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ENDURING PERFORMANCE OF SELF-TAPPING SCREW CONNECTION IN WOOD MEMBERS AND WPC MEMBERS

Xiaojun Yang, Lan Ma, Qi Zhao, Yihao Yu
Nanjing Forestry University, College of Materials Science and Engineering
Nanjing, Jiangsu, China

Xiaolan Tang
Nanjing Forestry University, College of Landscape Architecture
Nanjing, Jiangsu, China

Daoyuan Tang
Anhui Sentai Wpc Group Co. Ltd.
Xuancheng, Anhui, China

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ABSTRACT

This study examined the creep performance of self-tapping screw connection in wood members and wood-plastic composite (WPC) members that had been subjected to changes in moisture and stress levels. It was found that the self-tapping screw's joint strength depended on interlocking and friction force between wood and screw threads, between WPC and screw threads. The pine (*Pinus* spp.) and the WPC had almost the same creep properties. In wet condition, the pine's creep was higher than the WPC's. Burgers mode was able to precisely simulate the short-term creep performance of screw connection in the pine members and in the WPC members. In the wet condition, the creep was apparently higher than that in dry condition. Temperature and relative humidity were two important factors that influenced creep. The higher stress level was, the larger amount of creep would be. Creep rate was the largest in both wet condition and high stress level. It is recommended that the maximum tensile stress level should be limited to 40 % for screw connection in the wood members and the WPC members.

KEYWORDS: Wood members, WPC members, screw connection, creep performance

INTRODUCTION

It is well known that wood and wood based composites used in construction exhibits notable creep behavior under sustained loads, and such creep has a significant effect on the safety and service-ability of wood structures over their lifetime. Researchers have been studying time-dependent creep behavior for decades, and some methods of these investigations have included subjecting small or large specimens to constant or cyclic stress levels. Many of the creep characteristics and behaviors of most wood materials have been thoroughly documented, giving rise to the classical creep models and advanced creep models (Hoyle et al. 1985, Toratti et al. 2000, Svensson et al. 2002, Fortino et al. 2009).

Metal parts, indispensable components of modern wood constructions, act as a connective function. A screw connection is the most commonly used in connection mode of wood members, for its great strengths such as tightness, tenacity, simple construction, safety and reliability (Chen et al. 2008, Chen et al. 2010). For example, nail connections are applied in roof slabs and floor slabs; oblique nail-baseboard connections in wall studs and beams of light wood frame constructions. Another example is screw connections that are used in the connection parts of oriented strand boards (OSB) and studs of wood shear walls. Screw connection's reliability is often evaluated by a screw holding power. Owing to screw holding power's short test period and its long-term stress while used in wood structure members, reliability of screw connection will gradually decline with the length of its service. If the screw holding power is lower than the structure members' transferring load, "screw looseness" will occur. At present, the research on enduring performance of screw connection in wood construction has seldom been reported.

Wood-plastic composite (WPC) is a sort of composite material, characterized for its excellent mechanical properties, high dimensional stability, and replaceable of wood. Thus, it has been applied to the structure of buildings by the way of screw connection (Leu et al. 2012). Due to the viscoelasticity of wood and WPC, the screw connections in both wood members and WPC members accordingly possess such viscoelasticity property. Based on the viscoelasticity theory applied, short-term creep performance of self-tapping screw connection in wood members and WPC members has been studied in order to provide instruction on optimized application of screw.

Creep model analysis

The intensity of screw connection normally lies in the occlusion level and the force of friction between wood and screw, between WPC and screw (Zou et al. 2010). The creep of wood and WPC, that consists of instantaneous elastic deformation, delayed elastic deformation, and viscous deformation, is widely modeled as the Burger model (Hunt et al. 2004, Dean and Brought 2007, Samarasinghe et al. 1994, Yang et al. 2014). The Burger model is expressed in Eq. 1

$$\varepsilon = \sigma\left[\frac{1}{K_e} + \frac{1}{K_{de}}\left(1 - e^{-\frac{K_{de}}{\eta_{de}}t}\right) + \frac{t}{\eta_v}\right] \tag{1}$$

where: σ - the stress applied (Pa),
ε - the creep strain,
K_e and K_{de} - the instantaneous and delayed elastic moduli ($N \cdot mm^{-2}$),
η_v - the viscosity coefficient for the permanent strain ($N \cdot min \cdot mm^{-2}$),
η_{de} - the viscosity coefficient ($N \cdot min \cdot mm^{-2}$) ,
t - the loading time (min).

To facilitate calculation, Eq. 1 can be simplified into Eq. 2,

$$Y(t) = A_1 + A_2[1 - \exp(-A_3 t)] + A_4 t \tag{2}$$

where: $Y(t)$ - denotes deflection (mm) at time t (min),
t - the creep time (min),
A_1 through A_4 - the undetermined coefficients, with A_1 (mm) and A_4 (mm·min^{-1}) reflecting the elastic deformation and viscous deformation, respectively, while A_2 (mm) and A_3 (min^{-1}) reflect the viscoelastic deformation.

In this study, the screw holding viscoelastic behavior of wood and WPC was simulated using the Burger model. The average deflection of each set of specimens was used to determine the model parameters (Eq. 2) using the nonlinear fitting method via Origin8.0 software (OriginLab Corporation 2008).

MATERIALS AND METHODS

Materials

The wood species used in the study was pine (*Pinus* spp.) in the category of SPF (spruce-pine-fir), which had an air-dry density of 0.581 g·cm^{-3} and an average moisture content of 13 %. The WPC used in the study, composed of polyethylene and wood powder, was a hollow structure with a wall thickness of 8 mm, and a basic density of 0.78 g·cm^{-3}. Self-tapping screws with dimensions of 4.2 mm in diameter and 40 mm in length, were galvanized wood screws only applicable to wood structure.

Samples preparation

The wood specimens were selected from the same lumber in order to minimize the influence varied from different lumbers on testing result. Whereas only tangent-sawn lumber segments, having dimensions of 90 mm in length, 80 mm in width, and 38 mm in depth, were sorted out for experimental samples. Meanwhile the dimensions of each WPC specimens were 90 mm in length, 80 mm in width, and 35 mm in depth.

The screw connection samples were fabricated as follows. Firstly, a drill was used to make guide holes with a diameter of 2.8 mm, and a depth of 25 mm, in the center of the wood sample's wide face and the WPC sample's wide face. Secondly, screw was implanted in the wood sample or the WPC sample along the guide hole. Then, it was indicated that the magnitude of interference between screw and guide hole was 1.4 mm.

Screw holding power test

The screw holding power tests were conducted on both wood and WPC specimens under the normal condition by using a universal testing machine (Model: UTM5105). And the normal condition was set with a temperature of 20°C and relative moisture content of 65 % in accordance with the Chinese National Standard (GB/T 14018-1992). Ten specimens were tested in each group.

Tab. 1: Summary of the screw holding power test

Material	Mean (N)	Coefficient of variation (COV) (%)
Wood	2892.50	4.30
WPC	1418.16	3.41

Tab. 1 gives the means and COVs of the screw holding power test of wood and WPC. The average screw holding power of the wood specimens was 2.03 times larger than that of the WPC specimens. However, the COV of the WPC was about 20% lower than that of wood, suggesting that the WPC had uinform structure and properties.

Creep test

The stress levels used in the creep tests corresponded to 40 %, 50 %, and 70 % of the average screw holding powers. In addition, two specified climate conditions were used during the creep tests to effects of the moisture content of wood and WPC on the creep behavior: (1) a 'dry' condition with a temperature of 24°C and a relative moisture content of 45 % and (2) a 'wet' condition with a temperature of 50°C and a relative moisture content of 90 %. Testing period is 720 minutes. Creep experimental design of samples was illustrated in Tab. 2.

Tab. 2: Creep experimental design of samples.

Set code	Material	Stress level (%)	Environmental condition
LD	Wood	40	Dry
LW	Wood	40	Wet
LDP	WPC	40	Dry
LWP	WPC	40	Wet
MD	Wood	50	Dry
MW	Wood	50	Wet
MWP	WPC	50	Wet
HD	Wood	70	Dry
HW	Wood	70	Wet
HWP	WPC	70	Wet

Creep program design of testing machine

The creep tests were carried out using a universal testing machine (Model: GDS-100/UTM4304), which was equipped with a conditioning chamber with a temperature range from 0 to 100°C and relative moisture content range of 15 % to 98 %. The creep testing program was set as follows:

1) Set displacement control with a speed of 5 mm·min^{-1} as start control mode.
2) Set power control (stress level mentioned above) as final control mode.
3) Set sampling interval (30-600 sec) as start control mode.
4) Set loading time (720 min) as start control mode.
5) Set power control (50 N) as final control mode. Loading method of screw connection was as shown in Fig.1.

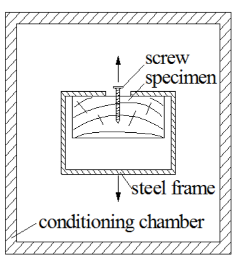

Fig. 1: Schematic of experimental setup.

RESULTS AND DISCUSSION

Fig. 2 shows the load-displacement curves of representative samples tested in screw holding power. As indicated from Fig. 2, during the loading process, the load value (screw holding power) increased linearly dramatically with the increase of pullout displacement.

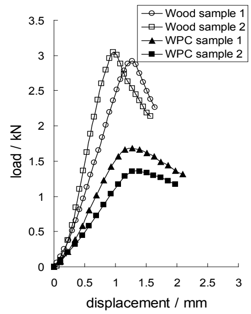

Fig. 2: Load-displacement curves of representative samples tested in screw holding power.

Under the function of interlocking and friction force between screw threads and materials (wood or WPC), the screw holding powers reached their peak loads quickly and then decreased gradually. After checking the destroyed test samples, it was found that the screw threads were filled with tiny wood or WPC. Accordingly, It was demonstrated that the screw threads and materials (wood or WPC) were completely interlocked. Therefore, the proposed method of making testing samples by setting guide holes with a diameter of 2.8 mm was proved rational.

From Fig. 3 to Fig. 12, they illustrate the creep curve and fitting data of every group. Each creep curve as mentioned in above figures represents the average response of three specimens in a group. In addition, the fitting curve of each group plotted in these figures is constructed on the basis of the displacement data points by using the nonlinear fitting method via Origin 8.0 software.

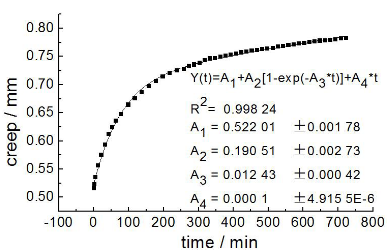

Fig. 3: Creep curve and fitting data of group LD.

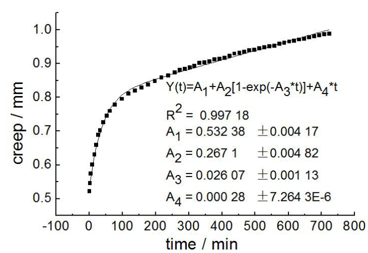

Fig. 4: Creep curve and fitting data of group LW.

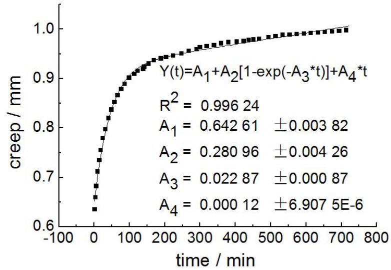

Fig. 5: Creep curve and fitting data of group MD.

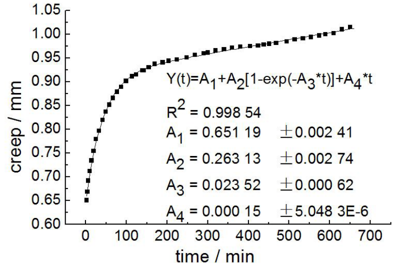

Fig. 6: Creep curve and fitting data of group MW.

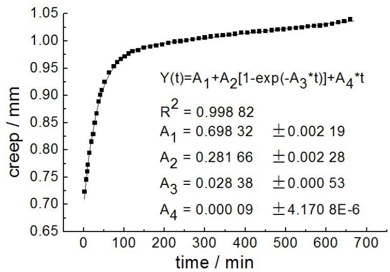

Fig. 7: Creep curve and fitting data of group HD.

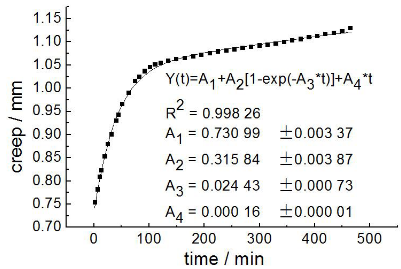

Fig. 8: Creep curve and fitting data of group HW.

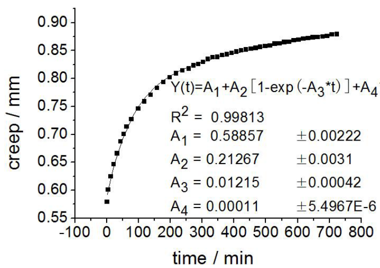

Fig. 9: Creep curve and fitting data of group LDP.

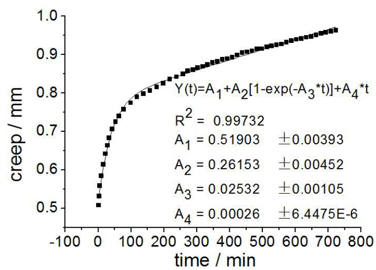

Fig. 10: Creep curve and fitting data of group LWP.

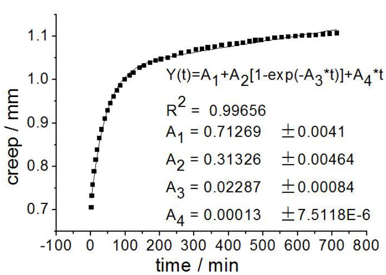

Fig. 11: Creep curve and fitting data of group MWP.

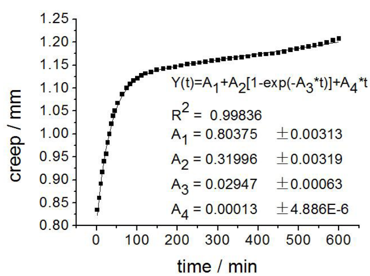

Fig. 12: Creep curve and fitting data of group HWP.

As indicated from Fig. 3 to Fig. 12, under the function of 3 stress levels, all the creep curves were nearly similar. Furthermore, they all exhibited preliminary and steady creep's short-term characteristics. During the preliminary stage, the creep was unstable. The beginning creep velocity was high, but the velocity declined with time going. The next stage was the steady creep, which developed with the lowest velocity under certain stress level and condition. Its characteristic was illustrated with low slope straight line on the creep curve.

Burgers creep model (2) , used as regression equation, was applied to data processing of each creep curve respectively in dry and wet environment. To be better explained, equation parameters (i.e., A_1, A_2, A_3 and A_4 in Eq. 2) were indicated in every figure from Fig. 3 to Fig. 12. As indicated from figures, the fitting curves and the creep curves almost matched with each other, because their correlation coefficient R^2 was above 99%. So, Burger model coud be applied in the screw connection creep.

Four groups (LD vs. LW, MD vs. MW, HD vs. HW, LDP vs. LWP) were in the same stress level and different condition. Those instantaneous elastic deformation was almost the same. However, as the load time went on, the difference of creep in each groups became more and more significant. The reason for this change was that samples for creep testing were transferred gradually from the room temperature condition to the conditioning chamber condition. During the transferring pross, screw connection parts in the initial loading were almost in the state of the room temperature condition. As time prolonged, wood and WPC in the connection parts became adapted to the conditioning chamber condition. Since wood and WPC absorbed moisture from air in the wet condition, their texture was apt to be soft. Therefore, moisture absorption creep would inevitably occur in screw connection parts. Such creep phenomenon led to the increase of creep rate. In extreme condition (i.e., wet condition and stress level of 70 %) screw connection parts broke down on the moment of 460 min for group HW, and 602 min for group HWP. It's experimentally observed that screw connection parts were unable to adapt to high temperature and high humidity. In short words, once applied in engineering, screw connection parts were suggested to aovid dampness and also necessary measurements be taken to protect these screw connection parts.

When put in dry condition and different stress level (40 %, 50 % and 70 %), test samples' creep deformations differed greatly per different stress levels. But the creep deformations followed the same rule. In the stress level of 40 % and 50 %, creep deformation rate increased slowly. However, in the stress level of 70 %, creep deformation rate increased obviously higher than that in other stress level, and the possibility of creep damage would be dramatically increased. Compared with dry condition, creep deformation rate in wet condition was higher. And test samples in stress level of 50 % and 70 % were all destroyed in a short time.

Model parameter A1 reflected the screw connection parts' ability of resistance to deformation in tensile stress within the scope of elasticity. The ratio of stress level and A1 were calculated almost unanimous. Therefore, it could be derived that elastic properties of connection parts of screw-wood and screw-WPC had less to do with stress level. After unloading, they could be recovered completely. A2 and A3 showed connection parts' viscoelastic deformation. Based on the fitted data from Fig. 3 to Fig. 12, A2 and A3 were demonstrated closely related to stress level and wet environment. Also, in wet condition and high stress level, the connection parts became more and more difficult to restore their original sizes. A4 indicated connection parts viscosity creep deformation. In wet environment, the higher stress level was, the greater the permanent deformation of screw connection parts in wood and WPC were.

In a word, all of the model parameters in Eq. 2 were associated with peak stress level and climate condition. The short-term creep characteristics of the screw-wood connection and the screw-WPC connection could be accurately simulated using the Burger model. The loading time, temperature, moisture content, and peak stress level were all found to be important factors affecting the creep of screw-wood and screw-WPC connection. High climate temperature and moisture content played an important role in accelerating the creep by increasing the moisture content of the wood and the WPC. The stress level governed the creep of screw-wood and screw-WPC connection.

During the past few decades, researchers have been studying time-dependent creep behavior. And some methods on subjecting specimens to constant climate conditions as well as subjecting specimens to constant or cyclic stress levels have been researched (Fortino et al. 2009, Yang et al. 2014). Many of the creep characteristics and behaviors of most wood species have been thoroughly documented, giving rise to the classical creep models and advanced creep models. However, there is not any work considering a significant factor: cyclic climate condition that is considered in the creep of materials. Moreover, there is no study on creep of screw connection parts between screw and wood, between screw and WPC.

This study focused on enduring performance of self-tapping screw connection in wood members and WPC members. The climate condition was firstly taken into account for creep characteristics research. Meanwhile, the stress level and the creep mode were also studied. Thus, it is recommended that the maximum tensile stress level should be limited to 40 % for screw connection in the wood members and the WPC members.

CONCLUSIONS

1. Self-tapping screw's joint strength depended on interlocking and friction force between wood and screw threads, between WPC and screw threads.
2. Creep deformation of screw connection appeared in a relative short period of time. The creep deformation depended on the loading time and the value of tensile stress applied on screw joint. Short-term creep process of screw connection could be divided into two phases. The first one is creep deformation increasing rapidly in a nonlinear way; The second one is creep deformation growing linearly with low rate.
3. The pine and the WPC have almost the same creep properties. In the wet condition, the pine's creep was higher than the WPC's, because the former was more easily hygroscopic than the latter.
4. Under the wet condition, creep of screw connection was apparently larger than that in dry condition. Connection parts could be easily destroyed in wet condition and in high stress level. Temperature and relative humidity were two important factors that influenced creep.
5. Burgers mode could be used to simulate short-term creep of screw connection in the pine members and the WPC members, whether in wet condition or in dry condition. The mode's accuracy was sufficient to meet the requirements of engineering.
6. Creep deformation of screw connection increased with the growth of tensile stress level. The creep curves in different tensile stress level complied with the same rule, namely, creep deformation increased rapidly in an early phase and then slowed down in the later phase. It is recommended that the maximum tensile stress level should be limited to 40% for screw connection in the wood members and the WPC members.

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Xiaojun Yang*, Lan Ma, Qi Zhao, Yihao Yu
Nanjing Forestry University
College of Materials Science and Engineering
Nanjing, Jiangsu 210037
China
*Corresponding author: yxj5460@163.com