. These cracks propagate in the concrete medium and eventually result in concrete spalling and failure of the structural system.

Unlike raw bamboo, our composite material is waterproof and therefore capable of standing tensile loads in long-term conditions without the problems of swelling, shrinkage and insect or fungi attacks. This chemical resistance makes it suitable for exterior and concrete applications – especially in regions with natural bamboo occurrence.

Concrete Beams – Preparation

To evaluate the mechanical properties of bamboo composite reinforced concrete, four beams were cast using grade 50 MPa concrete due to its common usage in Singapore (Table 1). The tension reinforcement is made from the bamboo composite material. Further, shear reinforcement for flexure was used in the shear span at close spacing of 70 mm center to center distance. The middle part of the beam (140 mm) contained neither compression nor shear reinforcement. This design approach guarantees that the compressive zone of the concrete is not preventing the tension reinforcement from absorbing the loads and yielding under flexural strain. Therefore, already before the concrete begins to crush, the bamboo composite reinfrocements will be activated and bear the tension force. As a result, the estimation of tensile forces on the bamboo composite reinfrocmeents becomes straightforward and can be simply calculated from the experimental parameters.

Table 1. Mix proporation for concrete beams

Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)
400	750	1100	140

Bamboo Reinforcement – Structure

The bamboo composite material in this study was produced out of Gigantochloa Apus bamboo (see above). Before using it as a concrete as reinforcement, the tensile properties of dogbone-shaped samples were measured according to ASTM D7031. The average tensile strength of the utilized material along the fiber direction was in range of 330 to 380MPa, which was comparable to the tensile properties of the raw bamboo culm (363MPa). The reinforcement length was chosen to to guarantee sufficient concrete coverage at both ends of the beam and also to provide additional mechanical anchorage between the composite reinforcement and the concrete matrix. The bars were cut into dogbone shapes as well with square sections.

Testing and Results

The experimental test set up and the instrumentation are shown in Figure 3. Four point bending tests were chosen to study the flexural properites of the concrete beams reinforced with the bamboo composite bars. A universal testing machine (UTM) with a load capaicy of 100 kN was employed and the load was applied at a constant rate of 1 mm/min. The deflection at the center was measured with a dispalacement gauge. The beams were tested until rupture.

Throughout the tests, the first cracks were marked immediately after their formation and the propagation was followed on the exterior surface of the entire beam. It also has been observed that rupture occurred in the mid span of the beam and in the tension bars. Figure 4 shows the crack patterns within the concrete beams and the rupture of the bamboo composite bars. Importantly, the fact that the bamboo composite reinforcements failed in the mid span of the beam indicates that the tension force was taken by the bamboo composite reinforcements before concrete matrix failure, which has been expected. Thus, the maximum load recorded during the tests is an estimate for the actual tensile capacity of the bamboo composite reinforcements in the concrete beam.

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The maximum load recorded during the test was 29 kN, based on the American Concrete Institute design code for structural concrete design corresponds to a value of 310 MPa in design strength. Given the fact that our bamboo composite reinforcement has a modulus of elasticity of not more than 50 GPa such strength is above the expected values for such a flexible reinforcing material. Furthermore, it nearly matches the inherent tensile capacity of the separately tested bars, which hints to efficient load transfer and activation within the concrete matrix. The slight differences between both values could be attributed to the differences in design codes and safety factors for steel reinforced concrete and bamboo composite reinforced concrete. Due to the lack of a design code for the new bamboo composite reinforcement, the material safety factors need to be adjusted to obtain more accurate values. Corresponding design codes are currently being developed at the AFCL in Singapore, as well.

A visual inspection of the tested samples did not reveal any signs of debonding between our material and the concrete environment (Figure 4) which demonstrates an efficient bonding between the composite and the concrete matrix. Moreover, a careful examination of the two ends of the beams did not reveal any slippage throughout the test, which proves a good mechanical friction during bending due to the dogbone shape of the bars. Summarizing, the newly developed and tested bamboo composite reinforcement showed efficient load bearing capacity and bonding throughout our tests, which shows its advantage in comparison with many other alternative reinforcing materials.

Figure 3. four point flexural strength test set-up

Figure 4. crack patterns of the concrete beam and rupture of bamboo composite reinfrocements

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Conclusions

Achieving the successfull activation of the remarkable mechanical strength of a renewable resource in the form of a sustainable composite material, which can be successfully applied as a reinforcement system for structural concrete, does not only come along with huge environmental benefits (e.g. the reduction of carbon footprints) but has an immense socio-economic impact. Considering the fact that the herein presented reinforcement system can actually be produced within those territories, which are less developed but expect the highest demand for building materials within the next decades, the true asset is not a new sustainable material technology but the creation of social equity. An emerging local industry would be able to satisfy the building material demand and, in addition, create new value chains for the rising economies in the developing world. Hence, the true innovation of this research is not the creation and application of a new material that can serve as an alternative to steel in terms of mechanical properties but – most importantly – also as an alternative in view of global socio-economic aspects.