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Assessment of bamboo application in building envelope by comparison with reference timber

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HIGHLIGHTS

- Typical bamboos hygrothermal properties test based on building envelope HAM model.
- Performance comparison between bamboo and timber exterior wall and space units.
- Bamboo units had better heat storage and vapor resistance but worse heat transport performance.
- Bamboo surpassed timber in lightweight construction in hot and temperate regions.

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ABSTRACT

For obtaining material parameters of typical bamboos, assessing the performance of bamboo in building envelope, timber units were set as reference model, accordingly bamboo units of the same construction and space size as evaluation model, by which the performances in aspects of material, building component and enclosed space unit were compared. Results showed that bamboo units had strengths on heat storage and vapor resistance but weakness on heat transport performance, which varied with climate condition, building function and construction type. Bamboo showed disadvantages in severe cold and cold zones, and advantages in full bamboo/timber constructions in hot and temperate regions.

1. Introduction

1.1. Industrial utilization of bamboo resources and the strategy of 'substitute timber with bamboo'

Bamboo forests were widely distributed in the tropical, subtropical and temperate 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]. Strategy of 'substitute timber with bamboo' was promoted to efficiently use the bamboo resources and lessen the regional shortage of wood forest [4]. In Southeast countries including China, India, Thailand, Vietnam, Costa Rica, Malaysia, etc. timber processing technologies were introduced to the industrial utilization of bamboo, afterwards plybamboo (BMB) in the 1980s; bamboo particleboard, bamboo oriented strand board (BOSB), and bamboo laminated lumber (BSB) in the 1990s; bamboo scrimber (BFB) in the 2000s; and flattened bamboo panel (FB) in the 2010s were successively developed [5–7], and promoted to the concrete formworks, load-bearing components, truck and bus bottom boards, furniture and finishes industries [3].

Building industry was of huge potential to the consumption of bamboo. In China, scholars and architects took reference from the multilayer timber construction system to carry out the

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application of bamboo panels in construction practices. Qisheng ZHANG, Zhitao LU developed bamboo anti-seismic housing in 2009, in which plybamboo was used as wall framework and insulation material were filled inside to achieve favorable thermal performance [8]. Yan Xiao carried out a series of housing construction with 2440 × 1220 mm wall and ceiling panel units that were composed of plybamboo board as partition, plybamboo square as inner support, and insulation material as filler [9,10]. Hao Lin adopted the 2 × 4 construction method (2 × 4 inch, 5 × 10 cm) in bamboo housing, in which bamboo laminated lumber and bamboo scrimber were used as wall framework and insulation material as filler [11]. Various bamboo panel profiles for flooring, ceiling and wall were applied in building envelope, which formed a parallel and competitive product series with timber in some regions [12]. Vogtlander, J.G. and Van der Lugt, P. carried out LCA assessment on typical bamboo flooring products and showed that the long-distance transport would accounted for a major part of the CO_2 footprint and eco-costs [13,14]. Therefore the performance comparison with timber competitive products and adaptability evaluation in local regions were of great significance.

1.2. Research status of bamboo material parameters and the comparison with timber

The existing substantial mechanical studies on bamboo could support the application in load-bearing structure, however owing to lack of hygrothermal properties, bamboo was not regarded as an independent material when used in building envelope, for example the thermal design code in China [15]. Due to the insufficiency of material study, bamboo properties were commonly substituted with timber parameters, which caused inaccuracy to the projects, as material parameters had significant impacts on the building envelope calculation results [16].

In terms of the hygrothermal properties studies on bamboo, there were previous experiments performed on bulk density, porosity, specific heat capacity, thermal conductivity, sorption isotherm and water vapor permeability on raw bamboo [17]. Wu et al. showed that the bulk density of Moso bamboo was from 600 to 800 kg/m^3 [18]. Huang et al. carried out CT measurement on porosity test and concluded that the average porosity of Moso bamboo internode was between 44.9% and 63.4% [19]. Wu and Huang showed that the specific heat capacity of Moso bamboo varied from 1.08 to 2.29 kJ/kg·K [18], and from 1.7 to 2.3 kJ/kg·K at 40 °C using differential scanning calorimetry (DSC) method [20]. Wu et al. measured the thermal diffusivity of Moso bamboo in longitudinal direction by a laser flash method [18]. Huang et al. found that both morphological structure and thermal properties of Moso bamboo were non-homogenous in different directions [21]. Ohmae and Nakano tested the sorption isotherm of Moso bamboo in longitudinal direction by a saturated solution method [22]. Wang et al. found that the equilibrium moisture content (EMC) of the hemicelluloses was much higher than the lignin, and the EMC of bamboo fiber was higher than the bamboo block [23]. Huang et al. measured the moisture transport properties of Moso bamboo, and found that the water vapor diffusion resistance factor by dry cup was from 30 to 57 in the radial and tangential directions [24], and the water adsorption coefficients were 0.014, 0.008, and 0.0019 kg/m^{2}s$^{0.5}$ for exterior, middle, and interior parts of bamboo culm wall, and respectively the capillary saturation moisture contents were 572, 479, and 385 kg/m^3 [25].

In terms of the comparison between bamboo and timber, Du Fuyuan and Oscar Hidalgo found that the density of bamboo was approximately equal to or higher than hardwood [26,1]. Walter Liese, Qisheng Zhang, D. Grosser, Xian Xingjuan observed the microstructure of bamboo and found that the fibers were almost totally longitudinally arranged in parallel, with extremely few radial fibers at the nodes, which was far different from wood [27–30]. Qisheng Zhang and Youdi Chen analyzed the chemical composition and showed that the main compositions of bamboo were similar to wood, while the trace elements difference made bamboo more vulnerable to erosion [31]. Oscar Hidalgo studied on the microscopic drying characteristics of bamboo and found that compared with wood, bamboo was more prone to cracking in the process of losing water [1]. The existing knowledge prompted that the hygrothermal properties of bamboo were different from timber to some degree, which meant an individual parameters system was necessary to support its practical application.

The reviewed studies provided certain hygrothermal properties that could support the evaluation of bamboo applicability in building envelope at an initial stage. However, these studies on bamboo properties generally concentrated on raw bamboo, which couldn't represent bamboo-based panels that were more commonly used in practical application. Bamboo-based panels were changed in terms of constituent units, assembly methods and protective treatments during the manufacturing process [7], which resulted in the change of hygrothermal properties; The existing works generally focused on certain basic properties, hygric properties or thermal properties in steady state that couldn't cover completely the parameters necessary for a full model to simulate the heat and moisture process in building envelope.

On the other hand, the comparison between bamboo and timber were performed only between raw bamboo and raw wood, and mostly on microstructure characteristics, rather than the hygrothermal properties necessary for the building envelope calculation; Comparison on building component and enclosed space couldn't be found; Actual application conditions such as climate, building function, construction type, HVAC, and so on, had not been taken into consideration; To promote the strategy of 'substitute timber with bamboo', the discussion on substitutability of bamboo for timber in terms of forest production, prices and mechanical performance were mostly stressed, but the physical performance of bamboo compared with timber wasn't sufficiently studied.

Based on these, the paper systematically tested typical bamboos for the hygrothermal properties and showed the relative position in the range of corresponding reference timbers; designed exterior walls with three groups of bamboos and timbers in same construction size that met the requirement of different climate zones, and compared the thermal and hygric performance; finally constructed enclosed space units with the above exterior walls in EnergyPlus and simulated the indoor environment and energy consumption. The motivation of this study was to gain preliminary comparative results between bamboo and timber, synthetically from progressive perspectives of material, building component and enclosed space, prejudge the physical performance feasibility of substituting timber with bamboo, and provide reference for the practical application, with consideration to climate condition, building function and construction type.

2. Bamboo hygrothermal properties test

2.1. Material samples

Bamboo products were classified by the "decomposition" and "recombination" manufacturing process, which decided the constituent units and assembly methods of the final products [7,6]. Based on the literature, market and material producers investigation in bamboo industry, six typical bamboo products were chosen as the test objects, which were distinguished and named according to the terminology standard [6]. Flattened bamboo panel (FB) was composed of flattened bamboo culm wall [32,33]; Bamboo laminated lumber (BSB) was composed of bamboo strips [34];