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Understanding the effect of combined thermal treatment and phenol-formaldehyde resin impregnation on the compressive stress of wood

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Abstract: Thermal modification is widely applied to improve moisture dynamics of wood, however often decreasing the mechanical strength. It is therefore required to enhance the mechanical strength of thermally modified timber (TMT), for example by impregnation with adhesives. Specimens, cut from Douglas-fir, were thermally modified (TM) either after phenol formaldehyde (PF) resin impregnation (IM-TM) or before (TM-IM). The microstructural and chemical properties were investigated with SEM and FTIR. Compressive stress, as one of the important mechanical properties, was measured using a universal testing machine, while strain distribution was recorded with digital image correlation (DIC). The results show that the compressive stress of TM specimens can be enhanced significantly by PF resin impregnation. Compressive stress differences between IM-TM and TM-IM specimens are small despite of the larger amount of resin in TM-IM specimens. Thermal modification decomposes part of the PF resin in the cell lumens and promotes chemical reaction between the PF resin and wood. PF resin improves the stiffness and ductility of the wood cell wall, resulting in smaller strain and homogenous distribution thereof. These factors lead to high compressive stress of IM-TM and TM-IM specimens. Although PF resin impregnation contributes to narrowing strain accumulation in earlywood of TM specimens, control specimens have the smallest strain ratio between earlywood and latewood. The findings of this study are helpful for optimizing the cost effective thermal-impregnation technology of producing TMT with improved compressive stress.

Keywords: *Wood; Thermal modification; PF resin impregnation; compressive stress; Strain distribution*

1. Introduction

Wood is an important construction material thanks to its high strength/weight ratio, ease of processing and renewable origin (Singh et al. 2019). Wood is hygroscopic, and as such moisture can decrease the mechanical strength and a high moisture content can even induce decay (Zhan et al. 2019). Thermal modification is a well-known method to reduce the hygroscopicity of wood fibers and increase dimensional stability. This method has been widely applied in industry to treat wood and other bio-based materials (Wang et al. 2018b, 2020a). Typical temperatures usually range between 160°C and 260°C, where lower temperatures do

not cause any significant changes in the wood constituents (Boonstra et al. 2007). Thermally modified timber (TMT) can be produced in different media, such as water steam, inert gas and oil. All of these are able to induce, to a different extent, changes in the wood properties (Lee et al. 2018). Combining thermal modification with functional emulsion impregnation has been an interesting topic to improve the physical and mechanical properties of wood (Awoyemi and Westermark 2005; Salman et al. 2016; Taghiyari et al. 2020; Wu et al. 2020).

Mechanical strength decrease is one crucial impact, which narrows the use of TMT as loadbearing material (Widmann et al. 2012). To compensate this decrease in mechanical strength, TMT can be further treated by resin and wax impregnation. Wang et al. (2018a) have pre-impregnated TMT with wax emulsions and disodium octoborate tetrahydrate. The results indicated that both water repellency and bending strength could be improved. Researchers also utilized a silica/wax composite emulsion to treat TMT, and the surface hardness, compressive strength, modulus of elasticity and modulus of rupture were increased (Wang et al. 2020b). Hemp oil impregnation could decrease the brittleness and increase the modulus of elasticity of TMT (Baar et al. 2021). By conducting in situ polymerization of polystyrene into TMT, it could recover losses in both stiffness and strength attributed to thermal modification (Acosta et al. 2021). Combining functional emulsified polymer impregnation with thermal modification could be a promising approach to improve the mechanical performance of TMT. Functional emulsion impregnation, however, increases the economic and environmental burden of wood products, which limits its large scale application in TMT industry. It is, therefore, necessary to improve the mechanical performance of TMT as well as decrease the functional emulsion consumption. Understanding the mechanisms of functional emulsion impregnation treatment on the improvement of the mechanical performance of TMT is certainly helpful to achieve the above target. An interesting option to use in combination with thermal modification, is phenol formaldehyde (PF) resin, which has been widely used to improve the mechanical performance of wood and wood based composites (Shams et al. 2004; Wang et al. 2019a).

During impregnation, resin distribution could be inhomogeneous due to the different microstructure, which further influences the effect of thermal modification. The mechanical performance of the thermal-impregnation modified wood products is affected by structural characteristics, thermal modification and resin impregnation treatment. Growth ring orientation for instance significantly influences the compressive strength of TMT because of the stiffness difference in latewood and earlywood (Li et al. 2021). Bending failure in TMT initiated mainly at knot interfaces and fractures often propagated from checks (Van Blokland et al. 2020). The effect of thermal modification on the microstructural characteristics of wood has been intensively studied (de Abreu Neto et al. 2021, Bernabei and Salvatici 2016, Cabezas-Romero et al. 2021). To the best knowledge of the authors, the mechanical performance of thermal-impregnation modified wood has not been investigated by involving the structural characteristics and in-situ strain distribution of wood.

The objective of this work is to study the influence of thermal modification and PF resin

impregnation on the compressive stress of wood. It is commonly believed that compressive stress is one of the parameters for wood aimed as construction materials, especially important in flooring materials. The Douglas-fir specimens were treated by combining thermal modification and PF resin impregnation. They were compressed up to failure and the strain distribution was recorded simultaneously with digital image correlation (DIC). The relationship between earlywood/latewood and strain distribution was investigated. The microstructure, resin distribution and chemical changes of the specimens were assessed. Understanding the effect of thermal modification and PF resin impregnation on the compressive stress of wood contributes to an optimal application of combined thermal modification and resin impregnation.

2. Material and Methods

2.1 Preparation of specimens

Wood specimens with dimensions of 10mm×10mm×15mm (radial, tangential, and longitudinal) were cut from wood blocks located around the 18th annual ring counting from the pith, which was harvested from a single batch of 30-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). The specimens' width was along the longitudinal direction of wood. The air dry density of the wood blocks is 0.54±0.05g/cm^3. There were no defects, such as knots and cracks, in the specimens. A total of 24 specimens were prepared and the influence of growth rings angle on the mechanical strength was minimized by selecting the specimens with consistent growth rings angle (Fig.1). Commercially available PF resin (Table 1) was diluted with demineralized water to the resin concentration of 25% and used in this experiment.

Six untreated specimens were used as a control. Six specimens were only thermally modified. Six specimens were soaked in impregnating PF resin before thermal modification, further referred to as IM-TM. Six specimens were impregnated with PF resin after thermal modification, further referred to as TM-IM. The specimens were modified for 2h with argon at 200℃ and temperature increase rate was 1℃/min. After switching off the heating system, the specimens were cooled in a tube furnace to a temperature below 100 ℃ within 2h. The specimens were immersed in PF resin and placed in a stainless-steel vacuum chamber. Next, air pressure in the vacuum chamber decreased to 0.08MPa, which took more or less 90s, and then this air pressure was kept for one hour. Excessive PF on the specimens' surface was removed. For IM-TM specimens, after PF resin impregnation, the specimens were kept at 20 ±2℃ and 65±3% relative humidity (RH) condition for 24 hours and then dried in an oven at 103°C for 12h. Next, thermal modification was conducted. For TM-IM specimens, after thermal modification, the specimens were conditioned for 12h at 20±2℃ and 65±3%RH, and then PF resin impregnation was conducted. Next, they were kept at 20±2℃ and 65±3%RH condition for 24 hours and then dried in an oven at 103°C for 12h. To reach constant moisture content, all specimens were conditioned at 65±3% RH and 20±2℃ for four weeks. Sandpaper was used to polish one side of the specimens before spraying with speckle patterns (Fig.1). The

specimens were weighed before and after each step of the entire procedure.

Table 1 Properties of PF resin

Technical specifications	Properties
Specific gravity(20℃)	1.186
Molar mass (Da)	300-600
Viscosity(mPa*s(25˚C))	76.2
PH value(25˚C)	9.84
Solid content (%)	57.71%

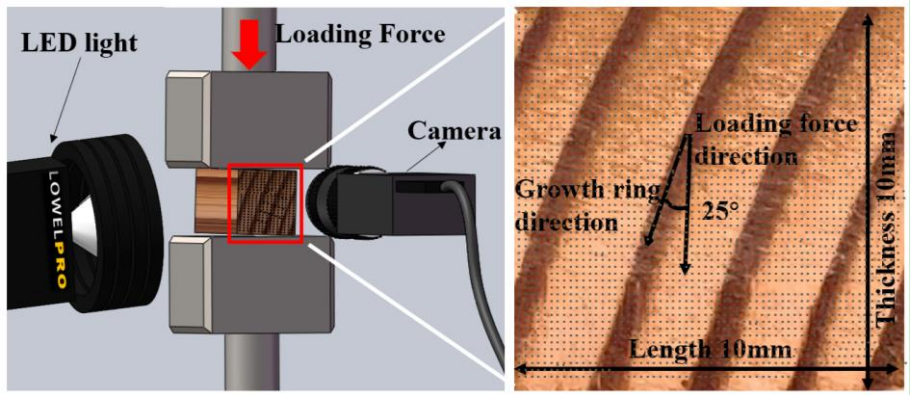


Fig.1 Illustration of the compression and DIC test set-up

2.2 Compression test experimental setup

A universal testing machine (Instron 5966, USA) was used to compress the specimens. The loading wedge, with the surface area of 50.0 × 50.0mm^2, was manually adjusted to a loading force of 75.0N (compressive stress 0.5MPa). Next, the specimens were automatically compressed according to a fixed velocity of the loading wedge of 1mm/min. The maximum compressive stress of different specimens was inconsistent. For all specimens, compression stopped as soon as the continuous loading force decrease was larger than 100N.

Strain distribution was recorded using digital image correlation (DIC) as conducting the compression test (Fig.1). Image correlation was performed using the commercial software package Correlated Solutions (www.correlatedsolutions.com). Ten photographs of the speckle patterns in the specimens' side face were captured per second by a CCD camera. There are approximately 490 strain pixels in each square millimeter. A Lowel Pro LED light was used to illuminate the speckles. Image acquisition and compression of the specimen were then started simultaneously.

2.3 Scanning electron microscopy

One specimen from each type of modification method was used for visualizing the wood microstructure and resin distribution. The specimens were cut to obtain cross sections located 2mm away from the surface. The specimens were oven-dried at 103℃ to minimize the impact of moisture on the image quality obtained with scanning electron microscope (SEM, model PW-100-018). The specimens were placed in a sputter coater (SBC-12) and conductive coating

was sprayed on the transverse sections. The microstructure of the transverse sections was then visualized by SEM.

The microstructure of the specimens' ruptured section was also visualized. The specimens used in the compression tests were oven-dried and the conductive coating was sprayed on the ruptured section in a vacuum chamber. Finally, images of the ruptured sections were obtained with SEM.

2.4 FTIR spectroscopy

To examine the chemical differences between the different specimens, slices, measuring 10mm×10mm×1mm (Radial, tangential, and longitudinal), were cut from specimens with a microtome. Before testing, all slices were dried at 103℃ for 8 hours. To compare chemical composition variation due to modification, slices were cut from twin specimens without treatments. After modification and mechanical testing, slices were obtained from the specimens. A VERTEX 80V FTIR spectrometer (Bruker Corporation, Karlsruhe, Germany) was used to record the spectra in the range of 4000-400cm^{-1} with a resolution of 4cm^{-1}.

2.5 Data analysis

The mass loss of TM and TM-IM specimens caused by thermal modification was obtained according to Eq.1. The mass loss of IM-TM specimens by thermal modification was calculated by Eq.2. Weight percent gain from PF resin impregnation was obtained with Eq.3.

$$ML= [(m_c/(1+MC_c))-m_t]\times 100/ (m_c/(1+MC_c)) \quad (1)$$

$$ML_i=(m_1-m_0) \times 100/ m_0 \quad (2)$$

$$WG= [(m_i-m_c/(1+MC_c)]\times 100/ [m_c/(1+MC_c)] \quad (3)$$

where ML is the mass loss of a specimen caused by thermal modification (%), ML_i is the mass loss of a PF resin impregnated specimen caused by thermal modification (%), m_c is the mass of a specimen after conditioning at 65±3% (RH) and 20±2℃ (g), MC_c is the average moisture content of control specimens after conditioning at 65±3%RH and 20±2℃ (%), m_t is the oven-dried weight of a specimen after thermal modification (g), m_1 is the oven-dried weight of a specimen after PF resin impregnation and m_0 is the oven-dried weight of a specimen after PF resin impregnation and thermal modification, WG is the weight gain of a specimen after PF resin impregnation (%), m_i is the oven-dried weight of a specimen after thermal modification and impregnation treatment.

The compressive stress of a specimen was calculated according to Eq.4. It was regarded that the contact area of a specimen was kept constant in compression test. Therefore, the contact area before compression test was used. The deformation of specimens along the thickness direction was obtained according to the displacement of loading wedge.

$$CS=F/S \quad (4),$$

where CS is the compressive stress of a specimen (MPa), F is the loading force on a specimen (N), and S is the contact area of a specimen (mm^2).

For the strain along the thickness direction of the specimens, the positive strain represents

tension, and the negative strain represents compression. For shear strain, positive values represent clockwise shearing and negative values represent counterclockwise shearing. Strain distribution in earlywood and latewood was quantified. Specifically, strain values of 30 different spots in earlywood and latewood were randomly collected respectively from each type of specimen. The absolute value of compression and shear strain was then averaged across these 30 spots.

3 **Results and discussion**

3.1 Physical and mechanical properties

PF resin impregnation increased the weight of the specimens. Weight percent gain in IM-TM specimens is smaller than in TM-IM specimens (Table 2). Thermal modification could decrease cell wall thickness and slightly increase average lumen diameter of wood (Cabezas-Romero et al. 2021), which would contribute to PF resin impregnation in TMT. Larger weight percent gain in TM-IM than IM-TM specimens attributes to decomposition of the PF resin. Thermal modification induces approximately 2% mass loss of wood. Larger mass loss of IM-TM specimens is due to PF resin decomposition and wood degradation. Thermal modification decreases the equilibrium moisture content (EMC) of wood, resulting from hemicellulose degradation and a decrease in hydroxyl groups (Cademartori et al. 2013). In comparison to TM specimens, the moisture content of IM-TM and TM-IM specimens is higher, which is caused by the hygroscopic nature of the PF resin. Researchers have reported that phenol-resorcinol-formaldehyde resin can take up moisture as high as 18% (Wimmer et al. 2013). The effect of thermal modification on water sorption of PF resin is hardly detectable because of the slight moisture content difference between IM-TM and TM-IM specimens.

Table 2 Mass loss, weight gain and moisture content of four different types of specimens

Sample (N=6)	Control(SD)	TM(SD)	IM-TM (SD)	TM-IM (SD)
Weight percent gain (%)	——	——	12.31(0.45)	16.38(0.20)
Mass loss (%)	——	1.91(0.08)	3.37(0.09)	2.15(0.08)
MC (%)	8.32(0.08)	5.49(0.09)	7.18(0.08)	7.26(0.05)

Note: The MC was measured after conditioning the specimens at 65±3% relative humidity and 20±2℃ for 4 weeks. TM indicates thermally modified specimens; IM-TM indicates PF resin impregnated and thermally modified specimens; TM-IM indicates thermally modified and PF resin impregnated specimens. SD indicates standard deviation.

Figure 2 shows that both compressive stress and deformation at the point of larger than 100N continuous loading force decrease. TM specimens have the lowest compressive stress and displacement. This is because thermal modification can decrease the mechanical strength of wood due to an increased brittleness of the fibers (Bekhta 2020). PF resin impregnation substantially enhances the compressive stress of TM specimens. In comparison to control specimens, IM-TM and TM-IM specimens' compressive stress is even higher. Hence, resin impregnation is proven to be an effective method to compensate mechanical strength decrease from thermal modification. Although the weight percent gain of TM-IM specimens is larger

than IM-TM specimens, the difference in compressive stress between the two types of specimens is small and non-significant. Based on the multi-sample t-test results listed in Table 3, thermal modification significantly ($\alpha = 0.1$ confidence level) decreases both compressive stress and displacement of wood. PF resin impregnation significantly ($\alpha = 0.05$ confidence level) increases both compressive stress and deformation of TM specimens.

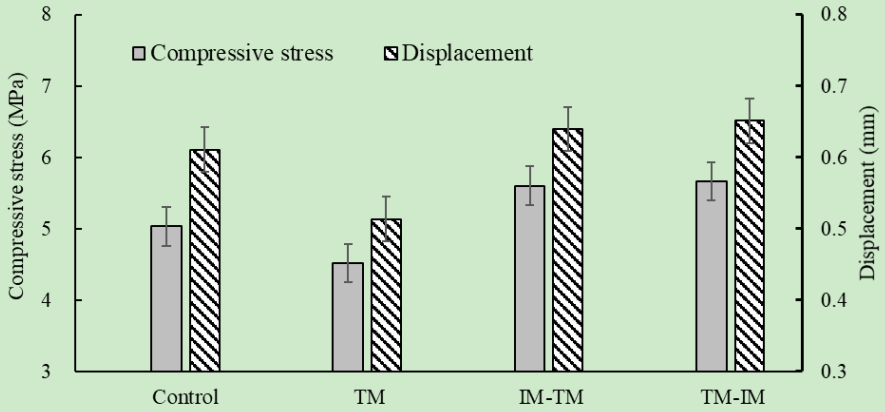


Fig.2 Compressive stress and deformation of four different types of specimens

Table 3: T-test results of compressive stress and deformation of three groups of specimens

Interactions	Control/TM	Control/IM-TM	Control/TM-IM	TM/IM-TM	TM/ TM-IM
Compressive stress	0.076*	0.110	0.042**	0.022**	0.010**
Deformation	0.057*	0.296	0.213	0.008**	0.037**

Note: ** significant at 5% level, * significant at 10% level. TM indicates thermally modified specimens. IM-TM indicates PF resin impregnated and thermally modified specimens. TM-IM indicates thermally modified and PF resin impregnated specimens.

Figure 3 shows the relationship between compressive stress and displacement of the loading wedge, which was obtained from the average of 6 replicates of each type of specimens. For control specimens, arrow indicates an inflection point dividing the control curve into two domains (arrow in Fig.3), which could be caused by cell walls buckled at their yield point (Wolcott et al. 1989, 1994). Two domains are likely indicators of two types of internal structure changes, more specifically crushing, and plateau stress as reported in compression of solid wood (Wouts et al. 2016). For the other three types of specimens, this phenomenon, however, is not detectable. Thermal modification increases the stiffness of wood fibers, which limits the plastic deformation, i.e. the second domain of the curve. After PF resin impregnation, the specimens tend to be flexible, thus the specimens can deform but are more resistant to rupture.

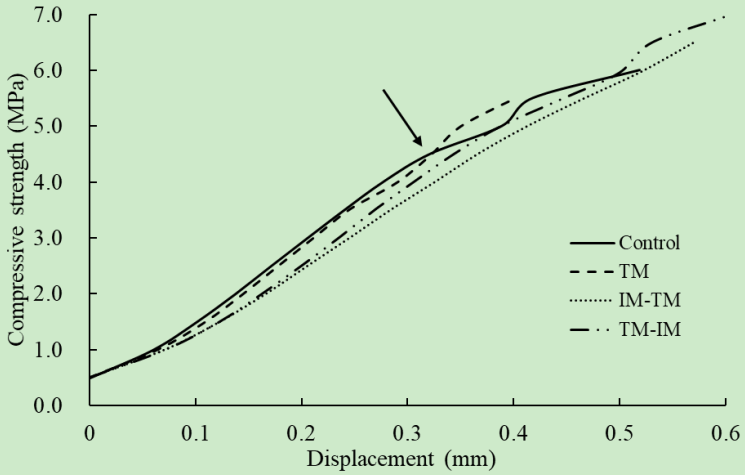


Fig.3 Relationship between compressive stress and deformation of four different types of specimens. Arrow indicates an inflection point divided the curve into two domains

3.2 Chemical and microstructural changes

Figure 4 shows the chemical composition of the four types of specimens. The slight decrease in the OH stretch vibration (3330 cm^{-1}) is most likely proof of the degradation of hemicelluloses. The decline of OH contributes to the improvement of water resistance and dimensional stability of wood. The decrease in the absorption peak near the C=O stretch vibration (1722 cm^{-1}) of TM specimens represents the degradation of hemicelluloses. This peak was attributed to the linkage of the acetyl group with the ester group or carboxyl group in hemicelluloses (Boonstra and Tjeerdsma 2006). For TM-IM specimens, the absorption peak at 1722 cm^{-1} originates from the C=O stretching vibration in formaldehyde. PF resin is a synthetic polymer obtained by additive reaction and polymerization of phenol with formaldehyde. The absorption at 1603 cm^{-1} is attributable to the C=C stretching vibration in the aromatic ring of the phenol, which is obvious in the TM-IM specimens. Compared to the other three types of specimens, several absorption peaks are no longer detectable in IM-TM specimens. Specifically, the 2885 cm^{-1} stretch vibration of C-H. 813 cm^{-1} and 1330 cm^{-1} bending vibration of C-H. Prominent bands at 1028 cm^{-1} and 1270 cm^{-1} arise from the C-O stretch vibration in cellulose, hemicellulose and PF resin. The decrease of these peaks could be due to a chemical reaction between wood and PF resin, which agrees with the findings of Wang et al. (2016) and Wu et al. (2020). This is possibly because of non-cured PF resin at 103°C, and it is cured and partially decomposed during thermal treatment (200°C). The curing behavior of PF resin could be affected by wood present in the curing system. Wood may accelerate the addition reactions and slow down the condensation ones during the curing process of PF resin (He and Riedl 2004).

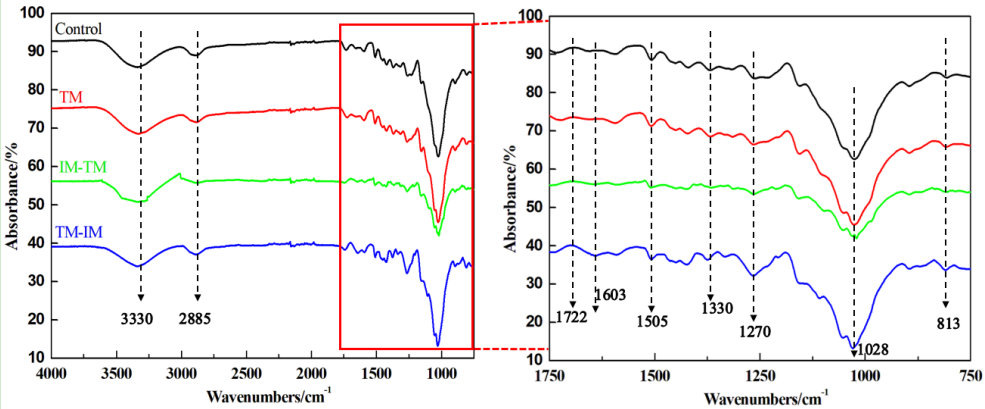


Fig.4 FTIR spectra for the four types of specimens

Figure 5 illustrates the microstructure of the four types of specimens. PF resin is mainly present in the cell lumens of IM-TM and TM-IM specimens. PF resin in TM-IM specimens is more prominently present than in IM-TM specimens. This could be due to decomposition of PF resin during thermal modification. The mechanical strength of wood is mainly determined by the cell wall. Based on the reference results obtained by using the same type of PF resin, small amount of PF resin has been found in the cell wall and the MOE and hardness of cell walls could be slightly increased due to PF resin impregnation (Wang et al. 2022, Wang et al. 2019b). Hence, a large amount of PF resin accumulation in the cell lumen has relatively small contribution to increasing compressive strength. This hypothesis is in agreement with the observation of slightly higher compressive stress of TM-IM than IM-TM specimens (Fig.2).

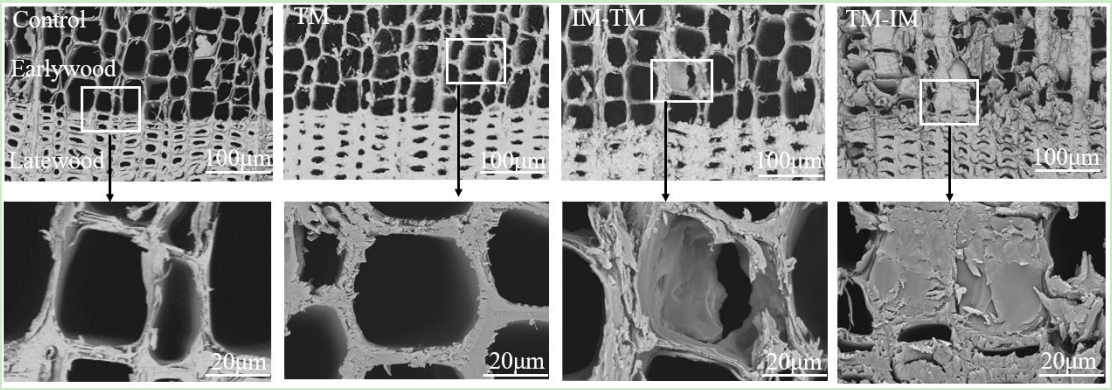


Fig.5 SEM pictures of the transverse section of the four types of specimens

Figure 6 shows the microstructure of the ruptured sections (tangential plane) of the four different types of specimens. The ruptured sections locate in earlywood adjacent to the interface between earlywood and latewood. Ruptures (shown with solid arrows) in TM, IM-TM and TM-IM specimens are more obvious than in control specimens. For control specimens, compression causes serious deformation but limited ruptures in wood (Li et al. 2021). Wood fibers become brittle due to thermal modification. During compression, wood fiber morphology could be compressed up to rupture. After impregnation, wood fibers are protected by the PF resin

resulting in the increase in strength and ductility. Thermal modification after PF resin impregnation decomposes part of the resin. Resin, especially in the cell lumen, can protect from propagation of cracks through the wood cells. Resin accumulation (shown with dashed arrows) is more obvious in TM-IM than IM-TM specimens. This is the reason for more obvious ruptures in IM-TM than TM-IM specimens.

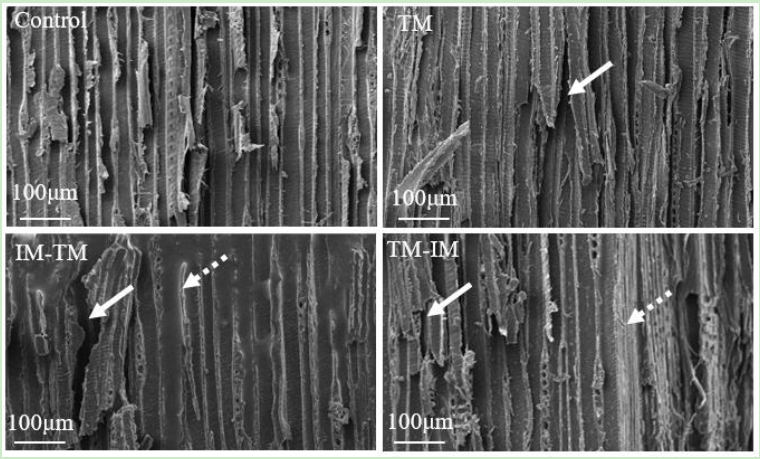


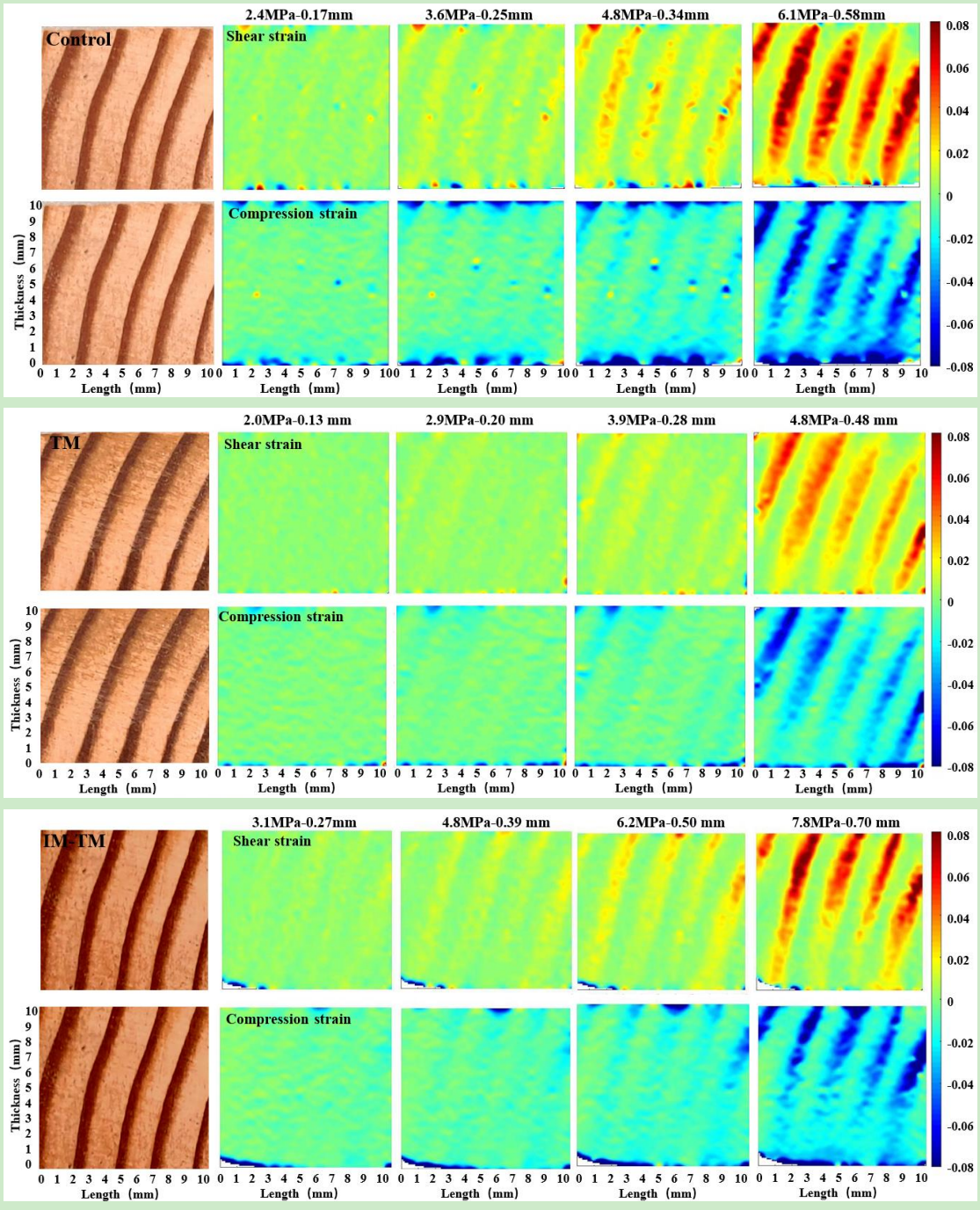
Fig.6 Ruptured tangential section microstructure of four different types of specimens. Solid arrows indicate the rupture of wood fiber. Dashed arrows indicate the accumulation of resin

3.3 Strain distribution

The impact of thermal modification on the compressive strength of wood is variable according to directions, i.e. tangential, radial and longitudinal, as reported by Gündüz et al. (2009). Hence, strain distribution is critically influenced by wood anatomy. Figure 7 shows that both shear and compression strain are closely correlated with the orientation of growth rings. Along with the increase in compression stress, clockwise shear strain and compression strain tend to accumulate in earlywood.

Looking at the general strain distribution profiles of the four different types of specimens, they are quite similar. It means that the way of strain distribution is dominated by the orientation of the growth ring regardless of the different modifications. Although any modifications hardly change the strain distribution, it influences the speed of strain accumulation during the compression test. Figure 7 shows high strain in the earlywood. Earlywood cells are more flexible than latewood cells due to the thin cell walls. We should expect failure to occur at the interface between earlywood and latewood, since stress will accumulate where high strain meets low strain. At a compressive stress of 4.8MPa, strain accumulation is more significant in the TM specimens than the other three types of specimens (Fig.7). For the TM specimens, brittleness would be correlated to low strength. An increased brittleness decreases the possibility of stress transfer through the wood fibers. Hence, strain is prone to occur and accumulate in the regions with low strength, leading to early failure of TM specimens. Combining PF resin impregnation with thermal modification, both strain value and accumulation are decreased. PF resin impregnation is able to enhance the stiffness of wood

fibers because PF resin penetrates into the cell wall and reacts with cell wall polymers (Wang et al. 2019b). Stiff cell walls certainly contribute to the increase in compression stress of wood. The PF resin could function as a bridge for strain transfer, which limits strain accumulation in earlywood at low compression stress.



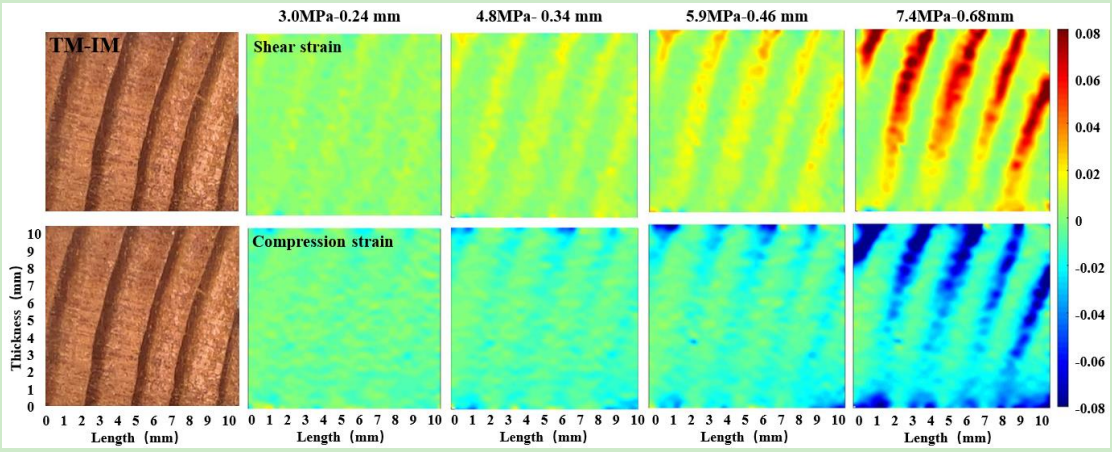


Fig.7 Shear strain (top row) and compression strain (bottom row) of four different types of specimens at four different compressive stress and displacement steps

To further investigate the strain distribution, strain value of 30 different spots in earlywood and latewood was quantified respectively. These spots were randomly collected from each type of specimens. Figure 8 shows that thermal modification increases the strain difference between earlywood and latewood. With PF resin impregnation, this difference could be narrowed. At the same compressive stress 4.8MPa, IM-TM specimens have the smallest shear and compression strain. This is related to the stiff cell wall. In addition to PF resin penetration, the reaction between resin and wood polymers during thermal modification could be the reason for the increased cell wall stiffness. As listed in Table 4, control specimens have the smallest strain ratio between earlywood and latewood. IM-TM and TM-IM specimens have smaller strain ratio than TM specimens. IM-TM specimens' strain ratio is smaller than that in TM-IM specimens. This means that PF resin impregnation before thermal modification can homogenize strain distribution more effectively. The strain ratio in both IM-TM and TM-IM specimens is still larger than the strain ratio in control specimens. This indicates that control specimens are able to transfer strain effectively, which is helpful for prohibiting wood failure. PF resin impregnation improves strain transfer of TM samples, however, can hardly fully compensate the decrease in strain transfer caused by thermal modification. To produce high strength TMT, it is crucial to strengthen the cell wall and improve strain transfer.

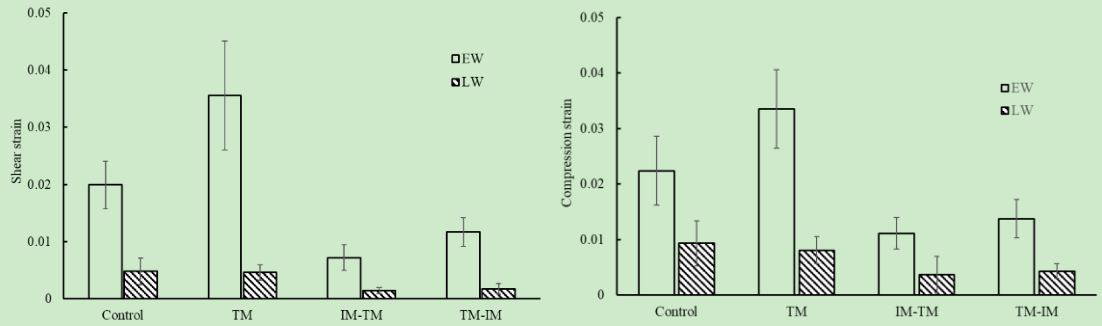


Fig.8 Shear strain distribution in earlywood (EW) and latewood (LW) of the four different types of specimens at compressive stress 4.8MPa

Table 4 Strain ratio between earlywood and latewood of four different types of specimens

Strain ratio	Control	TM	IM-TM	TM-IM
Compression strain	2.39	4.14	2.99	3.16
Shear strain	4.13	7.68	4.91	6.57

4. Conclusion

The influence of thermal modification and PF resin impregnation on the compressive stress of wood was studied. Thermal modification decreases the compressive stress of wood, while PF resin impregnation is able to significantly enhance the compressive stress of thermally modified timber (TMT). PF resin impregnation improves the stiffness and ductility of the wood cell walls, which increases both compressive stress and deformation of the samples in compression test. There is only a small difference in compressive stress between PF resin impregnation before thermal modification (IM-TM) and PF resin impregnation after thermal treatment (TM-IM). Weight percent gain in IM-TM specimens is smaller than in TM-IM specimens, resulting from PF resin decomposition in cell lumens caused by thermal modification. In addition to decomposition, PF resin could react with wood during thermal modification. The PF resin distribution and chemical reaction with wood change the strain distribution. Although the general strain distribution is dominated by the main anatomical feature (earlywood and latewood differences in cell size and cell wall thickness). The speed of strain transfer and accumulation is influenced by the modifications. In compression tests, both compression and shear strain are going to accumulate in earlywood, which is an issue in TM specimens even at low compressive stress. PF resin stiffens the wood cell wall and increases strain transfer efficiency, avoiding excess strain accumulation at low compressive stress. Although PF impregnation contributes to homogenizing strain distribution, the strain ratio between earlywood and latewood in IM-TM and TM-IM specimens is still larger than that in control specimens.

This study focused on understanding the effect of thermal modification and PF resin impregnation on the compressive stress of wood. This study shows that effective strain transfer is key to improve compressive stress of wood. Methods to further decrease strain accumulation are required to be explored in future. It is possible to precisely improve the strength and ductility of earlywood only, which could narrow the strength difference in the specimens' different regions and decrease PF resin consumption.

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