Shear strain distribution of bonding interface in ductile PF bonded 2-ply bamboo sheet by the method of electronic laser speckle interferometry

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Abstract

The shear strain distribution across a 2–ply bamboo sheet bonded with ductile PF is measured by means of electronic laser speckle interferometry, along with tensile strength experiment to prove shear strain distribution on macroscopic scale. This research will effectively combine macroscopic mechanical property with microcosmic interfacial mechanical property. Study on shear strain distribution of bonding interface will contribute to understand bamboo bonding interface response mechanism under deformation conditions and solve problems of plybamboo deformation or bonding failure. Moreover, it is supposed that this study will be conducive to choosing bamboo-specific adhesives under different conditions.

Key words bamboo, electronic laser speckle interferometry, ductile PF, bonding interface
Introduction

Phenol-formaldehyde resin is commonly used in bamboo-based panels (Yiping Ren. 2008, Mingjie Guan et al. 2005, 2006, Fengwen Sun et al. 1999), for which it is one of the mainly used adhesives in wood-based panels industry. But, due to differences of structure and chemical composition between bamboo and wood, there may be diversities upon characters of bonding interface and the stress transfer mechanism between these two materials (Hongxia Ma. 2009). As previous studies shown, there are many researches on strain and stress of wood bonding interface (Ulrich Müller et al. 2006, Wolfgang Gind et al. 2004, Andreas Valla. 2011). The high spatial resolution of ESPI was sufficient to reveal differences in strain concentration occurring in lap-shear wood specimens bonded with PUR and PRF (Ulrich Müller et al 2005). Stiff latewood bonded with PUR was strained little compared to less stiff earlywood, and stress concentration is evenly compared to PRF with ESPI (Wolfgang Gindl et al 2009). The strain concentration caused by penetration of PUR and PRF into poplar cell cavities was also measured (Wolfgang Gindl 2005). However, studies on strain and stress of bamboo bonding interface are scarce.

In the present study, we tested the micro-scale strain distribution and strain concentration in the vicinity of bonding interface of 2-ply bamboo panels by means of ESPI (electronic speckle pattern interferometry), along with the bonding line shear strength of bamboo-based panels with phenol-formaldehyde resin modified by different content of PVA (polyving akohol). We compared the values glued with phenol-formaldehyde resin to modified phenol-formaldehyde resin on macro- and micro-scale. In addition, we analyzed the failure model of bonding interface of 2-ply bamboo.

Materials and methods

Shear testing

Shear specimens in accordance with DIN EN 302-1-2004 with a total length of 150mm, a width of 20mm and a thickness of 2×5mm, were manufactured from a 5mm thick planed, bleaching moso bamboo. Phenol-formaldehyde resin was manufactured experimentally and modified by different content of polyving akohol (5%, 10%, 20%). These adhesives were used to glue the specimens and then the specimens were all cured in a press 2MPa and at ambient temperature 140℃ for 15minutes. After curing, specimens were maintained in a condition room at 65% RH and 20℃ for 1 week until constant weight was attained. Incisions were made by using a circular saw to detect the notches towards the glue line, allowing for a tested bond length of 10mm as suggestion by DIN EN 302-1-2004. Shear testing was done on universal testing machine applying the load at a speed of 2.5mm/min. We tested a sufficient number of specimens to get 10 valid numbers, permitting the bamboo failure to nearest 30%.

ESPI measurement
In order to monitor shear displacement on the surface of the two lap joint specimens, as depicted in Figure 1, shear testing corresponding to DIN EN 302-1-2004 was performed on a universal testing machine equipped with TS-S1-1XP ESPI system. The basic principle of ESPI technique was explained in detail in a previous paper (Ulrich Müller et al. 2006). With the optical set-up used here, the size of the field of view (FOV) observed with ESPI was 44×35mm², working distance between camera and specimen was about 300mm. Specimens were pre-loaded to 50N and then strained in 14 steps of 5N. We conducted the shear testing twice in two directions X and Y, for this kind of ESPI caught the deformation only from the X direction, so each deformation of 2-ply bamboo should be controlled in its elastic stage. At each displacement step, a interference fringe image of the observed field of view was taken. The displacement maps were computed by summing up information from all 14 displacement steps. Each adhesive with 5 specimens

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*Fig.1 Tensile shear experiment on a lap-shear specimen. One-dimensional deformation of the sample surface was observed by means of electronic speckle pattern interferometry.*
were tested at least five times until all the specimens showed similar results and then we chose only one specimen for calculation.

Results and discussion

Shear strength

![Graph showing shear strength with different content of PVA](image)

*Fig. 2 Shear testing of phenol-formaldehyde resin with different content of PVA (polyvinyl alcohol). Sample A to sample D with content of PVA: 0%, 5%, 10%, 20% respectively. The red line equals to the minimum allowed shear strength according to DIN EN302-1-2004.*

The shear strength glued with different content of PVA results in clear difference. As depicted in Figure 2, we can see that, with the percentage of PVA increasing, the shear strength start to descend at first, but rebound higher than before later. The maximum strength is 16.39MPa with the percentage of PVA 20%, while the minimum one is 11.95MPa with the percentage of PVA 5%.
For better understanding the diversity of shear strength, referring to Frihart’s bonding model (Charles R. Frihart et al. 2005, Christopher G. Hunt et al. 2007, Robert G. Schimidt et al. 1997), we set up a model to illustrate the difference between bonding interface and substrate considering the influence of PVA and bamboo. As it is shown in Figure 3, phenol-formaldehyde resin, composed of oligomers and monomers, easily forms polymer chain and cross-links by hot-pressing which have a high content of aromatic or resonance-stabilized structure with limited flexibility (Robert G. Schimidt et al. 1997), and easily lead to stress concentration with rigid backbone which are incompatible with ductile bamboo. In the contrast, PVA whose branched hydroxy makes it prone to combine hydroxymethyl of phenol-formaldehyde resin, belongs to the pre-polymerized adhesive with a flexible backbone (Charles R. Frihart et al. 2005). Thereby, more energy resulting from strain concentration in the vicinity of gluing line will be absorbed by interfacial slipping, and then, inducing higher shear strength. As shown in Figure 2, Shear strength decreases with a small number of PVA for entanglement networks created by PVA are not abundant, which leads to strain concentration between two glues while interface slips without obvious overall effect. However, as the percentage of PVA increasing, enough entanglement of PVA will ensure strain transmission (R. Garcia and A. Pizzi. 1998). Interface slipping will remove strain concentration and eliminate interface energy leading to shear strength increase.

In addition, considering the shear deformation of one-direction bamboo, ductile PF may be more suitable for bamboo-based materials than the commonly used stiff PF, for ductile bamboo fibers usually bear more deformation, which is more incompatible with stiff PF.
Shear strain distribution

Two-dimensional patterns of in-plane strain distribution across the FOV on tensile specimens glued with different adhesives are shown in Figure 4. In micro-scale strain distribution, ductile PF reflects more obvious than the normal stiff PF with higher strain concentration at both ends of the overlapping area and high gradient of strain along the bondline. Line plots of shear strains along the glue line are shown in Figure 4E, indicating continuity of stress transmission.

Fig. 4 (A-D) Strain distribution of specimens glued with phenol-formaldehyde resin in different content of PVA with observed fields of view. Sample A, B, C, D represent phenol-formaldehyde resin with PVA, 0%, 5%, 10%, 20% respectively. Scale bars indicate strains multiplied by $10^{-3}$ mm. (E) Values of strain with different samples (A, B, C, D) along the bond line.

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that the values and the range values of strain are higher with ductile PF. With the percentage of PVA increasing, continuity of stress transmission and isostrain area become larger, resulting in increasing values of shear strain.

In the region of bonding interface, strains from $4.6 \times 10^{-3}$ to $6.4 \times 10^{-3}$ mm are observed for PF samples compared with strains from $5.2 \times 10^{-3}$ - $7.2 \times 10^{-3}$ mm for PF with 20% PVA samples. According to Frihart’s models (Charles R. Frihart et al. 2005, Christopher G. Hunt et al. 2007, Robert G. Schmidt et al. 1997), pre-polymerized adhesives could offset the energy created from stress concentration by itself slipping, while being applied lateral load. So it is reasonable for PVA to drive all stiff PF slipping when being applied lateral load, for which its branched hydroxyl combines hydroxyl of hydroxymethyl from PF on hot-pressing. As shown in Figure 4C at the arrow, there are discontinuous breaks in strain distribution with little PVA. In accordance with models we have set before, inadequate entanglement network of each PVA leads to strain transmission failure, which results in bonding interface slipping. However, as the arrow depicted in Figure 4D, the breaks of strain transmission disappear with enough PVA entangling which leads to overall effect. As shown in Figure 4E, the values of shear strain increase as a whole with the percentage of PVA increasing, which is another way to demonstrate that flexible bonding interface could improve strain transmission effects.

**Conclusion**

In terms of shear testing and strain distribution by ESPI along the bond line, it displays marked difference among shear strength and strain distribution glued with PF modified by different content of PVA. The results obtained here have shown that ductile PF could diminish stress distribution in adhesive assemblies and lead to bonding interface slipping, which could effectively reduce destructive energy in their overall strength. The amount of pre-polymerized adhesive-PVA could have a positive influence on the stress transmission and strain distribution in the vicinity of bonding interface, which may contribute to compatibility with ductile bamboo.

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