Wood Composite Plates with Reversible Humidity-driven Deformation

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Abstract. Four types of beech/spruce composite plates were fabricated from beech with different wood textures under different initial ambient relative humidity, and the impacts of the changes in ambient relative humidity on the deformation characteristics and mechanical properties of the composite plates were studied. It was found that the reversible bending deformation of the composite plates can be achieved by adjusting the ambient humidity. The bending deformation characteristics of the composite plates were related to the initial fabrication conditions and humidity expansion characteristics of the wood, and conformed to the improved Timoshenko theoretical model for bilayer humidity expansion materials. The experiments on humidity-driven deformation of the counter-balanced composite plates showed that external load would hinder the deformation of the composite plates driven by the ambient humidity, but the composite plates still had a good load-bearing capacity.

1. Introduction
Controllable deformation in materials and structures is an important research subject in the field of intelligent materials [1-4]. The heterogeneous inside some natural plants would expand/shrink during moisture absorption/loss, achieving reversible changes in the overall shape [5-7]. Inspired by plant heterogeneous, the researchers have developed a variety of composite materials for reversible deformation under ambient humidity, and fabricated a variety of biomimetic sensors and actuators based on humidity control mechanism, such as humidity-driven composite bracket of solar panels for automatically tracking the sun according to ambient humidity changes [8], connectors for automatically adjusting the degree of opening and closing of windows according to air humidity [9], biomimetic building skins of environment friendly buildings adaptive to the environment [10,11], and self-shaping wood grid shell made of bi-layered composites and with double curvature fidelity [12]. In recent years, the research on humidity-driven composite materials is mostly on structural diversity design for extending humidity driven composite materials [13-15], and mechanical properties of humidity-driven composite materials are rarely studied. In this paper, four types of humidity-driven beech/spruce composite plates with different reversible deformation characteristics were fabricated, and the impacts of the humidity changes on the deformation characteristics and mechanical properties were studied.
2. Experimental methods

2.1. Materials and preparation

In this experiment, beech with an air-dry density of 0.71 g/cm³ and spruce with an air-dry density of 0.52 g/cm³ were used. Two types of beech with the same size but different textures were selected as an active layer of the composite plates, the dimensions were 150 mm (tangential) in length, 20 mm (longitudinal) in width and 4 mm (radial) in thickness, and 150 mm (radial) in length, 20 mm (tangential) in width and 4 mm (longitudinal) in thickness. Spruce with a length of 150 mm (longitudinal), a width of 20 mm (tangential) and a thickness of 0.9 mm (radial) is selected as the resistive layer of the composite plates, as shown in figure 1. In view of the anisotropy of wood humidity expansion, by testing the linear humidity expansion coefficient of the active layer and the resistive layer, it can be known that tangential and radial linear humidity expansion coefficients of beech were 20.1% and 25.1% at 25°C respectively, and the linear humidity expansion coefficient of spruce was 6.3%.

![Figure 1. Structural diagram of beech/spruce composite wood plate](image)

The resistive layer and two active layers were allowed to stand for 72 hours in a humidity experimental box with an initial ambient humidity of 30% or 99%. The active layer and resistive layer were glued for 36 hours using polyvinyl acetate emulsion adhesive (white emulsion) in an indoor environment with about 30%-35% humidity. Finally, four types of humidity-driven composite plates with different humidity deformation characteristics were fabricated. Among them, the wood composite plates formed by curing the active layer and the resistive layer with an ambient humidity of 30% are collectively referred to as dry humidity-driven composite plates, including dry tangential composite plates and dry radial composite plates; the wood composite plates formed with an ambient humidity of 99% are collectively referred to as wet humidity-driven composite plates, including wet tangential composite plates and wet radial composite plates.

2.2. Humidity-driven deformation experiment on composite plates

Fabricated four types of composite plates were put in a humidity experimental box, and a humidity experiment was conducted using a humidification device. In the process of continuous humidification, the composite plates were weighed every five minutes to determine its moisture content, and their shapes were recorded during humidification until no identifiable change with the increase of the humidity. Afterwards, the humidity was reduced to 35%, then the shape restoration of the composite plates was recorded. The moisture content of the composite plates was measured by the weighing method [16] using the following formula:

\[
\text{Moisture content} = \frac{m - m_0}{m_0} \times 100\%
\]

where \(m\) is the final weight of the composite plates, and \(m_0\) is the initial weight of the composite plates.
\[ u = \left( \frac{m_u - m_{dr}}{m_{dr}} \right) \times 100\% \]  

(1)

Where, \( u \) is the moisture content of the composite plates; \( m_u \) is the actual weight of the composite plates under moisture content \( u \); \( m_{dr} \) is the absolute dry weight.

In order to explore the impacts of the counterweight on the humidity-driven deformation of the composite plates, the humidity-driven deformation of the composite plates was tested after 0.2 kg, 0.5 kg and 1.0 kg weights were placed on a free end of the dry tangential composite plates in the vertical state.

3. Results and discussion

The beech as an active layer would experience relatively significant expansion or contraction when the humidity changes, while the spruce as a resistive layer would experience relatively minor deformation. Different deformation of these two layers eventually led to the bending deformation of plates in case of water absorption/loss, as shown in figure 2. The moisture content of the dry composite plates was about 21% under 25%-35% ambient humidity, without obvious deformation, keeping the straight shape after fabrication. As the ambient relative humidity gradually increased, the dry composite plates would gradually bend towards the resistive layer after moisture absorption, and had the maximum deformation when the moisture content reached 55%-60%. At this time, no identifiable deformation would be made with the increase of the ambient humidity. Afterwards, the composite plates would gradually restore to the original straight state when the ambient humidity gradually decreased. Among them, the dry tangential composite plates only bent in the water absorption process. In addition to bending deformation, the dry radial composite plates may also produce certain torsional deformation in the water absorption process, mainly because the heterogeneous structure of the natural beech materials led to a certain angle between the longitudinal deformation direction and the long side of the composite plates. The initial moisture content of the wet composite plates was about 20% under about 25%-35% ambient humidity, and the composite plates bent towards the active layer. In the humidity-driven deformation experiment, as the ambient humidity gradually increased, the wet composite plates would gradually stretch to the resistive layer after bending. When the moisture content reached 65%-75%, the wet composite plates would stretch to a straight state, and then their shape would not change with the increase of ambient humidity. Afterwards, the wet composite plates would slowly restore to the original bending state when the ambient humidity gradually decreased. Similar to dry composite plates, wet tangential composite plates only bent while wet radial composite plates may undergo torsional deformation.

![Figure 2. Shape changes of four types of composite plates before and after humidification](image)

Assuming that the deformation of the active layer and the resistive layer in the length direction was uniform, the bending process can be approximately seen as a pure bending process of the straight beam with constant cross section, and the deformation curve can be seen as a circular arc. The shape curvature of the composite plates under different moisture content can be obtained by fitting its shape
curve based on a circular function. Figure 3a-3b show the reversible deformation of dry humidity-driven composite plates under different moisture content. The red dotted line in Figure 3a shows the circular function based fitting curve of the dry tangential humidity-driven composite plates when the moisture content was 35.82%. It can be seen that the humidity-driven bending deformation can be approximately described using a circular function.

![Circle function fitting](image)

Figure 3. The reversible deformation of dry humidity-driven composite plates with different moisture content (a) tangential (b) radial; curvature of dry humidity-driven composite plates with moisture content change (c) tangential (d) radial

The deformation of the active layer and the resistive layer was mainly caused by water absorption/loss of the materials. The deformation of the beech/spruce presented a simple linear relationship with the change in the moisture content of the materials. The linear coefficient was the humidity expansion rate of the materials, highly similar to the deformation mechanism of the thermal expansion composite materials. With reference to the curvature calculation model of the bimetal thermostats by Timoshenko [17], its temperature change was modified to the moisture content change of the composite plates. Considering that the strain of the resistive layer and active layer was mainly caused by humidity expansion, axial force and bending moment, and the strain of the active layer and resistive layer on the joint surface of composite plates were equal, a curvature calculation model was built for pure humidity-driven bending of the composite plates made of bilayer humidity expansion materials:

$$\kappa = \frac{1}{\rho} = f(m,n) \frac{\Delta \beta \Delta u}{h} \quad (2)$$
Where, $\kappa$ is the curvature of the humidity-driven composite plates; $\rho$ is the radius of curvature; $\Delta \beta$ is the difference in the linear humidity expansion coefficient between the active layer and the resistive layer of the humidity-driven composite plates; $\Delta u$ is the change in moisture content; $E_1$ and $h_1$ are elasticity modulus and thickness of the resistive layer in the deformation direction; $E_2$ and $h_2$ are the elastic modulus and thickness of the active layer in the deformation direction respectively; and $h$ is the total thickness of the composite plates. According to formula (2), the bending curvature and the change in moisture content of the composite plates are linearly increasing. Figure 3c-3d show the curvature of experimental results for two types of dry composite plates and theoretical curvature calculated by formula (2). By comparison, it can be seen that the shape curvature of the dry composite plates was monotonically increasing with the increase of the moisture content. When the change range of moisture content is less than 0.2, the experimental value is well in line with the theoretical solution; when the change range of moisture content is more than 0.2, the experimental value is slightly greater than the theoretical solution. This was mainly caused by the rapid decrease in the glass-transition temperature (GTT) of amorphous polymers such as lignin and hemicellulose in the active layer under high moisture content [18]. During high-humidity experiment at room temperature, the wood for the active layer would soften to a certain extent, leading to that $n$ in formula (3) increased, which was ultimately manifested as the curvature deviation of the composite plates from the theoretical value under high moisture content.

\[
f(m,n) = \frac{6(1 + m)^2}{3(1 + m)^2 + 1 + mn \left( m^2 + \frac{1}{kn} \right)}
\]

(3)

\[
m = \frac{h_1}{h_2}, \quad n = \frac{E_1}{E_2}
\]

(4)

Figure 4a shows the final shape curve for humidity-driven deformation of the composite plates after 0.2 kg, 0.5 kg and 1.0 kg weights were placed on an end of the dry tangential composite plates. It can be found that the composite plates still produced different bending for greater counterweight after external load equal to 20-100 times of dead load was imposed. The composite plates with a 1.0 kg load had significantly less deformability than those with a 0.2 kg load. However, through energy calculation, the work $\Delta W_g$ for counter weight of the composite plates was 0.16 J, 0.14 J and 0.12 J respectively. It means that the energy output of the composite plates did not significantly decrease with counter weight increase. In order to further obtain the empirical formula for the humidity-driven
deformation of the counter-balanced composite plates, the corresponding curvature was obtained by fitting the shape curve for humidity-driven deformation of the composite plates based on a circular function under three counter weights, as shown in figure 4b. The fitting results showed that the changes in the curvature and moisture content of the composite plates in the humidity-driven deformation process under three external loads were approximately linear, consistent with the characteristics of the improved Timoshenko formula for the curvature of the composite plates made of bilayer humidity expansion materials as mentioned above. This meant that the empirical formula for the humidity-driven deformation curvature of the counter-balanced composite plates can be simply obtained by introducing a correction term related to the counter weight to the formula (2). According to the experimental results, we get:

$$\kappa' = \exp\left(-\frac{P_n}{P_0}\right) \kappa = \exp\left(-\frac{P_n}{P_0}\right) f(m,n)\frac{\Delta \beta\Delta u}{h}$$  (5)

Where $\kappa'$ is the deformation curvature of the composite plates under load; $P_n$ is the external load; $P_0$ is the characteristic load. In this experiment, $P_0=0.93\text{kg}$.

4. Conclusion
The beech/spruce composite plates have the characteristic of reversible humidity-driven deformation, among which the dry composite plates change from a straight state to a bent state in the moisture absorption process, while the wet composite plates change from a bent state to a straight state. The improved Timoshenko formula for the curvature of the composite plates made of bilayer humidity expansion materials can be used to describe the shape of the composite plates under different moisture content. The composite plates have a high degree of deformability and load-bearing capacity under external load dozens of times the self-weight. The increase of external load will hinder the bending deformation of the composite plate. The empirical formula for humidity-driven deformation of the counter-balanced composite plate is proposed based on the improved Timoshenko composite plate curvature formula.

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