Assessment on bamboo scrimber as a substitute for timber in building envelope in tropical and humid subtropical climate zones - part 2 performance in building envelope

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Abstract. Bamboo scrimber was fiber based panel developed in 2000s that was potential to be an ideal substitute for construction timber in bamboo growing areas. For evaluating the performance of applying bamboo scrimber in building envelope by clarifying the performance difference with timber, softwood (SW) and hardwood (HW) units were set as reference model, accordingly bamboo scrimber (BFB) units of the same construction and space size as evaluation model, by which performance regarding to building component and space unit were compared. Space units enclosed with bamboo, softwood and hardwood exterior walls were constructed and simulated in WUFI Plus for 16 cities from tropical and humid subtropical regions overlapped with the bamboo forest distribution. Bamboo scrimber showed changeable strengths of heat storage and vapor resistance and weakness of heat transport properties, which varied with the external climate, building function, construction type and HVAC condition.

1. Introduction

The world’s bamboo forest distribution largely overlapped the tropical and humid subtropical climate zones where existed dense population, large construction timber consumption, meanwhile enduring bamboo tradition and extensive bamboo research accumulation, which made bamboo, in panel or square forms, to be an ideal substitute for timber. Different from the other bamboo based panels, mainly including plybamboo (1980s), bamboo particleboard (1990s), bamboo OSB (1990s) and bamboo laminated lumber (1990s) [1, 2, 3] bamboo scrimber, developed in 2000s, was fiber based panel that could be made from herbaceous and small dimension bamboos, which were widely distributed but hadn’t been fully utilized. Thus bamboo scrimber was potential to be promoted in bamboo growing areas to relieve the local timber shortage situation. (Figure 1) The existing study on the bamboo scrimber from the perspective of building industry mostly focused on the mechanical properties for load bearing application, which showed bamboo scrimber had mechanical properties that were equal to or surpassed timber [4, 5, 6]. The construction practices were preceded in China, where scholars and architects took reference from the multilayer timber construction system to carry out the application of bamboo panels in building envelope. Qisheng ZHANG, Zhitao LU developed bamboo anti-seismic housing in 2009, in which various bamboo based panels including bamboo scrimber were used as wall framework with insulation material filled inside to achieve favorable thermal performance [7]. Hao Lin adopted the 2×4 construction method (2×4 inch, 5×10cm) in bamboo housing, in which bamboo laminated lumber and bamboo scrimber were...
used as wall framework and insulation material as filler[8]. Various bamboo profiles for flooring, ceiling and wall were applied in building envelope, which formed a parallel and competitive product series with timber in some regions. Vogtlander, J.G. and Van der Lugt, P. carried out LCA assessment on bamboo scrimber flooring products and showed that the long-distance transport would accounted for a major part of the CO₂ footprint and eco-costs [9]. Therefore the performance comparison with timber competitive products and adaptability evaluation in local regions were of great significance.

![Map of Köppen climate classification overlapped with bamboo forest distribution](image1)

**Figure 1.** Bamboo forest distribution and the overlapping with the climate zones.

Based on the hygrothermal properties test, bamboo scrimber, softwood and hardwood were designed for exterior walls with same construction size and compared for thermal and hygric performance, afterwards enclosed space units with the above exterior walls were constructed in WUFI Plus and simulated the annual dynamic hygrothermal performance of the exterior walls, indoor environment and HVAC demand. The test, calculation and simulation results could provide support for practical application, with consideration to climate condition, building function, construction type, etc.

2. **Simulation model design**

The simulation models were constructed in WUFI Plus, which were composed of external conditions, internal conditions, boundary conditions and HVAC conditions: (Figure 2)

![Simulation model design](image2)

**Figure 2.** Simulation model design (external, internal, boundary and HVAC conditions).
2.1. External conditions
According to Köppen-Geiger climate classification, 16 cities in 5 groups were chosen as the representative cities for Tropical rainforest climate zone (Af), Tropical monsoon climate zone (Am), Tropical savanna climate zone (Aw), Humid subtropical climate zone (Cwa and Cfa). The TMY weather data of the 16 cities were input as the external conditions for the model. (Table 1)

![Map of climate zones]

**Table 1.** Distribution of the 16 representative cities.

| Climate zone                  | Sub zone         | City      | Latitude    | Longitude   | Continent |
|-------------------------------|------------------|-----------|-------------|-------------|-----------|
| Tropical climate              | Af - Tropical rainforest climate | Kisumu    | -0.091702   | 34.767957  | Africa    |
|                               |                  | Kuching   | 1.607681    | 110.37854   | Asia      |
|                               |                  | Manaus    | -3.119028   | -60.021731  | South America |
|                               |                  | Guatemala | 15.783927   | -90.23037   | Central America |
|                               | Am - Tropical monsoon climate | Jacareacanga | -7.316864   | -57.462726  | South America |
|                               |                  | Mumbai    | 19.075984   | 72.877656   | Asia      |
|                               | Aw - Tropical savanna climate | Accra     | 5.603717    | -0.186964   | Africa    |
|                               |                  | Darwin    | -12.46344   | 130.84564   | Australia |
|                               |                  | Brasilia  | -15.794157  | -47.50529   | South America |
|                               |                  | Bogra     | 24.843559   | 89.37018    | Asia      |
|                               | Cwa - Humid subtropical climate | Harare    | -17.825166  | 31.03351    | Africa    |
|                               |                  | Raxaul    | 26.979768   | 84.85158    | Asia      |
|                               | Cfa - Humid subtropical climate | Xiamen    | 24.479833   | 118.08943   | Asia      |
|                               |                  | Santa.Maria | -29.685511  | -53.817054  | South America |
|                               |                  | Tokyo     | 35.689487   | 139.69171   | Asia      |
|                               |                  | Louisville | 38.252665   | -85.758456  | North America |

2.2. Internal conditions
Two types of building functions were set. Type O was office building represented by standard office that was 3.0m×6.0m×3.0m (width×depth×height). The occupancy schedule was 8:00 - 17:00, which represented the space for daytime use. Type R was residential building represented by sleeping room that was 3.0m×4.0m×3.0m (width×depth×height). The occupancy schedule was 22:00 - 07:00, which represented the space for night time use.

2.3. Boundary conditions, namely the building envelope
The exterior walls were chosen as the study objects, while the flooring and ceiling were set as partitions between the same interior conditions. Considering that in practical projects, the bamboo/timber boards were generally used in lightweight or heavyweight constructions, both types with approximate U values were designed. (Table 2)

For ensuring the comparability among different variables, the exterior walls were designed into 3 groups of gradient U values by adjusting single factors. From bamboo to timber components: replaced
the bamboo scrimber (BFB) with softwood (SW) and hardwood (HW) boards, while kept the remaining construction layers; From lightweight construction to heavyweight construction types: replaced the 18mm exterior board and the insulation layer with dena Brick 800 of the same thermal resistance value, while kept the remaining construction layers; The 3 groups of components were assigned to the 16 cities mainly according to the climate zones and the corresponding latitudes.

**Table 2. Boundary condition (Construction of the external walls).**

| Group Type | Exterior | Interior | Construction graph |
|------------|----------|----------|--------------------|
|            | 1-1      | 1-2      | 3                  | 4      | 5      | 6      | n-light construction | r-heavy construction |
| BFB HW     | dena Brick 800 | PE foil | EPS board | Air | BFB SW | HW |
| U 1        |  |
| BFB-a      | 18.0 | 0.002 | 0 | 40.0 | 12.5 | |
| SW-n       | 18.0 | 0.002 | 0 | 40.0 | 12.5 | |
| HW-n       | 18.0 | 0.002 | 0 | 40.0 | 12.5 | |
| BFB-r      | 40.0 | 0.002 | 40.0 | 12.5 |
| SW-r       | 40.0 | 0.002 | 40.0 | 12.5 |
| HW-r       | 40.0 | 0.002 | 40.0 | 12.5 |
| U 2        |  |
| BFB-a      | 18.0 | 0.002 | 20.0 | 40.0 | 12.5 | |
| SW-n       | 18.0 | 0.002 | 20.0 | 40.0 | 12.5 | |
| HW-n       | 18.0 | 0.002 | 20.0 | 40.0 | 12.5 | |
| BFB-r      | 180.0 | 0.002 | 40.0 | 12.5 |
| SW-r       | 180.0 | 0.002 | 40.0 | 12.5 |
| HW-r       | 180.0 | 0.002 | 40.0 | 12.5 |
| U 3        |  |
| BFB-a      | 18.0 | 0.002 | 60.0 | 40.0 | 12.5 | |
| SW-n       | 18.0 | 0.002 | 60.0 | 40.0 | 12.5 | |
| HW-n       | 18.0 | 0.002 | 60.0 | 40.0 | 12.5 | |
| BFB-r      | 460.0 | 0.002 | 40.0 | 12.5 |
| SW-r       | 460.0 | 0.002 | 40.0 | 12.5 |
| HW-r       | 460.0 | 0.002 | 40.0 | 12.5 |

n-lightweight construction, r-heavyweight construction; The group 1, 2 and 3 were designed with U value control of 1.5-2.0W/mK, 0.8-1.0W/mK and 0.4-0.5W/mK

2.4. HVAC conditions

Based on the models consisted of the above conditions, the HVAC were firstly turned off to evaluate hygrothermal performance of the exterior walls and the indoor environment, which was characterized by the indicators including heat and moisture flow, interior surface and air temperature, relative humidity, etc. during the occupancy hours. Afterwards the HVAC were turned on and ran the model with ideal heater & cooler, humidifier & dehumidifier and mechanical ventilation to maintain certain thermal comfort, and calculated the annual heating & cooling, and the humidification & dehumidification demand.

3. Results analysis

3.1. Building component static calculation results

Six indicators related to the thermal and hygric performances were chosen and compared between bamboo and timber building components. The heat transfer coefficient - U value was the most commonly used indicator to characterize the thermal transport performance. The heat capacity - S value, and thermal capacity inside - Si value were indicators to characterize the thermal stability, which had decisive effect on the temperature phase shift, attenuation and fluctuation on interior surface. The vapor diffusion thickness - sd value was chosen to characterize the total vapor permeation resistance of the whole components. (Table 3, Figure 3)
3.1.1. Heat transport properties. Calculated results showed that with the same construction dimensions and layer arrangement, the U values of bamboo components were higher than the timber components, which was caused by the higher thermal conductivity of bamboo scrimber. From U1-U3, the Bamboo-Timber U value magnitudes were narrowed from 0.058-0.270 W/m²K to 0.004-0.021 W/m²K.

3.1.2. Heat storage properties. Calculated results showed that the S values and Sₙ values of bamboo components was higher than the timber components, with magnitudes correspondingly of 10-30 KJ/m²K and 6.1-13.4 KJ/m²K. The magnitudes were larger between bamboo scrimber and softwood components than that between bamboo scrimber and hardwood components, and meanwhile larger in lightweight construction than in heavyweight construction. The temperature phase shifts of bamboo components were 0.7-2.0 h longer than timber components. The temperature attenuation magnitudes of bamboo components to timber components of Group U1 and U2 were 0.082-0.874 slightly larger than timber components, but were enlarged significantly to 1.194-1.652 in lightweight construction and 7.937-12.078 in heavyweight construction in U3.

3.1.3. Hygric performance. Calculated results showed that the sₙ values of bamboo scrimber components was larger than the timber components, with magnitudes of 11.62 m in lightweight construction and 4.77 m in heavyweight construction, which was caused by the higher water vapor permeation resistance factor - μ value of bamboo scrimber. It meant that the bamboo components were of higher resistance to moisture transport, which could be dialectical that could help to weaken the vapor transport on one side, while on the other side might slow down the indoor moisture from exhausting.

**Table 3. Building components thermal and hygric performance calculation results.**

| Group | Type  | Heat transfer coefficient [W/m²K] | Heat capacity [KJ/m²K] | Thermal capacity inside [KJ/m²K] | Phase shift [h] | Temperature attenuation [-] | Vapor diffusion thickness [m] |
|-------|------|----------------------------------|------------------------|----------------------------------|----------------|-----------------------------|-----------------------------|
| U1    | BFB-n| 1.880                            | 53                     | 17.1                             | 2.3            | 1.130                       | 23.64                       |
|       | SW-n | 1.610                            | 23                     | 6.7                              | 1.1            | 1.022                       | 12.02                       |
|       | HW-n | 1.727                            | 28                     | 9.5                              | 1.5            | 1.048                       | 12.02                       |
|       | BFB-r| 1.773                            | 48                     | 17.2                             | 2.5            | 1.159                       | 16.22                       |
|       | SW-r | 1.597                            | 33                     | 8.3                              | 1.0            | 1.030                       | 11.45                       |
|       | HW-r | 1.715                            | 37                     | 11.1                             | 1.7            | 1.057                       | 11.45                       |
| U2    | BFB-n| 0.969                            | 53                     | 19.3                             | 4.0            | 1.637                       | 24.24                       |
|       | SW-n | 0.892                            | 24                     | 7.1                              | 2.0            | 1.101                       | 12.62                       |
|       | HW-n | 0.927                            | 28                     | 10.5                             | 2.7            | 1.233                       | 12.62                       |
|       | BFB-r| 0.940                            | 139                    | 55.0                             | 8.0            | 3.731                       | 18.32                       |
|       | SW-r | 0.888                            | 124                    | 42.0                             | 7.0            | 2.857                       | 13.55                       |
|       | HW-r | 0.923                            | 129                    | 47.0                             | 7.3            | 3.096                       | 13.55                       |
| U3    | BFB-n| 0.492                            | 54                     | 21.0                             | 5.3            | 3.077                       | 25.44                       |
|       | SW-n | 0.471                            | 25                     | 7.6                              | 3.5            | 1.425                       | 13.82                       |
|       | HW-n | 0.481                            | 29                     | 11.5                             | 4.3            | 1.883                       | 13.82                       |
|       | BFB-r| 0.484                            | 321                    | 146.0                            | 17.5           | 55.556                      | 22.52                       |
|       | SW-r | 0.470                            | 306                    | 130.0                            | 16.5           | 43.478                      | 17.75                       |
|       | HW-r | 0.480                            | 311                    | 136.0                            | 16.8           | 47.619                      | 17.75                       |

n-lightweight construction, r-heavyweight construction
3.2. Enclosed space units dynamic simulation results
The enclosed space units were simulated for the whole year in both HVAC on and off condition. The hygrothermal behavior of the exterior walls and the indoor environment during the occupancy hours without HVAC, afterwards the annual heating & cooling, humidification & dehumidification demand with ideal HVAC were analyzed. The BFB-SW and BFB-HW ratios were calculated to show the strengths and weaknesses and evaluate how far the difference between bamboo and timber were.

3.2.1. Hygrothermal performance of the exterior walls. In HVAC off condition, the heat exchange with exterior walls and the interior surface temperature amplitude were chosen as indicators to characterize the thermal performance. As for the heat exchange, due to the higher U value, the BFB units were mostly up to 46.65% and 13.30% larger than SW and HW units, but in certain cases, mostly the residential space, the heat exchange with BFB units was lesser. The interior surface temperature of BFB components was up to 12.62% and 6.35% lower than the SW and HW units, which resulted from the higher S value. Moisture exchange with the exterior walls and the total moisture flow were chosen as indicators to characterize the hygroscopic performance (The former value was remainder of the moisture gain and moisture loss, while the latter was the sum of all the moisture flow through the components). Due to the higher $\mu$ value, the total moisture flow through BFB components were up to 33.54% smaller than the SW and HW units, which was beneficial for preventing the building component from moisture damage. However, the moisture exchange, which was affected by both the $\mu$ value and the vapor transfer direction, didn’t show that clear regularity. Mostly the moisture exchange of BFB components were 29.26% and 43.15% lesser that SW and HW units, while in some cases, mostly the SW residential space, the values of BFB components were 48.81% and 32.23% larger than the SW and HW units. (Figure 4)
3.2.2. Indoor environment. In HVAC off condition, the hours proportion in occupancy period of the interior air temperature between 20-26°C, and the interior relative humidity between 40%-60% were chosen as indicators to describe the hygrothermal environment of the enclosed space units. As for the interior temperature, the BFB units performed better than SW and HW units, corresponding with magnitudes up to 112.68% and 63.16%, but in certain cases, mostly the residential space, the BFB units performed worse than SW and HW units, corresponding with magnitudes up to 20.81% and 10.57%. The difference magnitudes between BFB and SW were larger than between BFB and HW, and in lightweight construction larger than in heavyweight construction, and both narrowed with thermal performance improvement of the whole components. As for the relative humidity, due to the continuous high relative humidity, in most cases there were very few or even none hours when the indoor relative humidity could maintain within 40%-60%, which led to incomparability between BFB and timber units. Probably, the BFB units performed worse in Cwa zones and better in Cfa zones than SW and HW units, and approximately in Af, Am and Aw zones. (Figure 5)
3.2.3. *HVAC demand.* In HVAC on condition, ideal heater & cooler, humidifier & dehumidifier and mechanical ventilation were arranged to maintain certain indoor comfort. The annual total energy, humidification & dehumidification demand were indicators for comparison. The energy demand of BFB units was mostly up to 22.22% larger than SW units, and 16.87% larger than HW units due to the higher $U$ values of BFB components, however in Kisumu and Brasilia, the BFB units could even consume lesser energy, which might result from the raising impact of $S$ values. In aspect of hygric performance, the BFB units required mostly up to 12.84% smaller humidification & dehumidification demand than SW and HW units, while in particular cases the BFB units would require up to 24.17% larger than SW and HW units, which meant that the higher $s_d$ value of BFB components didn’t ensure smaller humidification & dehumidification demand that was also affected by the vapor transfer direction. In hot and humid regions the higher $s_d$ value of BFB components could help to buffer the influence of outside humid air on the indoor environment, while in some cases it might also block the indoor moisture from exhausting. (Figure 6)
4. Conclusion

1) Static test and calculation results showed that, compared with the timber units, bamboo scrimber units had advantages in heat storage performance that provided stable indoor thermal environment particularly in non HVAC condition and lightweight construction; stronger vapor resistance that was beneficial for preventing from damage caused by moisture flow; on the other hand, the higher heat transport performance of bamboo scrimber components should be improved.

2) The dynamic annual simulation in WUFI Plus showed that thermal and hygric performance above had conclusive impact on hygrothermal performance of the enclosed space, however the weights of each indicators varied with climate condition, building function, construction type and HVAC control.

3) The difference between the static calculation and dynamic simulation results showed the necessity of a comprehensive evaluation approach that could cover progressive levels on the physical performance of material, building component and enclosed space. Verification for the simulation results by either test houses or practical application feedbacks were required in further works.

5. Reference

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