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Conception and feasibility of bamboo–precocious wood composite beams

YOSHIAKI AMINO*

Laboratory of Timber Construction, IBOIS, Swiss Federal Institute of Technology Lausanne, CH-1015 Lausanne, Switzerland

Abstract—Associating bamboo with weak precocious woods, a type of sandwich beam was conceived. This combination, having bamboo layers that act as a reinforcement, develops the usage of less marketed forest products. This paper is devoted to present the conception of this composite beam and its viability. Following the general description of the beam conception, the first half is focused on the manufacture feasibility including the bond ability of bamboo and the lamina production. In the latter half, in view of the realization, the supplemental cost of reinforcement related with the technical performance is discussed in respect of the economical viability of the product.

Key words: Composite; sandwich beam; bamboo; precocious wood; poplar; reinforcement; cost; optimisation.

INTRODUCTION

Regarding the poor economic potential evaluation of the warm regional forests, where profitable conifers are hardly available, inducing the utilization of their local wood species is important to motivate the sustainable exploitation of the forests followed by the maintenance of the local natural resources.

Except for some forests with protected species, such as those in tropical regions, there are huge warm regions yielding exploitable amounts of precocious woods like poplar, eucalyptus, balsa and so on. In spite of their abundant availability, present timber building engineering rarely uses these species, due to their mechanical weakness in comparison with conifers from cold regions. Some of the warm regions not only produce such species with relatively weak mechanical properties, but also produce bamboo. In spite of its fast growth, bamboo provides canes with mechanical advantages.

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*E-mail: yoshiaki.amino@epfl.ch

Combining bamboo and such precocious woods, where laminae taken from large bamboo canes are to be glued on the surfaces of precocious woods, a type of sandwich beam was proposed and studied. This combination allows bamboo laminae to work as load-bearing elements. The proposition of this sandwich beams is based on the idea to increase the utilization of these disregarded species in building constructions. This paper is dedicated to the introduction of the conception of the proposed sandwich beams and to report on their manufacture and economical feasibility.

CONCEPTION OF BAMBOO–PRECOCIOUS WOOD COMPOSITE

Interest in evaluating underestimated species in environmental context

Along with bamboo, there are many kinds of useful, but less used, forest resources in the world. The present timber market deals with very few kinds of wood. These commercialised species are, in the case of construction field, mostly conifers from the industrialized countries in the North Temperate Zone. Their highly standardized construction systems classify and limit the species admissible for the use, depending on their technical properties. The standardization in these countries with high lumber consumption causes the partiality in the commercial value of world wide forest resources (Fig. 1). Except for forests with commercialised species, the

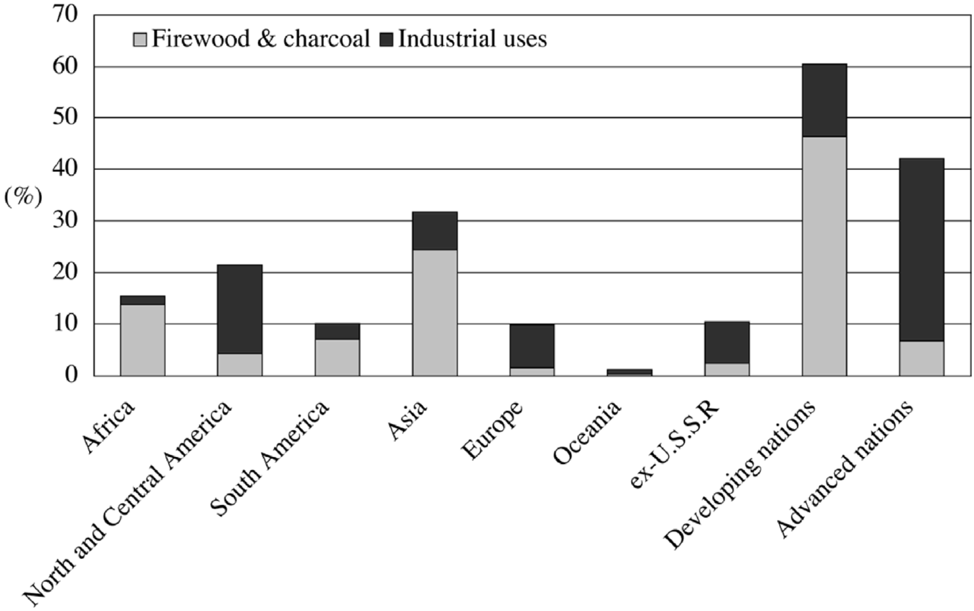

Figure 1. Comparison in main usage of local forest products, according Ref. [11]. Ratios of the industrial use in the developing and undeveloped zones are comparatively small. This figure suggests the commercial partiality of the forest resource value due to the different usage.

majority of forests are not evaluated sufficiently to provoke re-plantation and, therefore, resulting in degradation. In addition, the rapid rise of modern building materials has led to decline of the art of vernacular constructions based on local accessible resources.

The revaluation of variety of species must be effective enough to prevent such kind of forest destruction. Equitable exploitation of forest resources demands not only building systems based on high-performance conifers, but also the development of disregarded species including bamboo.

Materials and composition

Due to their limitation in obtaining massive materials from cylindrical bamboo canes, the bamboo laminae were used as the reinforcement for timber beams with low performance. Fine layers of bamboo laminae were glued on the top and bottom of the timber beams where the stress level was maximized by bending (Fig. 2).

The bending strength of the timber core between the bamboo layers has less mechanical importance. The climate conditions in the growing districts of bamboo, generally high in temperature and humidity, are favourable not only for the germination of bamboo but also for the fast growing woods with low mechanical quality like poplar, balsa, some kinds of sugi, etc. The combination of these minimally exploited fast growing species, bamboo with any timbers of low mechanical properties, can increase their usefulness as construction materials. The high yield of

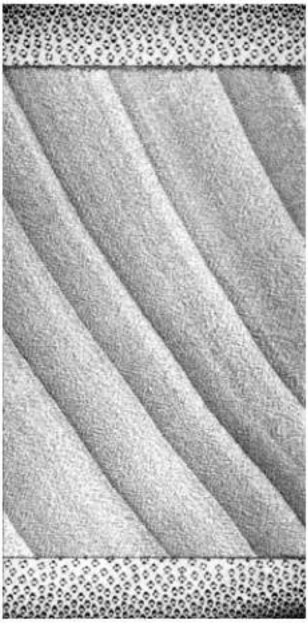

Figure 2. Cross-section of a bamboo–poplar sandwich beam with single layer reinforcement. Bamboo layers reinforce both the top and the bottom of beams, in order to gain the stiffness as well as the strength. The number of layers is to be decided in accordance with the required performance.

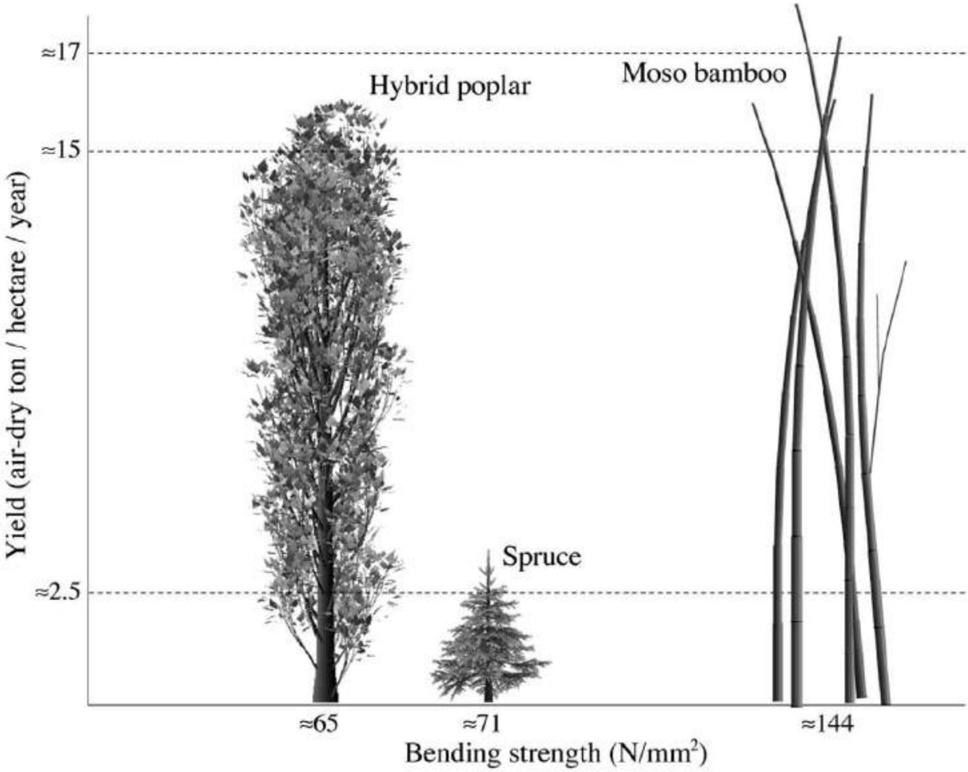

Figure 3. Yield and bending strength of three species: poplar, spruce and Moso bamboo [1, 2, 12, 13].

the components can provide rapid and stable material supply necessary for high productivity (Fig. 3).

Mechanical properties and applications

The mechanical performance of precocious wood beams is enhanced by the bamboo layers glued on their top and bottom, owing to the MoE (modulus of elasticity) and the strength of bamboo. Combining bamboo with any precocious woods enables the improvement in two different aspects of the bending properties of the beam: rigidity and strength. Each improved property suggests the proper applications possible. Following explains the gained mechanical property using poplar as available precocious wood, reinforced by Moso bamboo.

(1) Rigidity improvement. The MoE, or the modulus of elasticity in bending, of Moso bamboo averages about 12 500 $\mathrm{N/mm^2}$, while that of poplar is about 6500 $\mathrm{N/mm^2}$ [1, 2]. The rigidity of the sandwich beams ($\mathrm{MoE_{eff}}$) is in proportion to the MoE of the bamboo layers and to the third power of the distance between the layers and the neutral axis of the beams. In the case of

a n-layer beam, the rigidity, in terms of MoE, is given by

$$\mathrm{MoE}_{\mathrm{eff}} = \frac{\sum \mathrm{MoE}_n I_n}{\sum I_n}, \tag{1}$$

where MoE_n = MoE of the nth layer, I_n = moment of inertia of the nth layer about the neutral plane.

This equation promises an accurate estimate of actual value, if the glue joints of the beams are rigid enough to prevent the sliding of the components [3]. Supposing a symmetric sandwich beam consisting of average poplar and Moso bamboo, the rigidity rises in accordance with the thickening of the bamboo layers, as shown in Fig. 4.

Regarding the application, the rigidity gain is well received by common timber frames consisting of simple beams. The improvement of the rigidity permits diminishing the required dimensions of the simple beams practically determined to keep the maximal deflection below admissible value (e.g. 1/300 of the beam span).

(2) Strength improvement. The bending strength of Moso bamboo averages 144 N/mm^2, about twice the strength of poplar [1]. The bamboo layers, disposed at the adequate positions on the beams, bear higher stress and improve the loading capacity. In order to exploit effectively the mechanical advantages of bamboo, it is indispensable to reinforce the top of the beam as well as its bottom. The reinforcement on the top prevents the compressive rupture of

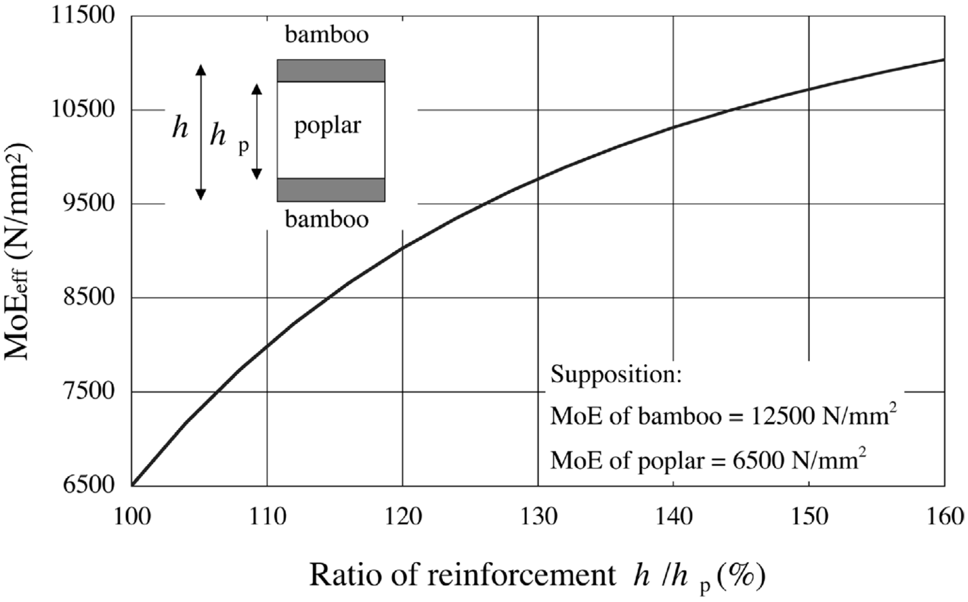

Figure 4. Relationship between the reinforcement ratio (h/h_{p}) and the composite rigidity ($\mathrm{MoE}_{\mathrm{eff}}$), computed using equation (1).

Figure 5. Bending rupture state of bamboo–poplar composite beams. The left beam has the bamboo reinforcement only on its bottom. The absence of the reinforcement on the beam-top allows the deformation increase due to the compressive rupture of poplar. Disposing the reinforcement on both sides is necessary for full exploitation of the bamboo strength.

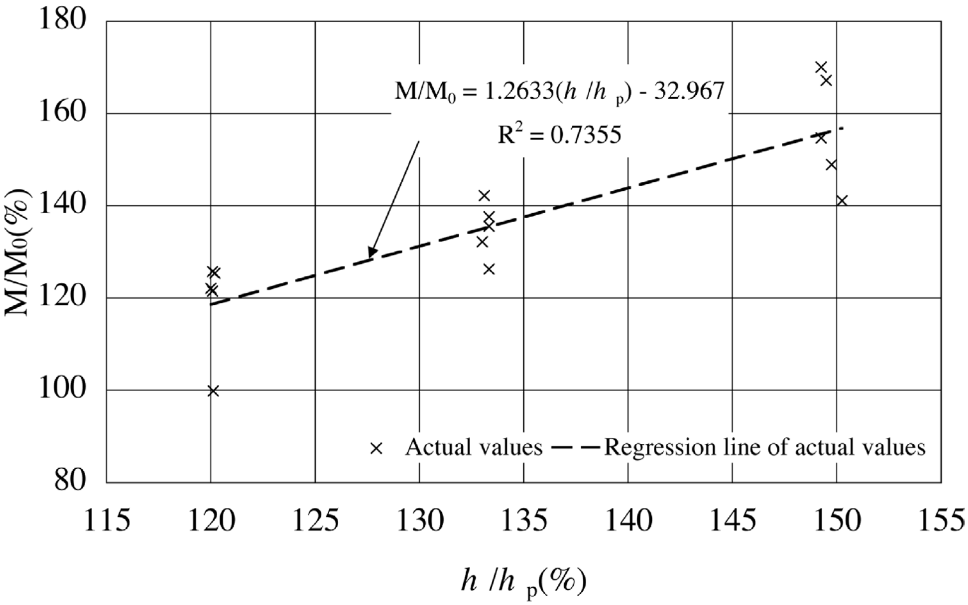

Figure 6. Relationship between the reinforcement ratio (h/h_p) and the strength gain (M/M_0), given by four point bending tests on the bamboo–poplar sandwich beams.

the core, and the beam continues to bear the load until the tensile rupture of the bamboo on the bottom arises (Fig. 5). Four point bending tests on the sandwich beams revealed the relationship between the reinforcement ratio and the strength gain, as shown in Fig. 6. The bamboo layers may be applied to the stress concentrated surfaces like part of the continuous beams (Fig. 7). Some high strength material like bamboo is needed to reinforce these critical parts.

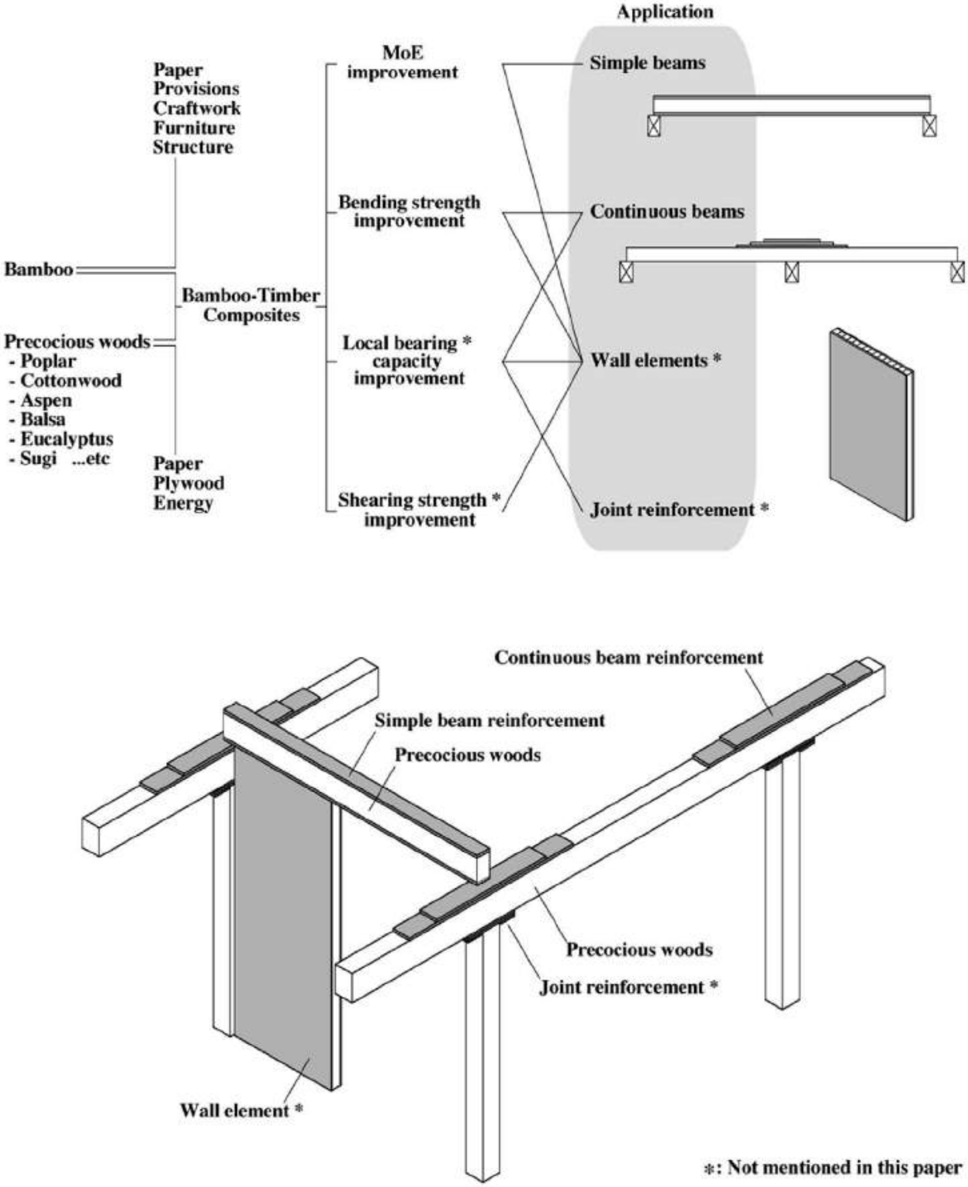

Figure 7. Synthetis pathway of bamboo–precocious wood composite structure.

MANUFACTURE OF THE BEAMS

Bonding feasibility

For beams composed of piled layers, utmost importance needs to be given to the layer joints. Needless to say, the mechanical advantages of composite beams are realized by well-bonded joints of the layers, as this enables the efficient distribution of bending stress to the outer layers.

The bond ability of some precocious woods, often used for plywood cores, has already been studied and proved by industries. On the other hand, the bond ability of bamboo has not been approved enough, similarly as in the case of high-density woods often considered unsuitable for bonding [4]. Further examinations are necessary.

As for bamboo lamination, the authors studied the influence of physical condition of bamboo laminas to the shearing strength of the adhesive joints. The tested specimens consisted of 2-ply 5-years-old Moso bamboo laminae differently bonded by two commercial glues: phenol-resorcinol formaldehyde adhesive and epoxy resin adhesive. Each specimen was composed of machine-planed laminae having approximately the same density. Regarding the gradient change of the tissue composition from the inside to the outside of the canes, three variations of surface combinations were examined: the outside to the outside, the inside to the inside and the outside to the inside (Fig. 8).

Figure 9 illustrates the results on the phenol-resorcinol formaldehyde adhesive joints, visualizing the relationship between the shearing strength, the density and the fibre disposition. As for the selection of the glues, epoxy resin adhesive showed almost the same results, apart from the negligible difference of the strength.

In the relationship between the shearing strength and density, a decrease of strength was found for the highest density specimens of the combinations EX//EX, IN//IN and EX⊥EX. In the other cases, the strength increased proportionally to the density. Although the number of the specimens was not sufficient to recognize the tendency, the results may suggest a difficulty of bonding high-density woods.

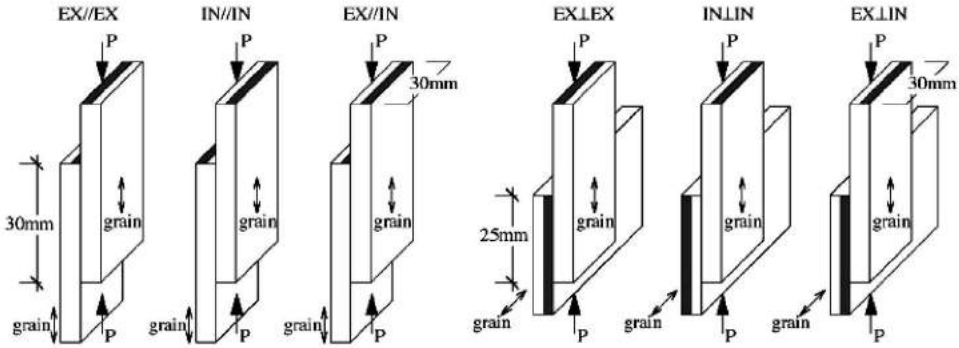

Figure 8. Specimens for the shearing test by compression loading. Each specimen consisted of 5-mm-thick two-ply Moso bamboo laminae. Laminae with near density were coupled. In addition to two types of grain angle, parallel and perpendicular, the difference of bondability between the inside and the outside was studied, considering the grain structure of bamboo. Totally, six types of specimens were prepared. For each combination type, four specimens were glued with phenol-resorcinol formaldehyde adhesive. The tests were carried out in a normal room condition, following the Japanese Industrial Standard K6852 [14].

The influence of the high density to the bonding strength is also observed in the relationship between the strength and the surface combinations. The combinations of the outsides, EX//EX or EX⊥EX, gave lower values than the others. The wood failure ratio of these combinations was also low (Fig. 10). The combinations of the insides, IN//IN or IN⊥IN, had an advantage. The strength of the outside to the inside combinations was between the values of the outside combinations and the inside combinations.

Regarding the combination of bamboo and poplar, the bamboo laminae are to be glued on the poplar beams in parallel. In the case of parallel lamination, the average shearing strength of the adhesive joints was 9.81 to 11.13 N/mm^2. This range of strength is lower than the shearing strength of solid bamboo (about 17 N/mm^2) but higher than that of solid poplar (about 6 N/mm^2) [1, 2]. Shearing the adhesive joints between bamboo and poplar, the failure will not start in the adhesive joints but in poplar.

These remarks suggests that the tested glues realize the necessary bonding strength for the bamboo–poplar sandwich beams, however the outer tissues of bamboo had a wood failure ratio noteworthy low. Since the wood failure ratio showed the fragility of the adhesive joints, it may be necessary to study the long-term reliability of bonding bamboo.

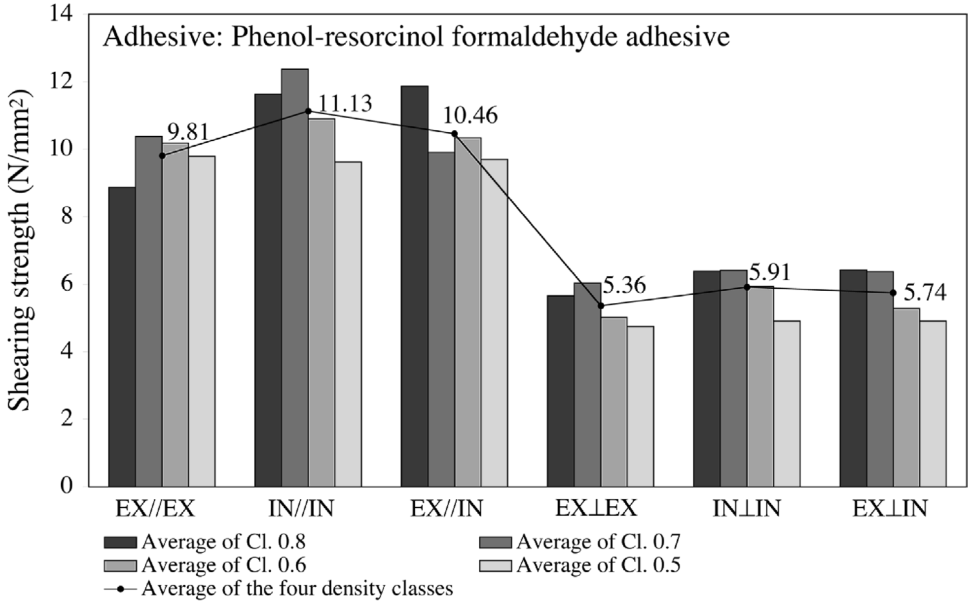

Figure 9. Shearing strength of the adhesive joints of two-ply Moso bamboo laminas. Phenol-resorcinol formaldehyde adhesive is used for bonding. The specimens were classed into four groups according to their density: class 0.5 g/cm^3, class 0.6 g/cm^3, class 0.7 g/cm^3 and class 0.8 g/cm^3. Each column represents the mean value of four specimens having near density. The line graph shows the mean values of each combination type.

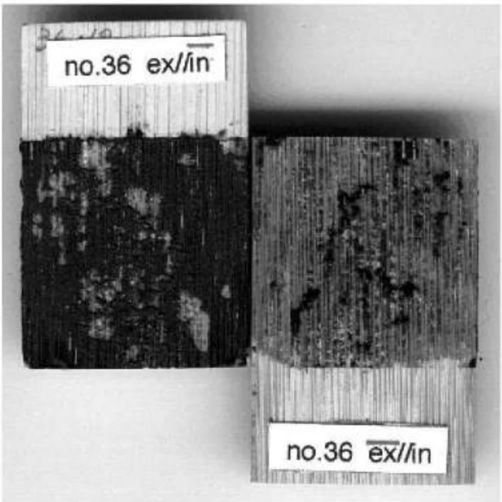

Figure 10. Sheared surfaces of a specimen EX//IN by phenol-resorcinol formaldehyde adhesive. In the case of parallel joints by phenol-resorcinol formaldehyde adhesive, the wood failure ratio rarely exceeded 10%. As shown in the figure, the large detachment of the resins was always observed on the outside (EX) of the laminae.

Lamina production

In addition to the mechanical properties of the material, the method of manufacturing must be an important criterion for the viability of the proposed beams. The complexity of manufacturing, for example the necessity to use machines, determinates the level of investment in the equipment.

The bamboo–precocious wood composite beams can be naturally considered as one of the structural elements for constructions in the developing countries. Financial power in such countries is not always strong enough to invest in highly industrialized equipment. From this aspect, the manufacturing system must not be chosen simply for its efficiency, but also for the accessibility and the possibility to use small equipment affordable with small investment.

The species of core wood and the types of glue are to be selected with regard to the availability and the usage conditions. Besides the choice of the core wood and glue, the preparation of bamboo laminas is an important economical factor for the beam production.

Sufficient investment for machinery can realize the production of wide bamboo laminae, such as Bamboo Flat Board developed by Kagoshima Institute of Industrial Technology (KIT) in Japan [5]. By their method, bamboo canes are automatically transformed into wide flat laminas by radio frequency heat and pressure (Fig. 11). These laminas, taken from common Moso bamboo canes, attain about 120 mm in width and 6 mm in thickness. Such wide laminas are suitable for the improvement in rigidity, which requires the reinforcement covering the full length of the beams.

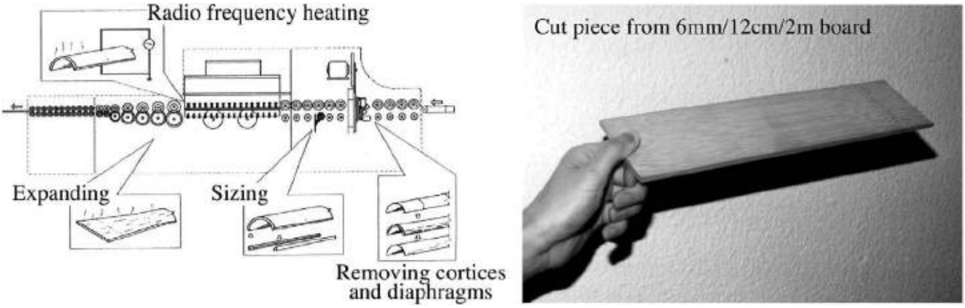

Figure 11. Bamboo Flat Board Production System, as developed by Kagoshima Institute of Industrial Technology, Japan. Half-cut bamboo canes are transformed into wide flat laminae by radio frequency heating and pressure application. This system was conceived as an economical solution to provide wide bamboo laminae. The optimal conditions for the production, such as temperature, humidity and pressure, were studied by Toya *et al.* [5].

Even with rather small investment, the unidirectional fibre arrangement of bamboo canes can be easily split into narrow laminae by the use of simple tools. In this case, the productivity is, needless to say, decreased in comparison with the precedent case. Such narrow laminae demand too much work to cover the whole surfaces of beam. However, they can be efficiently applied as the partial reinforcement needed for the improvement in strength at the stress-concentrated parts of continuous beams (Fig. 7).

From manual treatments to mechanization, the proposed bamboo–precocious wood composite beams can be adapted to different manufacture systems with different levels of investment for equipment.

OPTIMAL RELATIONSHIP BETWEEN LOADING CAPACITY AND REINFORCEMENT COST

Discussing the economical aspect is indispensable in the development of new products. Especially in the case of reinforced material, the cost of reinforcement must be carefully studied in comparison with the required performance. In spite of the importance, it is difficult to precise the cost–performance relation of the bamboo–poplar sandwich beam due to the limited availability of cost information on these materials. Bamboo, poplar or any other of the precocious woods are not traded as construction materials, though they are commercialised for furniture, paper pulp, etc. In addition, the cost of bamboo is very variable, depending on the utilization.

Although there is no commercial value reference to the cost estimation, it will be possible to establish a guideline by the mathematical programming method. This method is often used to optimise the relationship between the cost and the performance [6–9]. Obtaining such a reference is important to evaluate materials of unstable cost.

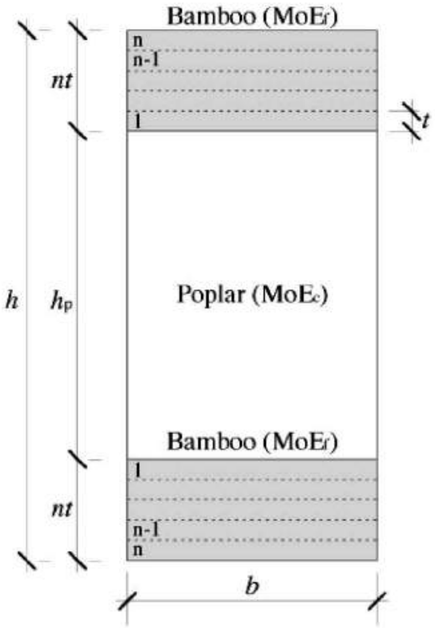

Figure 12. Cross-section of a n-layer symmetric sandwich beam consisting of bamboo reinforcement and solid poplar core. MoE of every bamboo layer is supposed identical, simplifying the cost model definition.

Defining the cost function

Before discussing the optimum relationship between the expected performance and the additional cost for the bamboo reinforcement, it is necessary to introduce an adequate function enabling the cost accounting.

Supposing the production of a bamboo–poplar sandwich beam, illustrated in Fig. 12, consisting of three elements (n-layer bamboo facings, a poplar core and glue), the total cost C can be described as follows:

$$C = C_\mathrm{f}\bigl(h - h_\mathrm{p}\bigr) + C_\mathrm{c}h_\mathrm{p} + C_\mathrm{g}n, \tag{2}$$

where h = depth of sandwich beam, h_p = depth of poplar core, C = cost of sandwich beam, C_f = unit cost of bamboo facing, C_c = unit cost of poplar core ($C_\mathrm{f} > C_\mathrm{c}$), C_g = cost of gluing one layer of bamboo lamina, n = number of bamboo layers.

When the thickness of every bamboo layer is t, equation (2) can be written as

$$\begin{aligned} C &= C_\mathrm{f}\bigl(h - h_\mathrm{p}\bigr) + C_\mathrm{c}h_\mathrm{p} + C_\mathrm{g}\frac{h - h_\mathrm{p}}{2t} \\ &= \left(C_\mathrm{f} + \frac{C_\mathrm{g}}{2t}\right)h - \left(C_\mathrm{f} + \frac{C_\mathrm{g}}{2t} - C_\mathrm{c}\right)h_\mathrm{p} \\ &= C_\mathrm{l}h - (C_\mathrm{l} - C_\mathrm{c})h_\mathrm{p}, \end{aligned} \tag{3}$$

where the coefficient C_l represents the unit cost of the bamboo lamination containing the unit cost of bamboo facing and gluing. In other words, C_l signifies the additional cost required for reinforcing the solid poplar beam.

Optimum stiffness gain–cost relationship

In order to obtain the optimum relationship between the stiffness gain and the additional cost, this section relates the cost function to the equation for stiffness estimation.

As for a sandwich beam with symmetrical cross-section about both axes, x and y, like in Fig. 12, the bending stiffness D is given by

$$\frac{12D}{b} = \mathrm{MoE_c} h_\mathrm{p}^3 + \mathrm{MoE_f}\left(h^3 - h_\mathrm{p}^3\right), \tag{4}$$

$$12D' = \mathrm{MoE_c} h_\mathrm{p}^3 + \mathrm{MoE_f}\left(h^3 - h_\mathrm{p}^3\right). \tag{5}$$

Equation (5) gives h_p:

$$h_\mathrm{p} = \sqrt[3]{\frac{\mathrm{MoE_f} h^3 - 12D'}{\mathrm{MoE_f} - \mathrm{MoE_c}}}. \tag{6}$$

Note that $\mathrm{MoE_f}$ is larger than $\mathrm{MoE_c}$.

Substituting h_p into equation (3) gives the following equation:

$$C = C_l h - (C_l - C_c)\left(\frac{\mathrm{MoE_f} h^3 - 12D'}{\mathrm{MoE_f} - \mathrm{MoE_c}}\right)^{1/3}. \tag{7}$$

This equation is the objective function on the stiffness-cost relationship and traces the curves in Fig. 13. The minimum value of C is drawn, when the differential equation of equation (7) with respect to h follows $\mathrm{d}C/\mathrm{d}h = 0$.

$$\frac{\mathrm{d}C}{\mathrm{d}h} = C_l - \frac{C_l - C_c}{\sqrt[3]{\mathrm{MoE_f} - \mathrm{MoE_c}}}\left(\mathrm{MoE_f} h^3 - 12D'\right)^{-2/3} \mathrm{MoE_f} h^2 = 0. \tag{8}$$

Eliminating D' by using equation (5),

$$\left(\frac{h_\mathrm{p}}{h}\right)^2 = \left(1 - \frac{\mathrm{MoE_c}}{\mathrm{MoE_f}}\right)^{-1}\left(1 - \frac{C_c}{C_l}\right). \tag{9}$$

The proportion h/h_p, satisfying equation (9), minimizes the cost coefficient C.

Comparing with the non-reinforced poplar cross-section with the same dimensions, the ratio of the stiffness gain D/D_o is

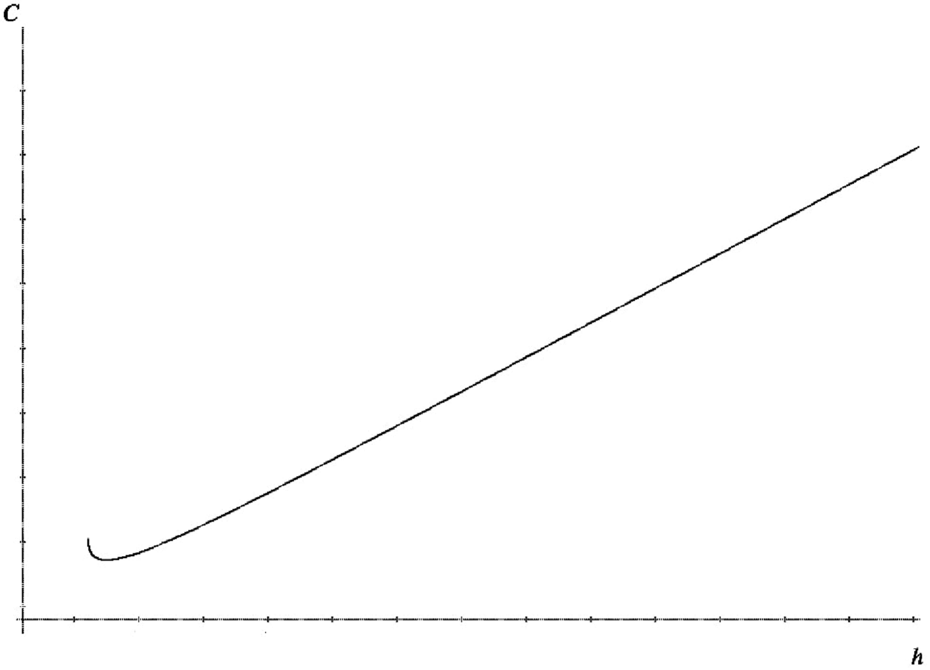

Figure 13. Objective stiffness gain–cost relationship function given by equation (7).

$$\begin{aligned}\frac{D}{D_\mathrm{o}} &= \frac{(\mathrm{MoE_c} - \mathrm{MoE_f})h_\mathrm{p}^3 + \mathrm{MoE_f}h^3}{12}b\left(\frac{\mathrm{MoE_c}h^3}{12}b\right)^{-1}\\ &= \frac{\mathrm{MoE_c} - \mathrm{MoE_f}}{\mathrm{MoE_c}}\left(\frac{h_\mathrm{p}}{h}\right)^3 + \frac{\mathrm{MoE_f}}{\mathrm{MoE_c}}\\ &= \frac{\mathrm{MoE_f}}{\mathrm{MoE_c}}\left(1 - \left(\frac{\mathrm{MoE_f}}{\mathrm{MoE_f} - \mathrm{MoE_c}}\right)^{1/2}\left(1 - \frac{C_\mathrm{c}}{C_\mathrm{l}}\right)^{3/2}\right). \end{aligned} \tag{10}$$

Equation (10) signifies the stiffness gain by the reinforcement proportion h/h_p minimizing the cost.

Substituting the published average values of MoE [1, 2], i.e. $\mathrm{MoE_f} = 12\,500\ \mathrm{N/mm^2}$ and $\mathrm{MoE} = 6500\ \mathrm{N/mm^2}$, into equations (9) and (10), gives,

$$\frac{h_\mathrm{p}}{h} = 2.08\left(1 - \frac{C_\mathrm{c}}{C_\mathrm{l}}\right)^{1/2}, \tag{11}$$

$$\frac{D}{D_\mathrm{o}} = 1.92\left(1 - 1.44\left(1 - \frac{C_\mathrm{c}}{C_\mathrm{l}}\right)^{3/2}\right). \tag{12}$$

The curves obtained using equations (11) and (12) are shown in Fig. 14.

Figure 14 shows the optimum relationship between the reinforcement ratio h/h_p, the stiffness gain D/D_o and the cost ratio $C_\mathrm{l}/C_\mathrm{c}$. For example, for a sandwich beam

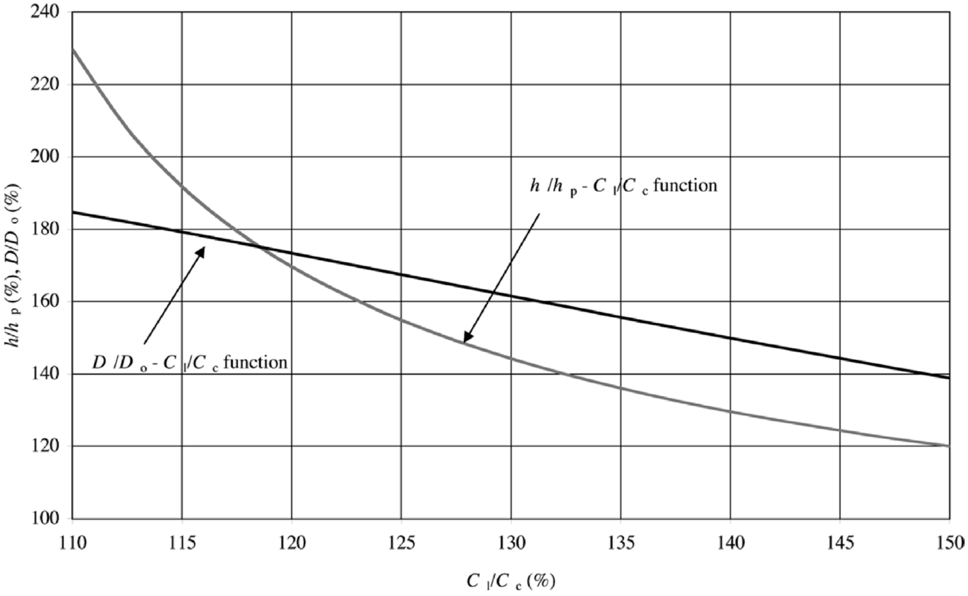

Figure 14. Relationship between h/h_p, D/D_o and $C_\mathrm{l}/C_\mathrm{c}$.

with the reinforcement ratio $h/h_\mathrm{p} = 120\%$, the stiffness gain is $D/D_\mathrm{o} = 139\%$. In this case, the optimum ratio of the bamboo lamination cost to the poplar core cost is computed as $C_\mathrm{l}/C_\mathrm{c} = 150\%$.

Optimum strength gain–cost relationship

This section deals with the optimum cost relation from the viewpoint of strength gain.

In the first place, a simple description of bending strength must be introduced (equation (13)), in order to apply the mathematical programming method to the relationship between the bending strength gain and the cost.

$$M = \sigma_\mathrm{f}\frac{b(h^3 - h_\mathrm{p}^3)}{6h}, \tag{13}$$

where σ_f is equal to the MoR of bamboo in bending.

Equation (13) gives the maximum bending strength of sandwich beam without counting the strength of the core. In the case where the facings have remarkably higher MoE than the core, the bending stress working across this beam section will concentrate on the facings, and the contribution of the core to the whole strength can be considered negligible. A series of tests by the author confirmed the applicability of this assumption, named the stressed skin assumption, to the proposed sandwich beams [10] (Fig. 15).

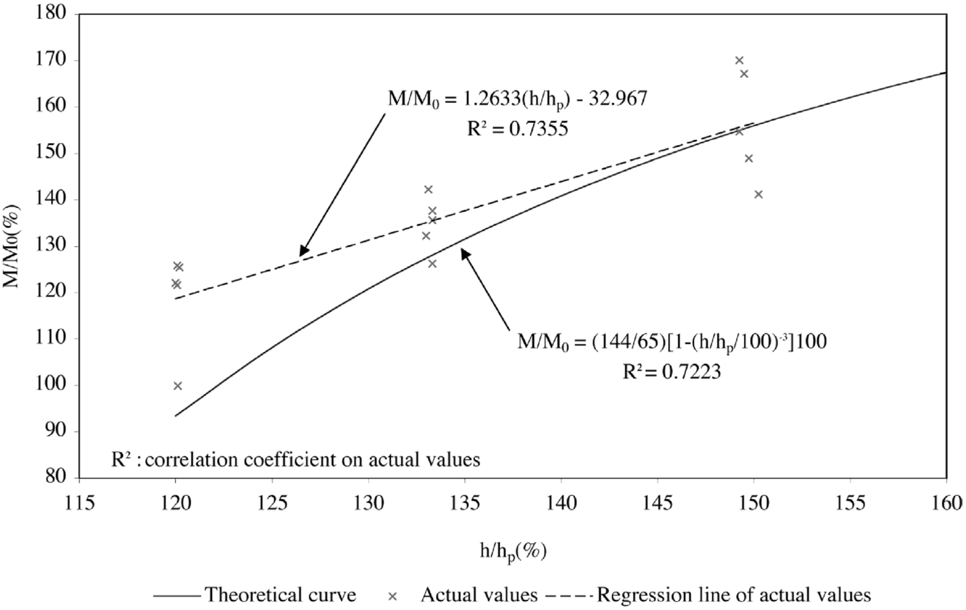

Figure 15. Adequacy of the stressed skin assumption [10]. As for the bamboo-poplar sandwich beams, this figure shows the comparison of the theoretical bending strength given by the assumption with the actual values from tests. With the ratio h/h_p increasing towards 150%, the difference between the estimation and the actual values becomes negligible. Though the assumption is not capable to estimate the bending strength precisely, the accuracy can be considered sufficiently practical. Furthermore, the simplicity allows wider mathematical applications.

Eliminating h_p from equation (3) by equation (13), the objective function respecting the bending strength is given as

$$\begin{aligned} C &= C_\mathrm{l}h - (C_\mathrm{l} - C_\mathrm{c})h_\mathrm{p} \\ &= C_\mathrm{l}h - (C_\mathrm{l} - C_\mathrm{c})\left(h^3 - \frac{6M}{\sigma_\mathrm{f}b}h\right)^{1/3}. \end{aligned} \tag{14}$$

From Fig. 16, in which the curve obtained using equation (14) is shown, we can conclude that the objective function can give a positive minimal solution for C. When the solution is given, the differential equation of equation (14) with respect to h must be $\mathrm{d}C/\mathrm{d}h = 0$.

$$\frac{\mathrm{d}C}{\mathrm{d}h} = C_\mathrm{l} - \frac{C_\mathrm{l} - C_\mathrm{c}}{3}\left(h^3 - \frac{6M}{\sigma_\mathrm{f}b}h\right)^{-2/3}\left(3h^2 - \frac{6M}{\sigma_\mathrm{f}b}\right) = 0. \tag{15}$$

Substituting M from equation (13) gives:

$$\frac{C_\mathrm{l}}{C_\mathrm{c}} = \left(1 - \frac{3(h/h_\mathrm{p})}{2(h/h_\mathrm{p})^3 + 1}\right)^{-1}. \tag{16}$$

The proportion h/h_p satisfying equation (16) minimizes the cost coefficient C.

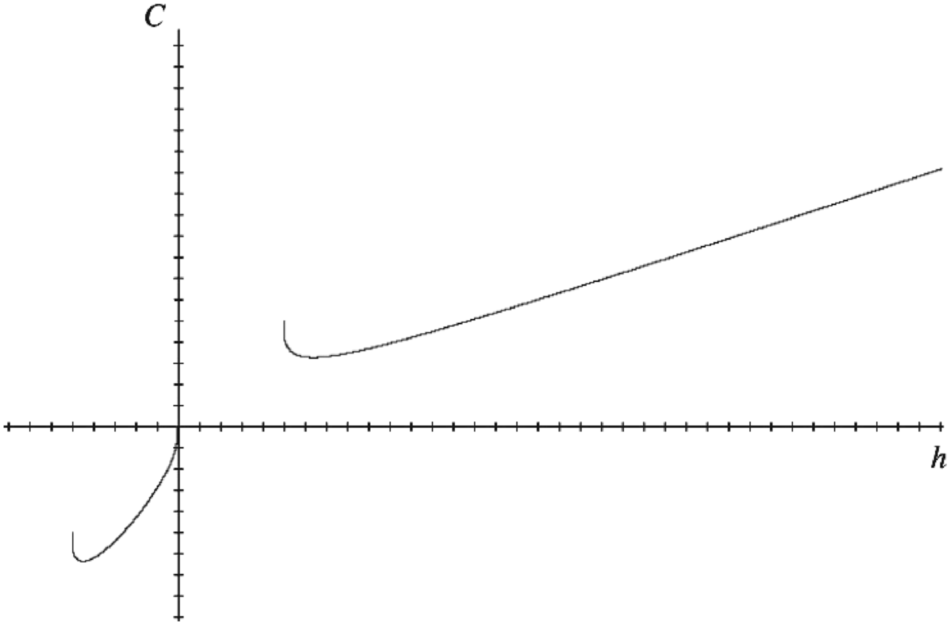

Figure 16. Objective strength gain–cost relationship function given by equation (14).

The maximum bending moment of the non-reinforced poplar beam with the same dimension to the reinforced beam is

$$M_o = \sigma_c \frac{bh^2}{6}, \tag{17}$$

where σ_c represents the MoR of poplar in bending.

Dividing equation (13) by equation (17), the improvement ratio of the bending strength by the bamboo reinforcement is expressed as

$$\frac{M}{M_o} = \frac{\sigma_f}{\sigma_c}\left(1 - \left(\frac{h}{h_p}\right)^{-3}\right). \tag{18}$$

Thus equations (16) and (18) give the optimum relationship between the reinforcement ratio h/h_p, the strength gain M/M_o and the cost ratio C_l/C_c.

Introducing the published MoR of bamboo and poplar [1, 2], $\text{MoE}_f = \text{MoR}_f = 144\ \text{N/mm}^2$, $\text{MoE}_c = \text{MoR}_c = 65\ \text{M/mm}^2$, into equations (16) and 18, this relationship gives the curves shown in Fig. 17.

For example, in the case of the sandwich beam $h/h_p = 130\%$, the approximate bending strength gain is computed $M/M_o = 121\%$ and the figure indicates that the optimum cost ratio of the bamboo lamination to the poplar core is $C_l/C_c = 361\%$. In other words, the cost of bamboo lamination must not exceed $3.61C_c$ to economically realize the bending capacity gain $M/M_o = 121\%$.

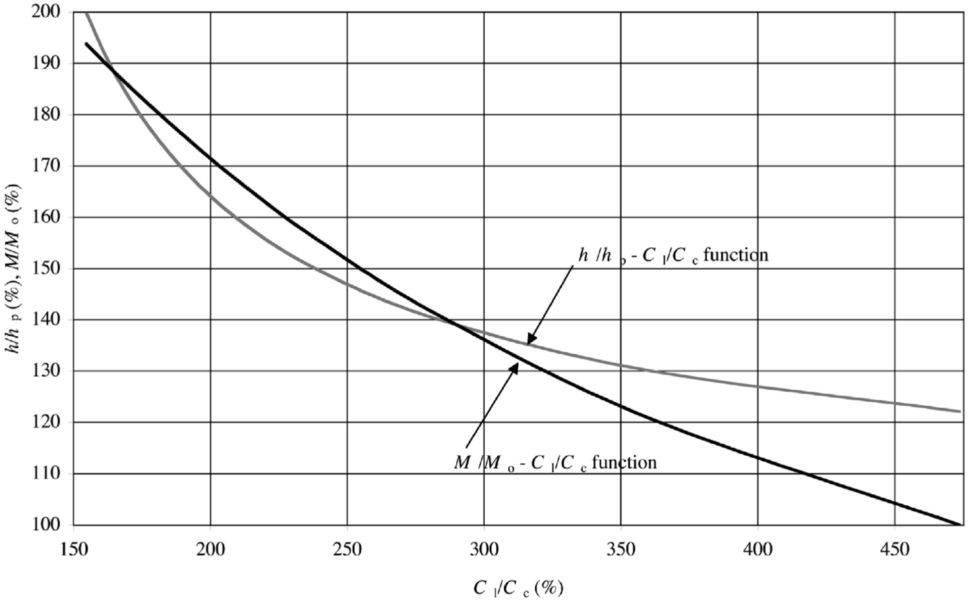

Figure 17. Relationship between h/h_p, M/M_o and $C_\mathrm{l}/C_\mathrm{c}$.

CONCLUSIONS

The adequate combination of bamboo and precocious woods with low mechanical quality can produce a type of beam element in which bamboo plays the role of mechanical reinforcement improving the loading capacity.

The feasibility of the proposed beams is designed to adapt not only to mechanized manufacturing but also to manual treatments with simple tools and commercialised glues, in order to realize the wide popularisation.

In view of real application of the proposed beams, further attention must be paid for the long-term reliability of the adhesive joints that was not covered by this study.

The optimum relationship between the cost ratio, the reinforcement proportion, the stiffness gain and the strength gain was given by the mathematical programming method. The obtained relationship computes approximately the proportion of the reinforcement satisfying the required stiffness or strength, and offers a guideline for determining the optimum cost of the bamboo reinforcement.

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