Assessment on bamboo scrimber as a substitute for timber in building envelope in tropical and humid subtropical climate zones - part 1 hygrothermal properties test

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Abstract. Bamboo scrimber was bamboo fiber based panel developed in 2000s that was potential to be an ideal substitute for timber in bamboo growing areas. For obtaining material parameters and evaluating the performance in building envelope, bamboo scrimber was systematically tested for hygrothermal properties, based on the building envelope heat and moisture process model. Static test items included density calculation and vacuum saturation test for basic properties; sorption test for moisture storage properties; capillary absorption test, water vapour transmission test and drying test for moisture transport properties; thermal analysis for heat storage properties; thermal conductivity test, surface light and thermal properties test for heat transport properties. The test results, by comparison with reference timbers showed that bamboo scrimber had higher heat storage and heat transport properties and lower moisture storage and transport properties. The dynamic test in wind tunnel with outdoor weather condition showed that bamboo scrimber had lower moisture absorption and desorption rate than reference hardwood. The significant magnitude difference between the static and dynamic test results showed the necessity of a comprehensive evaluation approach that could take more practical conditions into consideration.

1. Introduction
Bamboo forests were widely distributed in the tropical and humid subtropical climate zones in the Asia Pacific (ca. 67%), the Americas (ca. 30%) and Africa (ca. 3%) [1]. The application of bamboo in building industry varied with regional differences due to the local forest resources, economic conditions and construction technology. Large-diameter round bamboos, as an easily accessible, affordable and seismic construction material, were widely used in traditional bamboo building in the Southeast Asia and South America [2]. Since 1970s, restricted by the regional wood forest resources, modified bamboos in standard panel or square form were considered to be an ideal substitute for timber [3]. In countries including China, India, Thailand, Vietnam, Costa Rica, Malaysia, etc. timber processing technologies were introduced to the industrial utilization of bamboo, afterwards plybamboo (1980s), bamboo particleboard and bamboo OSB (1990s), bamboo laminated lumber (1990s) were successively developed [4,5,6], and promoted to the concrete formworks, load-bearing components, truck and bus bottom boards, furniture and finishes industries [3]. Microscopically, bamboo was composed of mostly parallel arranged fiber that had higher strength than wood fiber [1,2], which prompted that products based on bamboo fiber were beneficial for exploiting the inherent advantage. However, due to the low added value and complicated manufacturing process,
bamboo fiber boards in form of MDF consisted of fully separated fiber weren’t successfully promoted [7]. Bamboo scrimber simplified the constituent units as loose bamboo fiber bundle [8], could be made from those herbaceous and small dimension bamboos, and improve the raw material utilization rate to 90% [9], therefore rapidly grew as the mainstream of bamboo fiber boards and was widely promoted to the load-bearing components, indoor finishes, outdoor pavement, furniture and wind power blades, etc.[9,10] existing study on bamboo scrimber covered the manufacturing process, including the produce of constituent unit, dipping, assembly, cold and hot pressing method [11,12] and cracking proofing, deformation proofing, anti-corrosion [13] and frame retardant techniques [14]. In practical application, due to the insufficiency of material study, bamboo properties were commonly substituted with timber parameters, which caused inaccuracy to the projects. The paper tested bamboo scrimber for the hygrothermal properties with static and systematic standard methods, and afterwards carried out a wind tunnel test to examine the hygric behavior in outdoor condition. Corresponding timbers in both tests were set as reference for the evaluation of bamboo scrimber.

2. Hygrothermal properties test

2.1. Material
Before the test, based on the investigation of literature, market and material producers in bamboo industry, typical bamboo scrimber samples were chosen as the test objects, as shown in Table 1.

Table 1. Information of the bamboo scrimber sample.

| BFB (Bamboo scrimber) | Constituent unit | Assembly | Thickness | Main application | Sample sources |
|-----------------------|-----------------|----------|-----------|-----------------|----------------|
| Bamboo bundle (width:10-30mm) | Parallel | 30.0 mm | Load-bearing component, indoor/outdoor flooring, finishes, furniture | Dasso Industrial Group Co. Ltd. Hangzhou, China |

Main manufacturing processes of bamboo scrimber (Photos were taken in Zhejiang province, China by the author)
2.2. Static test items

There were dozens of hygrothermal properties that constituted different heat and moisture process models for simulation. Before 1990s, the steady vapor permeation model proposed by Glaser was widely used, which took purely the water vapor permeability for the calculation in one-dimensional steady-state moisture process, which couldn’t describe the actual situation that was generally non-steady and multiphase simultaneous. In the nearly 20 years, Mølend, Pedersen, Künzel, Häupl, Janssen, Mendes, Steeman and Tariku successively proposed heat-air-moisture transfer model (HAM model) to describe the coupled storage and transport of heat, moisture and air in building envelope [15,16,17,18,19,20,21,22] The models had been verified under various conditions, including the IEA Annex 41 in 2008 that compared 17 HAM models and their numerical simulation tools and completed 7 joint comparative tasks, which proved that the calculation results among the main HAM models and the measured results were close to each other [23,24]. HAM models normally consisted of highly coupled nonlinear partial differential equations that describe simultaneously the heat and moisture processes in building envelope, which were solved through numerical methods [25] Compared with the Glaser model, HAM models relied on much more detailed material parameters as calculation inputs. Hartwig M. Künzel simplified the necessary material parameters for one and two-dimensional heat and moisture process calculation, and used vapor pressure and relative humidity respectively as the driving potentials for gaseous water and liquid water. Two coupled differential equations were proposed to describe the non-steady heat and moisture transport processes in building components, which formed the basis for the computer program WUFI [17].

The heat and moisture transport mechanism and test items were showed in Figure 1, which were based on the equations from H M. Künzel. The above equation described the moisture process, which successively consisted of moisture storage, liquid water transport and gaseous water transport. The below equation was the heat process, which was successively composed of heat storage, heat transport and heat sink. Both equations consisted of storage terms on left side and transport terms on right side.

![Figure 1. Building envelope heat and moisture transport mechanism and the bamboo scrimber test items (the equations on left side were from H M. Künzel [17]).](image)
The running of the model based on these coupled differential equations required the input of material parameters, climate data, internal conditions, and control parameters such as numerical grid and time step width. The material parameters included basic properties such as bulk density, porosity, and the correlative properties characterized the storage and transport abilities of moisture and heat. Nine test items were carried out according to the corresponding test standards. The tests targeted only for the thickness direction, considering that the thickness of the bamboo panels in practical application was far less than the plane dimensions, which meant the heat and moisture transferred approximately one-dimensionally and vertically through the panels. As some previous studies had shown that the repeatability error was generally far smaller than the unevenness error of the samples [26], multiple copies were carried out simultaneously during the test, rather than repeated the specimens for the same items. (Table 2)

| Category          | Item                      | Operation method                                                                 | Equipment arrangement                                                                 | Specimens treatment                   |
|-------------------|---------------------------|----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|----------------------------------------|
| Basic properties  | 1. Density test           | -                                                                               | Drying oven: digital stainless steel electric blast oven 101A-2S, accuracy ±1°C       | Quantity: 9 copies, Size: 10x20cm      |
|                   | Target value: dry bulk    |                                                                                  | Balance: SHIMADZU UX6200H, accuracy 0.01g                                             |                                        |
|                   | density                   |                                                                                  |                                                                                       |                                        |
|                   | 2. Vacuum saturation test | Target value: open porosity, vacuum saturation moisture content                 | Drying oven: same as item 1                                                            | Quantity: 3 copies, Size: 10x10cm      |
|                   | Refer to the American standard ASTM D7370-2009, and the European standard DIN EN 1936-2007 [27, 28] |                                                                                  |                                                                                       |                                        |
|                   | 3. Sorption test          | Target value: isothermal absorption and desorption curve                        | Vacuum dryer (9 copies): inner diameters 30cm, Balance: same as item 1, T & RH recorder: TH10R-EX, with external sensor (9 copies), accuracy Ta=0.2°C, RH±2% | Quantity: 3 copies, including 1 large sample and 2 small samples |
|                   | Refer to the international standard ISO 12571:2012 and the American standard ASTM C1498-04a [29, 30] |                                                                                  |                                                                                       |                                        |
|                   | 4. Water vapor transmission test | Target value: water vapor transfer coefficient                            | Dry cups (3 copies), wet cups (3 copies), Balance: same as item 1, Constant T&RH curing box: HWS-250B, accuracy Ta±0.5°C, RH±5% | Quantity: 6 copies, Size: 10x10cm      |
|                   | Refer to the international standard ISO 12572:2001(E) [31] |                                                                                  |                                                                                       |                                        |
|                   | 5. Capillary absorption test | Target value: water absorption coefficient; capillary saturation moisture content | Water sink: length×width×height=40x30x10 cm, Stainless steel nuts supports of equal height were fixed on the bottom; Distilled water were injected in the sink and kept the water level 3mm above the supports, Balance: same as item 1 | Quantity: 3 copies, sealed on top and side surfaces, while kept 4 5×5mm air vents on top surface and 6mm gaps close to the bottom edges on side surfaces open |
|                   | Refer to the international standard ISO 15148:2002(E) [32] |                                                                                  |                                                                                       |                                        |
|                   | 6. Drying test            | Target value: drying curve; drying rate curve                                  | Balance: same as item 1, Constant T&RH curing box: same as item 5                     | Quantity: 3 copies, sealed on top and side surfaces Size: 10x10cm                  |
|                   | Refer to the test method of Fraunhofer IBP (accredited according to DIN EN ISO/IEC 17025) |                                                                                  |                                                                                       |                                        |
|                   | 7. Thermal analysis       | Target value: specific heat capacity                                           | Differential thermal scanning / thermogravimetric analyzer: TA4000/2910MDSC, Reference material: sapphire | Quantity: 3 copies, Mass: 20mg         |
|                   | Refer to the international standard ISO 11357-4-2005 [34] |                                                                                  |                                                                                       |                                        |
|                   | 8. Thermal conductivity test | Target value: thermal conductivity                                             | Guarded hot plate apparatus: CD-DR5030, hot plate T=35°C, cold plate T=15°C, size of central heat transfer area 15x15cm, accuracy ±2% | Quantity: 4 copies, including 3 large samples and 1 small sample Size: large samples 30x30cm, small sample 10x20cm²  |
|                   | Refer to the international standard ISO 11357-4-2005 [35] |                                                                                  |                                                                                       |                                        |
|                   | 9. Surface light and thermal properties test | Target value: hemispherical emissivity; light reflectivity; solar direct reflectivity; solar direct absorptivity | Refer to the European standard DIN EN 16012-2012 [36] | Quantity: 4 copies, including 1 large sample and 3 small samples Size: large sample 10x20cm², small samples 10x10cm²  |
|                   | Refer to the European standard DIN EN 16012-2012 [36] |                                                                                  |                                                                                       |                                        |

*a. Specimens after being dried in item 1 were put in the vacuum dryers for test item 3;  
*b. Specimens after reaching the equilibrium moisture content were carried on in test item 8 and 9;  
*c. Use the specimens after vacuum saturation test in test item 2;  
*d. Use the specimens after reaching the equilibrium moisture content in test item 3
2.3. Dynamic test in wind tunnel

For examining the behavior of the materials in outdoor conditions, a wind tunnel test was carried out with a typical summer day weather data of Guangzhou, a subtropical city located in south China. The weather data including dynamic solar radiation, air temperature, relative humidity and constant wind speed was repeated for 72 hours, of which the last 48 hours were selected for analysis. The reference timber in this test was Intsia.spp (Caesalpiniaceae), a kind of antiseptic hardwood for outdoor flooring. (Figure 2, Table 3)

![Figure 2. Bamboo scrimber wind tunnel test.](image)

Table 3. Weather condition, operation, equipment and specimens of the wind tunnel test.

| Weather condition (24h repeated) | Operation method | Main equipment arrangement | Specimens treatment |
|----------------------------------|------------------|---------------------------|---------------------|
| Solar radiation: sunset - 06:00 | Operated the weather condition until deviation of solar radiation, and relative humidity and wind speed ≤5%, and air temperature ≤0.3°C | HHCWT: Hot-Humid Climatic Wind Tunnel, including control systems for: Air temperature: 2 air conditioner (KFRd-60L/W/V-A-ZXF, 6kW, and KFR; 72LW/08EBBPC-a, 7.2kW) and 2 electric heating fans (1.5kW and 5kW), range 20-40°C, accuracy 0.3°C; Relative humidity: 2 electrode humidifiers (BFD-01-04, 0.4kg/h) and 1 dehumidifier (DH-800C, 90L/d), range 40-90%, accuracy 3%; Solar radiation: 8 infrared lights (305 - 3000nm), range 0-1030W/m², accuracy 10W/m²; Wind: axial fan, range 0-5m/s, accuracy 0.2m/s. | Size: $A_{FR}$ - 0.0822 m² (30x27.4cm) $A_{FW}$ - 0.0810m² (30x27cm) Side and bottom surfaces sealed with 1-2mm Vaseline The gaps between specimens and the slots were also sealed with Vaseline |
| sunset - 18:00 | | | |
| max. value - 539.0W/m² | | | |
| Air temperature: mean value - 28.7°C | | | |
| amplitude - 2.6°C | | | |
| max. time - 15:00 | | | |
| Relative humidity: mean value - 80.3% | | | |
| amplitude - 12.5% | | | |
| max. time - 05:00 | | | |
| Wind speed: constant as 0.6m/s | | | |

3. Test results analysis

3.1. Reference timber

Since the knowledge on timber was relatively sufficient, the comparison with timber could support the evaluation of bamboo scrimber. However, the timber parameters from different databases varied greatly, which meant that to obtain precise Bamboo-Timber ratio was impractical. Here the 28 timbers from Fraunhofer IBP in WUFI Plus material database were chosen as reference timber (RT). The range of RT defined by the maximum and minimum values, and the relative position of bamboo scrimber were analyzed below. (Table 4, Figure 3)

3.2. Comparison between bamboo scrimber and the reference timber

1) Basic properties. Both the bulk density and open porosity of bamboo scrimber exceeded the range of the reference timber. The high bulk density, as 1108.77 kg/m³, rarely existed in plant materials,
which mainly due to the high density of the raw material and strong pressing during the manufacturing process. The low open porosity resulted from the high pressure and waterproofing agent that compressed and blocked the pore structure, was conductive to the application in outdoor environment.  

2) Hygric properties. Compared with the reference timber, the isothermal absorption and desorption curve of bamboo scrimber was in a lower position. The gaseous water transport property was greatly influenced by the moisture content. The vapor transfer resistance factor fell from 921.28 to 47.67 when moisture content rose from \( w_{RH=20.0\%} \) to \( w_{RH=93.0\%} \). The relative position of bamboo scrimber to reference timber also fell with the increasing moisture content. Due to the lower open porosity, the liquid water storage and transport abilities were lower than the reference timber.  

3) Thermal properties. Both the heat storage and transport properties of bamboo scrimber were higher than the reference timber, which mainly caused by the high density. The thermal conductivity was in nonlinear relation with the moisture content, and that was normally described by an approximately linear fitted thermal conductivity supplement value, which was 0.0984 [\%/M.-%] in this test.

| Items | Unit | BFB-Bamboo scrimber | Reference Timber | Max. value |
|-------|------|----------------------|------------------|------------|
| Basic properties | | | | |
| Dry bulk density \( \rho \) | [kg/m³] | 1108.77 | 400 | 708 |
| Open porosity \( \Phi \) | [%] | 17.36 | 41 | 90 |
| Hygric properties | | | | |
| 20°C isothermal absorption and desorption curve | [kg/m³] | \( \rho_{RH-11.2\%} \) 6.79 | \( \rho_{RH-0\%} \) 0 | \( \rho_{RH-9\%} \) 0 |
| | | \( \rho_{RH-24.4\%} \) 14.05 | \( \rho_{RH-20\%} \) 5.70 | \( \rho_{RH-35\%} \) 42.00 |
| | | \( \rho_{RH-11.4\%} \) 20.26 | \( \rho_{RH-30\%} \) 9.70 | \( \rho_{RH-35\%} \) 61.00 |
| | | \( \rho_{RH-21.5\%} \) 25.55 | \( \rho_{RH-25\%} \) 22.10 | \( \rho_{RH-35\%} \) 74.00 |
| | | \( \rho_{RH-11.0\%} \) 30.19 | \( \rho_{RH-35\%} \) 31.90 | \( \rho_{RH-45\%} \) 90.00 |
| | | \( \rho_{RH-19.7\%} \) 32.24 | \( \rho_{RH-40\%} \) 45.50 | \( \rho_{RH-45\%} \) 115.00 |
| | | \( \rho_{RH-17.2\%} \) 53.75 | \( \rho_{RH-45\%} \) 62.29 | \( \rho_{RH-50\%} \) 151.00 |
| | | \( \rho_{RH-15.4\%} \) 69.58 | \( \rho_{RH-75\%} \) 80.10 | \( \rho_{RH-81\%} \) 197.00 |
| | | \( \rho_{RH-14.5\%} \) 155.04 | \( \rho_{RH-90\%} \) 88.00 | \( \rho_{RH-91\%} \) 245.00 |
| | | \( \rho_{RH-14.0\%} \) 44.40 | \( \rho_{RH-97\%} \) 94.40 | \( \rho_{RH-97\%} \) 318.00 |
| Water vapor transfer coefficient \( U_{\Phi} \) | [-] | \( U_{\Phi-0.0\%} \) 921.28 | \( U_{\Phi-0.0\%} \) 9 | \( U_{\Phi-9\%} \) 845 |
| | | \( U_{\Phi-0.2\%} \) 781.24 | \( U_{\Phi-10\%} \) 7 | \( U_{\Phi-0.2\%} \) 845 |
| Drying rate (T =23°C, RH=50%) | [E-07kg/(m².s)] | \( U_{\rho} \) 600.96 | \( U_{\rho} \) 376 | \( U_{\rho} \) 376 |
| | | \( U_{\rho} \) 489.50 | \( U_{\rho} \) 489.50 | \( U_{\rho} \) 489.50 |
| | | \( U_{\rho} \) 446.94 | \( U_{\rho} \) 446.94 | \( U_{\rho} \) 446.94 |
| | | \( U_{\rho} \) 106.15 | \( U_{\rho} \) 106.15 | \( U_{\rho} \) 106.15 |
| | | \( U_{\rho} \) 73.79 | \( U_{\rho} \) 73.79 | \( U_{\rho} \) 73.79 |
| | | \( U_{\rho} \) 47.67 | \( U_{\rho} \) 47.67 | \( U_{\rho} \) 47.67 |
| Capillary saturation moisture content \( w_{sat} \) | [kg/m³] | 115.93 | 326.00 | 864.50 |
| | | \( w_{sat} \) 0.000873 | \( w_{sat} \) 0.0004 | \( w_{sat} \) 0.0004 |
| Thermal properties | | | | |
| Specific heat capacity \( c \) | [J/kg·K] | 1550 | 1300 | 2100 |
| Thermal conductivity \( \lambda_{th} \) | [W/m·K] | 0.1625 | 0.09 | 0.13 |
| 24h heat storage coefficient \( S_{24h} \) | [W/m²·K] | 8.52 | 3.62 | 5.55 |
| Hemisphere emissivity \( \varepsilon \) | [-] | 0.66 | \( \varepsilon \) | \( \varepsilon \) |
| Light reflectivity (380-780nm) \( \nu_{l} \) | [%] | 19.74 | \( \nu_{l} \) | \( \nu_{l} \) |
| Solar direct reflectivity (200-2600nm) \( \nu_{s} \) | [%] | 44.51 | \( \nu_{s} \) | \( \nu_{s} \) |
| Solar direct absorptivity (200-2600nm) \( \alpha_{s} \) | [%] | 55.49 | \( \alpha_{s} \) | \( \alpha_{s} \) |
3.3. Wind tunnel test results

1) The hourly mass change rate comparison between bamboo scrimber and hardwood showed that bamboo scrimber had slower absorption and desorption rate $U_{ad}$ value. Except certain areas, mostly the absorption-desorption transition stage, the hourly $U_{ad}$ values of bamboo scrimber were up to 33.69 E-06 kg/m$^2$s smaller than that of hardwood specimen. (Figure 4)

2) Affected by the strong outdoor solar radiation and temperature, the absorption and desorption rate of bamboo scrimber were respectively up to 50.22 E-06 kg/m$^2$s and 67.41 E-06 kg/m$^2$s, much higher than the values 7.74-12.58 E-07 kg/m$^2$s resulted from the static drying test ($T=23^\circ C$, RH=50%). As a result of the comprehensive impacts of solar radiation, temperature, relative humidity and wind, the wind tunnel test results showed a much more mutative characteristic and contributed to describe the material in a way that was closer to the practical conditions.

Figure 3. Relative position of bamboo scrimber parameters in the range of reference timber.

Figure 4. Hourly mass change rate of bamboo scrimber and hardwood specimens of wind tunnel test.
4. Conclusion

1) Nine static test items for hygrothermal properties were carried out for bamboo scrimber. Results showed that, by comparison with reference timbers, bamboo scrimber had higher heat storage and heat transport properties, lower moisture storage and transport properties.

2) A dynamic test in wind tunnel was performed to examine the moisture absorption and desorption rate in practical outdoor climate condition. Results showed that bamboo scrimber had lower moisture absorption and desorption rate than the reference hardwood.

3) The significant magnitude difference between the static and dynamic test results showed the necessity of a comprehensive evaluation approach that could take more practical conditions into consideration. Further works to examine the performance of bamboo scrimber under practical external climate, internal load, construction type, HVAC conditions, etc. were required.

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