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# TIME-MOISTURE SUPERPOSITION PRINCIPLE IN CREEP BEHAVIOR OF WHITE OAK WITH VARIOUS EARLYWOOD VESSEL LOCATIONS

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## ABSTRACT

Creep behavior of wood plays a fundamental role in precision processing of wood. In this work, experimental creep tests have been conducted to determine the influence of earlywood vessel location and moisture content on creep behavior of *Quercus alba* (white oak). Time-moisture superposition principle was applied to predict long-term creep behavior of white oak. Results revealed that both of instantaneous and 45-min strain of specimens increased with the increasing of moisture content and decreased with increasing distance between earlywood vessel belt and load-bearing surface significantly. Additionally, the time-moisture superposition principle was found to have feasibility to predict creep behavior of white oak with various earlywood vessel locations and moisture content ranges (6 % - 18 %). We believe that the proposed investigation was beneficial for the processing precision and civil engineering applications of wood.

**Keywords**: America white oak, creep behavior, earlywood, vessel element*, Quercus alba*, time-moisture superposition principle.

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# INTRODUCTION

Bending emerges as an important methodology towards the precision process of wooden furniture parts and it provokes a wide attention (Moosavi *et al*. 2016; Wang 2017, Báder *et al*. 2019, Gaff *et al*. 2019, Hou *et al*. 2021). The application of bending in the wooden furniture manufacturing brings about beautiful curves and conformable visual/tactile experience, making it warmly welcomed by consumers (Chen 2002).

However, wood bending processing has under-overcome disadvantages lying in high production cost, hyper rate of waste products, great springback rate of bending parts and low utilization rate of materials (Wang and Xu 2014, Wang 2017). Therefore, it is of great significance to understand the bending mechanism of wood to stabilize the quality of bended wood products. It also possesses notable importance for an up-coming green society by reducing the waste of wood.

It has been confirmed that bending property of hardwood was better than the softwoods (Sedighi Moghaddam *et al.* 2017, Gaff *et al*. 2019, Zhang *et al*. 2013, Báder *et al*. 2019). The stress-strain relation was obviously affected by wrinkle formed on cell wall of vessel in the tension and compression surface of elm and ash after pretreatment and compression along the grain, contributing to the realization of compression along the grain of hardwood (Song *et al.* 2003, Song 2008).

Besides, the effect of steam-grain compression on bending property of beech and sessile oak was explored by investigation of the polysaccharides and lignin by FTIR (Báder *et al*. 2020). Another study revealed that a critical effect was generated to impact flexural strength (IBS) of summer oak and Norway spruce in different thermal modification temperature with corresponding critical temperature 160 °C (Gaff *et al*. 2019). Experiments have been conducted to investigate the creep behavior of white oak with various distributions of earlywood vessel, and it was found that instantaneous and 45-min strain of specimens would decrease with increasing distance between earlywood vessel belt and load-bearing surface obviously (Hou *et al*. 2021). The ring-porous wood exhibits obvious advantages in wood bending processing. The bending and compression process of ring-porous wood is composed of a series of vessel elements under different stress state conditions, exerting a significant influence on the bending processing quality of wood (Song *et al.* 2005, Zhang *et al.* 2013). The stress state of vessel element in different locations is mainly divided into compression, tension and neutral layer in wood bending process (Chen and Zhu 2019). Hence, it is necessary to explore the effect of vessel element with various stress states on wood creep behaviors to reveal the mechanism of wood bending.

Creep behaviors play a critical role in the bending process of wood regardless of tree species, i.e., the hardwood (Hou *et al*. 2021, Yin *et al*. 2021, Song 2008) and softwood (Nakai *et al*. 2018, Wang *et al.* 2020). Many studies have been carried out to investigate the effects of moisture content (MC), temperature and grain orientations on wood static viscoelasticity systematically (Kutnar *et al*. 2021, Hsieh and Chang 2018, Nakai *et al*. 2018). A critical effect appeared on the bending creep of white oak under different temperature, and the corresponding temperature threshold was 50 °C (Yin *et al*. 2021).

Instantaneous and creep strain of beech after thermo-hydro-mechanically treatment were confirmed to increase with increasing loadings (Kutnar *et al*. 2021). Besides, the time-stress superposition principle (TSSP) and time-temperatures-stress superposition principle (TTSSP) were applied to simulate the bending creep response characteristics of high temperature treated Chinese fir, indicating that the temperature threshold of TSSP and TTSSP for the prediction of flexural creep behavior of Chinese fir after high temperature treatment was 180 °C (Wang *et al*. 2020).

However, little efforts have been poured onto analyzing the effect of earlywood vessel locations and MC on creep behavior of ring-porous wood and its long-term creep behavior prediction in accordance with time-temperatures-moisture superposition principle (TTMSP). For this reason, it is crucial to analyze and predict the creep behavior and the applicability of TTMSP on ring-porous wood.

In this study, the effect of earlywood vessel location and moisture content (MC) on creep behavior of white oak was systematically investigated to reveal the bending mechanism of wood from wood viscoelastic behavior. The applicability of time-moisture superposition principle (TMSP) to creep behavior of white oak with various earlywood vessel location and MC conditions was also studied. This work provides great scientific basis and technical support for processing precision and civil engineering applications of wood.

## MATERIALS AND METHODS

### Materials

America white oak (*Quercus alba* L.), earlywood and sapwood lumber were purchased from Nanxun Timber Market in Huzhou, China. Size of white oak specimens was 40 mm (Longitudinal: L) × 12 mm (Tangential: T) × 2,2 mm (Radial: R). Four types of specimens were prepared for creep behavior analysis of white oak. As can be seen in Figure 1, a bending loading along the radial direction in a double cantilever fixture was applied to specimen during creep test (Figure 1).

As depicted, Specimen A is the specimen with earlywood vessel in the compression layer, B is with earlywood vessel in the mesne layer, C is with earlywood vessel in the tensile layer and D is the control without earlywood vessel.

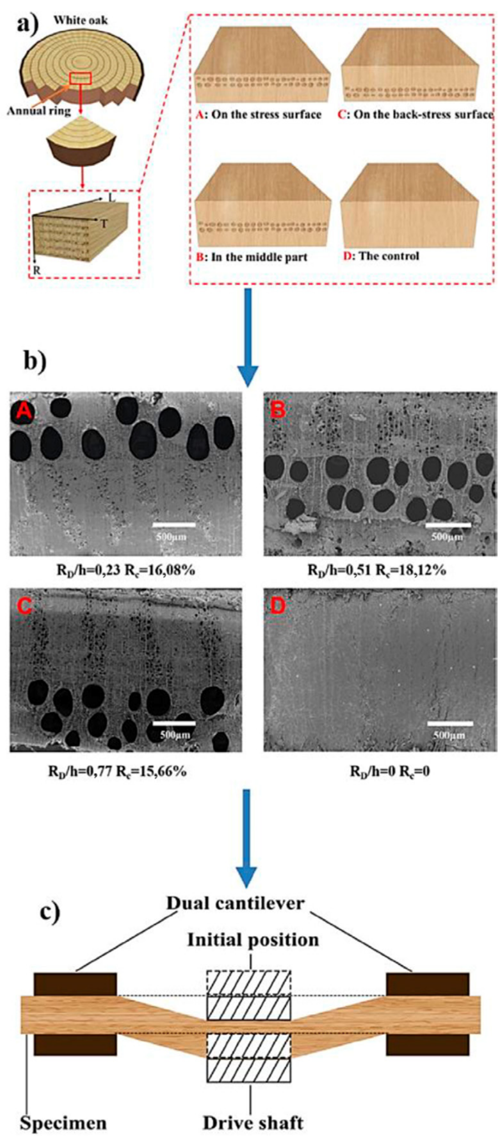


**Figure 1:** Preparation, numerical characterization and creep test of white oak specimens with various earlywood vessel locations: a) Sample preparation; b) Numerical characterization; c) Creep test.

**Numerical characterization of earlywood vessel location**

Numerical characterization process of earlywood vessel location characteristics by MATLAB 9.6 (2019) software is presented in Figure 2. Distribution of earlywood vessel element in the cross section of specimens was investigated by Scanning electron microscope (SEM, TM-3030, Hitachi Limited, and Tokyo, Japan).

Vessel area ratio ($R_C$) in the cross-section of specimens was calculated in accordance with the area of earlywood vessel elements and the total area of cross-section of specimens obtained by digital image using MATLAB 9.6 (2019) software (Figure 2a). Besides, the distance between earlywood vessel belt and load-bearing surface ($R_D$) was determined by the distance between the central location of earlywood vessel belt and load-bearing surface according to Figure 2b.

Twenty replicated SEM images from three adjacent repeated specimens were applied to calculate $R_C$ and $R_D$ for each type of specimen, and the average $R_C$ and $R_D$ values were used for the subsequent analysis.

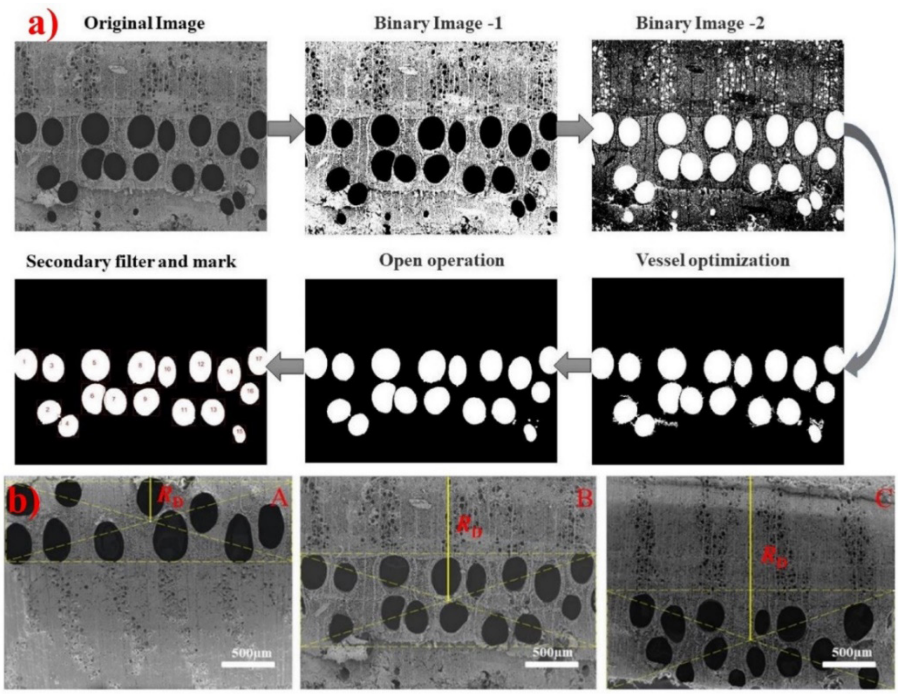


**Figure 2:** Numerical characterizations processes of earlywood vessel location parameters of specimens: a) Earlywood vessel area ratio ($R_C$); b) the distance between earlywood vessel and load-bearing surface ($R_D$).

**Creep behavior analysis of white oak**

The specimens were placed in a high-low humidity alternating test box (EL-10KA, Espec Corporation, USA) to adjust the corresponding moisture content (MC) to 6 %, 9 %, 12 %, 15 %, and 18 %, respectively. Creep behaviors were studied by a dynamic thermomechanical analyzer (DMA-Q800, TA instruments, New Castle, USA) with a bending loading along the radial direction in a double cantilever fixture (Figure 1c) (Hou *et al.* 2021).

In addition, the MC of specimen was controlled by a humidity accessory during creep test. Creep test of white oak specimens was performed at room temperature, and the corresponding RH was controlled to 30 %, 51 %, 71 %, 79 %, and 86 %. A constant stress of 5,0 MPa was applied to investigate bending creep behaviors of specimens as reported in the earlier studies (Wang *et al*. 2018, Yin *et al*. 2021, Hou *et al*. 2021). Besides, the holding time was set to 45 min during creep test. Data of bending creep behaviors was collected and recorded by a DMA procedure. Three repetitions for each type of specimens were prepared.

## RESULTS AND DISCUSSION

### Numerical characterization of earlywood vessel location in white oak specimens

Normality analysis (i.e., Gaussian distribution analysis) for earlywood vessel area ratio ($R_C$) and the distance between earlywood vessel and load-bearing surface ($R_D$) of specimens are presented in Figure 3 and Figure 4. As depicted in Figure 3, $R_C$ of specimens followed a normal distribution. It indicated that $R_C$ in the cross section of specimens with various earlywood vessel locations was almost the same. Therefore, the number and distribution state of earlywood vessel elements in specimens were consistent, providing basis for the investigation of creep behavior of white oak.

Besides, $R_D$ of specimens with various earlywood vessel distributions followed a normal distribution as illustrated in Figure 4. It indicated that $R_D$ of Specimen A, B, and C were 0,50 ± 0,03 mm, 1,12 mm ± 0,04 mm and 1,70 mm ± 0,02 mm. The obtained data for $R_D$ was then applied to analyze the effect of earlywood vessel locations on creep behavior of white oak. The same conclusion was obtained for the normality test result of $R_C$ and $R_D$ of specimens as shown in Table 1.

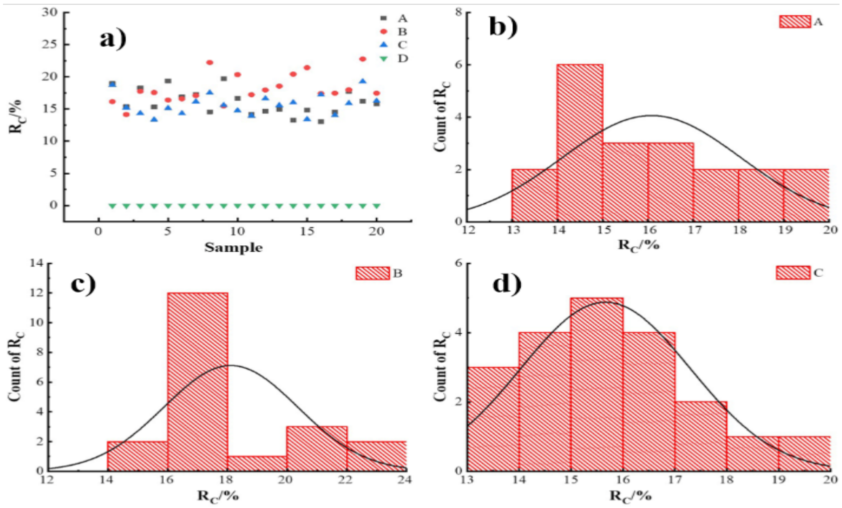


**Figure 3:** Normality analysis for vessel area ratio in specimens: a) Earlywood vessel area ratio of tested specimens; b) Normality analysis of Specimen A; c) Normality analysis of Specimen B; d) Normality analysis of Specimen C.

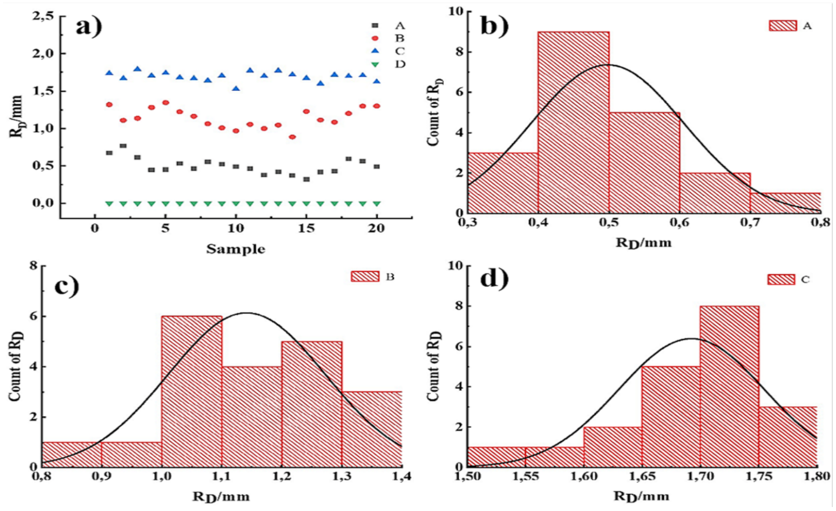


**Figure 4:** Normality analysis for the distance between earlywood vessel belt and load-bearing surface ($R_D$) of specimens: a) $R_D$ of specimens; b) Normality analysis of Specimen A; c) Normality analysis of Specimen B; d) Normality analysis of Specimen C.

**Table 1:** Normality test result of vessel area ratio ($R_C$) and the distance between vessel and load-bearing surface ($R_D$) of specimens.

| Parameter | A | B | C | D |
|---|---|---|---|---|
| $R_C$ (Mean[a]±SD, %) | 16,08±0,44 | 18,12±0,50 | 15,66±0,37 | 0±0 |
| DF | 20 | 20 | 20 | 20 |
| Statistic | 0,95 | 0,92 | 0,96 | - |
| Prob<W | 0,41 | 0,12 | 0,45 | - |
| $R_D$ (Mean[a]±SD, mm) | 0,50±0,03 | 1,12±0,04 | 1,70±0,02 | 0±0 |
| DF | 15 | 15 | 15 | 15 |
| Statistic | 0,97 | 0,95 | 0,91 | - |
| Prob<W | 0,58 | 0,86 | 0,14 | - |

[a] Mean is for repeated specimens. SD is standard deviation.

**Earlywood Vessel location-dependent creep behavior of white oak**

Figure 5 and Figure 6 presents the creep strain curves of white oak. As depicted in Figure 5, a gradual decrease was observed in creep strain of specimens and the decrement was increased with increasing $R_D$. The same conclusion was obtained to instantaneous and 45-min strain of specimens. Compared with the control, increment in instantaneous strain of specimens was 24,19 %, 12,89 % and 4,01 % with the increase of $R_D$ from 0, 50 mm to 1,70 mm at the MC of 12 % (Figure 6).

The same result was found in instantaneous strain and 45-min strain of specimens under different MC conditions. An obvious increment of creep strain was observed in Specimen A in comparison with that of Specimen B, C and D. It was also noted that the effect of vessel location on instantaneous strain and 45-min strain of specimens was significantly at 0,05 levels. As described in the stress concentration problem of holes or circular holes in elasticity based on Lamé equation of elasticity, stress at the edge of holes is much higher than that without holes, and it will also be higher than the stress slightly away from the holes as an elastic body with small holes is subjected to external stress (Hou *et al*. 2021).

The effects of stress on circular hole or circular channel were decreased with the increase of the distance between the circular hole or circular channel and stress in accordance with the Saint-Venant's principle of elastic mechanics (Yin *et al*. 2021, Hou *et al*. 2021). The stress concentration phenomenon of earlywood vessel was more obvious with the increase of $R_D$ as the specimens were subjected to an external stress. The similar conclusion was obtained from our previous study conducted to investigate the effect of temperature and early-wood vessel belt distribution on creep behavior of white oak (Hou *et al*. 2021).

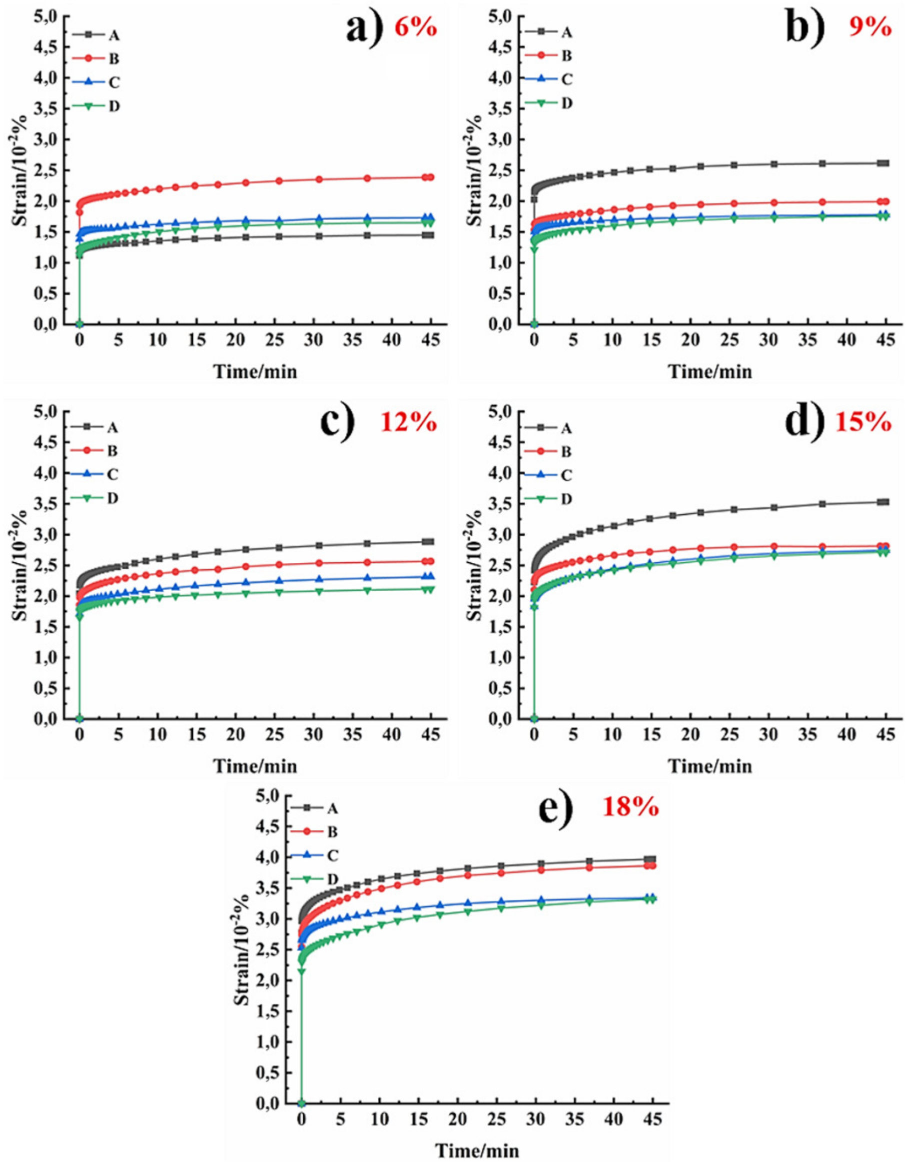


**Figure 5:** Creep curves of white oak specimens under different earlywood vessel location conditions: a) 6 %; b) 9 %; c) 12 %; d) 12% and e) 15 %.

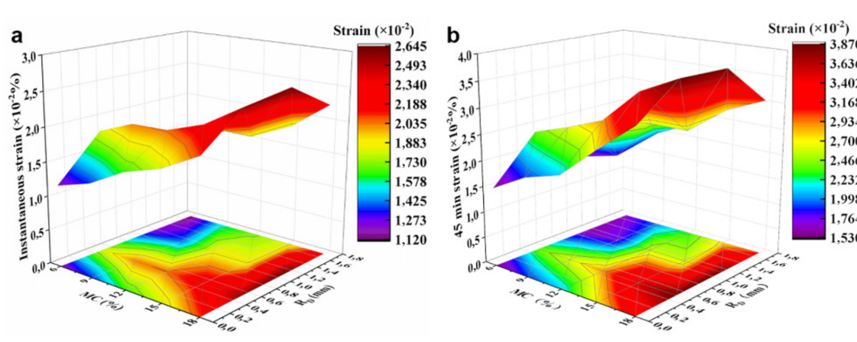


**Figure 6:** Instantaneous a) and 45-min strain b) of white oak under different MC and earlywood vessel location conditions.

**Table 2:** Values of variance analysis on instantaneous and 45-min strain of white oak under different MC and vessel location conditions.

| Parameter | Source | SS | DF | MS | F | P-value |
|---|---|---|---|---|---|---|
| Instantaneous strain | Vessel location | $7{,}69\times10^{-5}$ | 3 | $2{,}56\times10^{-5}$ | 14,33 | $2{,}85\times10^{-4}$ |
| | MC | $2{,}42\times10^{-4}$ | 4 | $6{,}05\times10^{-5}$ | 33,83 | $1{,}90\times10^{-6}$ |
| | Error | $2{,}15\times10^{-5}$ | 12 | $1{,}79\times10^{-6}$ | - | - |
| | Sum | $3{,}40\times10^{-4}$ | 19 | | | |
| 45-min strain | Vessel location | $1{,}80\times10^{-5}$ | 3 | $6{,}00\times10^{-5}$ | 14,85 | $2{,}42\times10^{-4}$ |
| | MC | $7{,}34\times10^{-4}$ | 4 | $1{,}83\times10^{-4}$ | 45,34 | $3{,}79\times10^{-7}$ |
| | Error | $4{,}85\times10^{-5}$ | 12 | $4{,}04\times10^{-6}$ | - | - |
| | Sum | $9{,}62\times10^{-4}$ | 19 | - | - | - |

**Moisture-dependent creep behavior of white oak**

Creep strain curves of specimens as a function of time under different MC conditions are displayed in Figure 7. Results revealed that MC significantly affected the creep behavior of specimens (Table 2). As illustrated in Figure 7, creep strain of specimens gradually increased with increasing MC. A slightly increase was observed to creep strain of specimens with the increase of MC from 6 % to 12 %. A remarkable increase in creep strain was generated with further increasing MC to 15 %.

Additionally, increment of creep strain of specimens was increased with increasing MC. This may be attributed to the fact that the bound water exists in microcapillary system of wood with MC lower than fiber saturation point (Placet *et al*. 2007, Placet *et al*. 2012). Hydrogen bonding among the molecular chains in cell wall was weakened with the introduction of water molecules, leading to a decline of mechanical properties in wood cell wall (Placet *et al*. 2007, Placet *et al*. 2012).

Additionally, obvious swelling is formed in wood cell wall with increasing MC, further resulting in the increase of the free volume and decrease of wood cell wall substance in accordance with free volume theory and an acceleration of molecular movement (Nimez *et al*. 2023). Relative slippage among microfibrils was also observed to increase with increasing MC due to the role of moisture as the plasticizer in wood (Salmén 2004, Navi and Stanzil-Tschegg 2008). Therefore, creep phenomenon of specimens became more and more obvious and increased with increasing MC as expected.

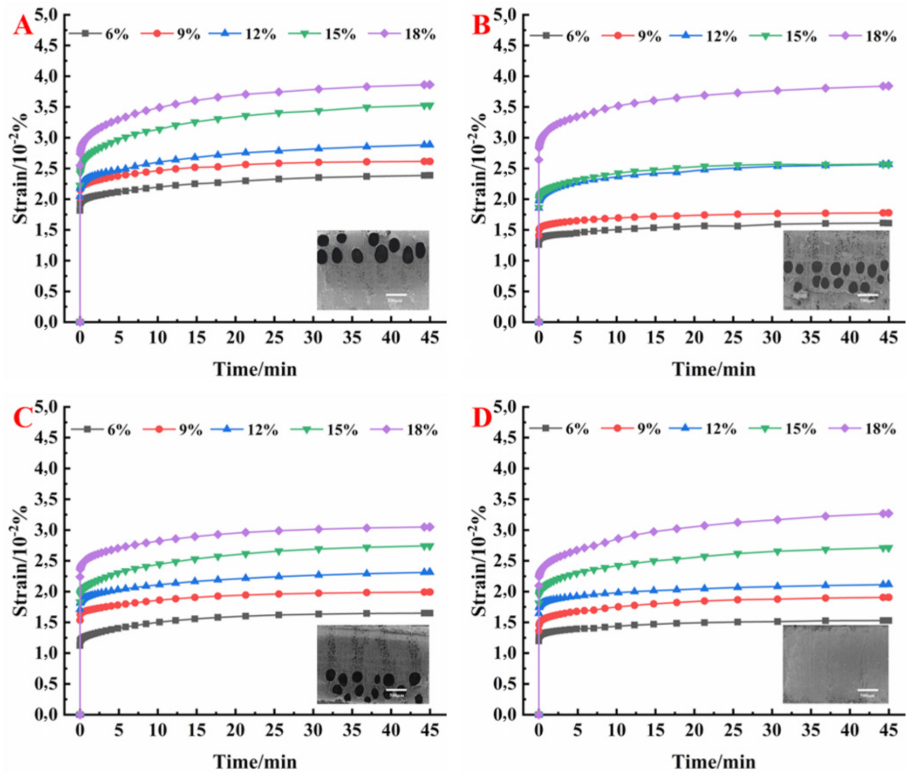


**Figure 7:** Creep curves of white oak under different MC conditions.

As can be seen in Figure 7, instantaneous and 45-min strain of specimens were increased with increasing MC. Compared with the control, increment of instantaneous strain of Specimen A was 51,59 %, 48,97 %, 24,19 %, 22,80 % and 21,61 % with the increase of the MC from 6 % to 18 %. The same result was obtained to 45-min strain of Specimen A. Moreover, the corresponding increment in instantaneous and 45-min strain of Specimen B and C was obviously decreased in comparison with that of Specimen A.

Besides, both effects of MC and vessel location on instantaneous and 45-min strain of white oak were significantly at 0,05 levels (Table 2). The F value of MC was greater than that of vessel location, indicating that MC change gradient had a more significant effect on instantaneous and 45-min strain of white oak compared to vessel location. It can be attributed to the fact that moisture absorption capacity of microfibrils is weaker than the matrix (Kojima and Yamamoto 2005, Englund and Svensson 2011).

Therefore, the effect of MC on creep strain of wood was mainly determined by microfibril angle. When longitudinal swelling was occurred to the matrix, binding force on the matrix longitudinal swelling caused by microfibrils increased with the decrease of microfibril angle, leading to a decline in the longitudinal creep deformation of wood cell wall finally (Lichtenegger *et al*. 1999, Hein and Liam 2012, de Borst *et al*. 2012, Thomas *et al*. 2014). The binding force on the matrix longitudinal swelling caused by microfibrils was also decreased with further increasing microfibril angle greater than 45°, and the longitudinal creep compliance of wood was obviously increased with increasing MC (Roszyk *et al*. 2012, Hein and Liam 2012, Kaboorani *et al*. 2013). Therefore, instantaneous and 45-min strain of white oak were increased with the increase of MC.

**Time-moisture superposition principle (TMSP) in creep response of white oak**

It was found that the increase of the MC and $R_D$ had an inverse effect on the creep behavior of white oak in the creep test process (Figure 5 and Figure 7). However, little efforts have been poured onto predicting long-term creep behavior of ring-porous wood with various earlywood vessel locations. It is crucial to analyze and predict the long-term creep behavior of ring-porous wood for its future application in processing precision of wood. Williams-Land-Ferry (WLF) model has been widely used to predict the long-term viscoelasticity behavior of wood (Dlouhá *et al*. 2009, Peng *et al*. 2021, Wang *et al*. 2020).

The moisture dependence of strain can be expressed as Equation 1 according to WLF model.

$$Log(a_T) = \frac{-D_1 x\left(MC - MC_0\right)}{-D_2 - \left(MC - MC_0\right)} \qquad (1)$$

Where, $log(a_T)$ is shifting factor; $MC$ is moisture content of specimen; $MC_0$ is the referenced moisture content of specimen; $D_1$ and $D_2$ is the constant.

45-min creep curves of specimen with various earlywood vessel locations and MCs (6 % - 18 %) were plotted as strain versus log time and shifted horizontally according to TMSP to build the master curves, as depicted in Figure 8. Creep test performed at 6 % MC was selected as a reference in this study. As depicted, the short-term creep curves of specimens for 45 min can be processed by TMSP to obtain the long-term creep curves for $10^{7,16}$ s (Specimen A), $10^{8,27}$ s (Specimen B), $10^{8,81}$ s (Specimen C) and $10^{8,83}$ s (Specimen D).

It was concluded that TMSP was feasible to predict creep behavior of white oak wood with various earlywood vessel locations and MC ranges. Additionally, the time span of long-term creep curves was increased with increasing $R_D$, and smaller than that of the control. It can be attributed to the fact that the creep of specimen with earlywood vessel is greater than that of the control in accordance with the stress concentration problem of holes or circular holes in elasticity based on Lamet equation of elasticity (Hou *et al*. 2021).

Additionally, the effects of stress on circular hole or circular channel were decreased with increasing distance between the circular hole or circular channel and stress in accordance with the Saint-Venant's principle of elastic mechanics. The stress concentration phenomenon of earlywood vessel was more obvious with the increase of the distance between the stress and earlywood vessel as the specimens were subjected to an external stress.

Relationship between shift factors (log ($a_T$)) and MC of specimens is presented in Figure 9. It indicated that the curves between horizontal shift factor (log ($a_T$)) and MC of specimens met the requirements of WLF equation with *R*2 values ranged from 0,991 to 0,999. It was concluded that the WLF model would provide excellent agreement with the shift factor (log ($a_T$)) over the measured MC ranges (6 % - 18 %) of specimens with various vessel locations. WLF equation can be used to effectively express the relationship between the MC and the time of bending creep of white oak wood, which provides the great scientific basis and technical support for processing precision and civil engineering applications of wood.

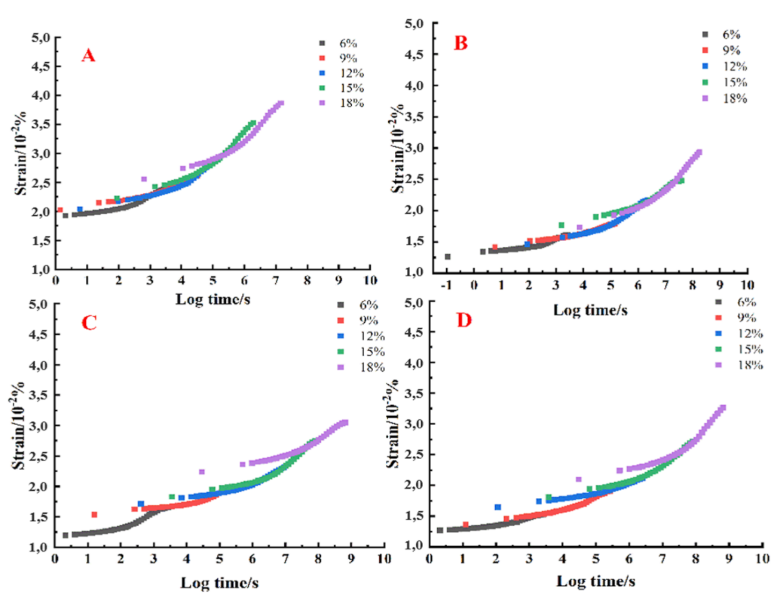


**Figure 8:** Master curve of creep behavior at different MCs at a referenced MC of 6 %.

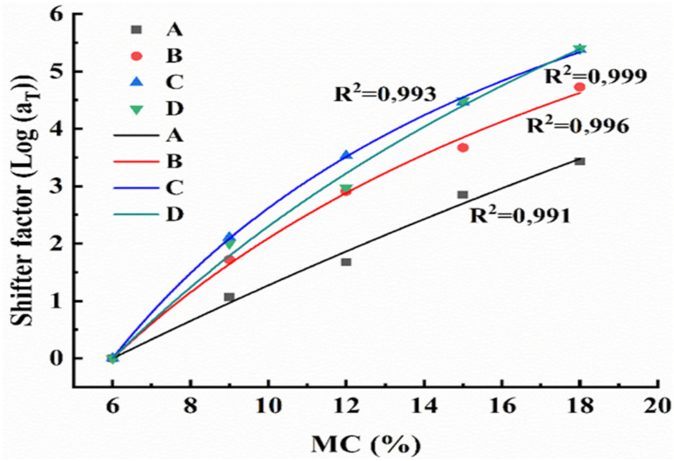


**Figure 9:** Relationship between shift factors (log ($a_T$)) and MC of specimens.

## CONCLUSIONS

The effect of earlywood vessel location and MC on creep behavior of white oak was systemically investigated by DMA. Results revealed that the effect of earlywood vessel location and MC on creep strain of white oak was significantly. Both instantaneous and 45-min strain of specimens were obviously increased with increasing MC and remarkably decreased with the increase of $R_D$. The short-term creep curves of specimens for 45 min can be processed by TMSP to obtain the long-term creep curves from $10^{7,16}$ s to $10^{8,83}$ s. Furthermore, the relationship between time and MC of creep characteristics for white oak can be effectively described by WLF equation. Therefore, we believe that the proposed investigation was beneficial for the processing precision and civil engineering applications of wood

## Authorship contributions

Y. Z.: Investigation, methodology, data curation, writing-original draft. J. H.: Conceptualization, methodology, writing-review & editing, funding acquisition. H. C.: Investigation, writing-review & editing. J. C.: Investigation, data curation. Z. J.: Writing-review & editing, funding acquisition. Y. Y.: Conceptualization, writing-review & editing, supervision, project administration.

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