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PREDICTION OF COMPRESSION STRENGTH OF WOOD USUALLY USED IN ANCIENT TIMBER BUILDINGS BY USING RESISTOGRAPH AND SCREW WITHDRAWAL TESTS

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ABSTRACT

Ultimate compression strength parallel to grain (UCS) of wood is one of important performance to evaluate the structural security of old wood buildings. Poplar wood (*Populus tomentosa* Carrière), Chinese larch wood (*Larix gmelinii* (Rupr.) Kuzen.) and Chinese fir wood (*Cunninghamia lanceolata* (Lamb.) Hook) were selected as the models in this paper. The aim of study is to predict UCS of wood by using resistograph and screw withdrawal methods. Compared with the screw withdrawal method (SW), resistograph method (RM) is generally more reliable, but because of the expenses involved, SW should also be considered as a much cheaper alternative. The results showed that the correlation coefficient between the RM and the UCS ranged from 0.5 to 0.7. The correlation coefficient between the double-start thread screw withdrawal force (SW_{DST}) and the UCS distributed from 0.1 to 0.65, while the values of coefficients for the single-start thread screw withdrawal (SW_{SST}) differed from 0.4 to 0.65. In screw withdrawal method, greater pitch of screw resulted in higher correlation coefficient.

KEYWORDS: Compression strength parallel to grain, density, resistograph, screw withdrawal.

INTRODUCTION

A number of buildings of wooden construction rank as important historic relics, such as the Yingxian Tower (1056, China), Horinji (682, Japan) and the South Gate of Seoul (1448, Korea)

(Tollefson 2017, Fang et al. 2001). These types of architecture, mainly based on wood, represent significant inventions in history. As wood is made of natural polymers it has some drawbacks, in particular it is prone to deformation as it ages, leading to a weakening of its properties (Lin 2015).

In order to investigate the effect of the variation of wood properties on the structural deformation of ancient buildings, Chen (2004) compared the physical properties of old original timbers with modern replacement woods that had been installed during maintenance work. The results showed that tensile strength and compression strength transverse to grain of ancient wood was significantly reduced compared with the modern woods. Chinese fir and poplar exhibited a 50% reduction of tensile strength and an 80% reduction of compression strength transverse to grain. The researchers measured the mechanical properties of common species used in ancient buildings, including beech (service life of 240, 650 years), Red pine (service life of 115, 270, 290 years), and cypress (service life of 35 up to1300 years) (Ni and Li 1994, Hirashima et al. 2004a, 2004b, 2005). The compression strength parallel to grain, bending strength, and Young's modulus of cypress were higher than the corresponding fresh wood. However, the beech presented a 10.8% reduction of compression strength parallel to grain, and an evident 50% reduction of bending strength. This resulted from the gradual development of bending, splitting and fracturing in wood from ancient buildings. Therefore, having an understanding of the structural properties of wood helps to ensure that the most appropriate measurements can be made on ancient wooden structures to enhance their protection.

The methods used to estimate the mechanical properties of wood were divided into two types: destructive and non-destructive (Kloiber et al. 2014). While the destructive method enabled the mechanical properties to be determined accurately, it was not considered appropriate for use on in situ ancient woods (Kasal 2003). Non-destruction was therefore considered the optimal approach (Kloiber et al. 2014). When historical constructions are repaired, the original materials including wood that, may have sufficient mechanical properties to continue to be in function, is often replaced without reasonable evaluation. This situation can be prevented if in-situ and non-destructive testing (NDT) technology is applied to diagnose wood. The most frequently used NDT devices are currently semi-destructive devices, which identify the range and location of degradation by means of material resistance to various tools (drilling and screw withdrawal) (Kloiber et al. 2015). In order to apply these semi-destructive methods, it is indispensible to investigate the relationship among resistographic measurements, wood properties and screw withdrawal force (Bo and Anthony 2004).

Wood density has been known to be statistically correlated to screw withdrawal force and screw diameter since 1926 (Mclain 1997). Subsequently, Mclain (1997) proved that the screw diameter, screw depth in wood, and the wood grain had a significant influence on this linear correlation. Ceraldi et al. (2001) and Cai et al. (2003) evaluated density and mechanical properties by using resistograph and screw withdrawal methods, respectively. The results showed that there was a strong linear relationship between density and the mechanical properties.

To determine internal cavity morphology, Brashaw et al. (2009) studied Hungarian wooden buildings by using stress wave and screw withdrawal; they showed that these methods accurately predicted the bending strength and internal cavity morphology of individual in situ woods in ancient buildings.

With the development of sophisticated instruments and the improvement of testing regimes, resistograph and screw withdrawal methods were widely used to estimate the mechanical properties and Young's moduli of wood (Feio 2005, Lechner et al. 2014, Zhang et al. 2015). However, the relationship was affected by many factors including screw pitch and wood species, which was barely studied in earlier research. As a result, the aim of this work is to use different species (as tangential sections) as the raw materials for measuring the compression strength parallel to grain, density, RM results, as well as screw withdrawal force. The results are used to establish the models for predicting the practical properties of wood by RM and screw withdrawal force, and to explore the influence of species and screw pitch on the modeling equations.

MATERIALS AND METHODS

Materials

The clear wood specimens were obtained from the plainsawn boards. The dimension, physical properties and dimensions of test specimens from three species (poplar, Chinese larch, Chinese fir) are listed in Tab. 1. Each specimen was divided into two parts, L1 and L2, as shown in Fig. 1.

Tab. 1: Specification and physical properties of specimens.

Type of wood	Specimen dimensions (mm)		Annual ring width (mm)	Moisture content (%)	Simple size
Poplar (*Populustomentosa Carrière*)	R	50	12.76	10.17	30
	T	50			
	L	300			
Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook)	R	50	3.8	11.10	30
	T	50			
	L	300			
Chinese larch (*Larix gmelinii* (Rupr.) Kuzen.)	R	50	0.64	10.69	30
	T	50			
	L	300			

Note: R, L and T represent the radial, tangential and longitudinal dimensions of the specimens, respectively.

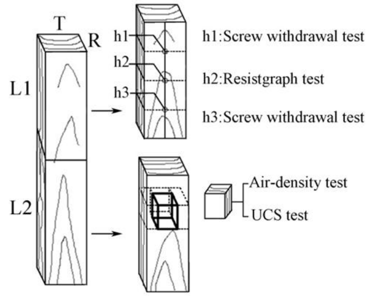


Fig. 1: Test specimens.

Three test points (h1, h2, h3) were selected at the outside tangential section of the L1 section for testing, and the L1 length was equally divided by these test points. Test points h1 and h3 were used to test screw withdrawal while h2 was used for Resistograph testing. The L2 was used to determine the density and the ultimate compression strength parallel to grain (UCS) with a size of 20 x 20 x 30 mm (R × T × L).

Testing methods

Density and UCS testing

Air density was measured in accordance with the Chinese standard (GB/T 1933-2009 2009). The density was calibrated to the value under the moisture content of 12% by using Eq. 1.

$$P_{12}=P_M\,[1-0.01(1-K)\,(W-12)], \tag{1}$$

where: K - volumetric shrinkage coefficient with 1 percent variation of moisture content,
W - moisture content (%),
P12 - air density at a moisture content of 12 percent ($g{\cdot}cm^{-3}$),
PM - air density with a moisture content of M ($g{\cdot}cm^{-3}$).

The UCS was tested in accordance with (GB/T 1935-2009 2009) using an INSTRON 5582 universal testing machine. The UCS results were calibrated using Eq. 2.

$$\delta_{12}=\delta_W[1+0.05\times(W-12)], \tag{2}$$

where: δ_{12} - compression strength parallel to grain (MPa),
δ_w - compression strength parallel to grain with moisture content of 12% (MPa),
W - moisture content (%).

Resistograph testing

In this paper, RESISTOGRAPH 4453-S (Germany, RINNTECH Company) was used to obtain the RM average drilling resistance value. The resistance distribution was collected by using microdrilling, perpendicularly drilling through the sample surface with a constant speed. Resistance distribution is shown in Fig. 2.

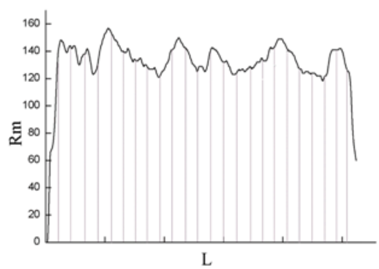


Fig. 2: The resistance distribution.

The RM parameter was calculated using Eq. 3:

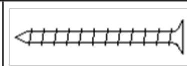
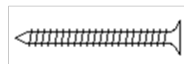
$$\mathrm{RM}=\frac{\int_0^l Rm}{l} \tag{3}$$

where: R_m - the momentary drill resistance,
l - total drilling distance (mm).

Screw withdrawal testing

The screw withdrawal force was measured in accordance with the Chinese Standard (LY/T 2377-2014 2014), using sites h1 and h3. The testing times are listed in Tab. 1. The screw satisfied the standard of (GB/T 14210-1993 1993), as shown in Tab. 2.

Tab. 2: Major specifications of screws.

Screw type	Nominal diameter (mm)	Nut diameter (mm)	Pitch (mm)	Nominal length (mm)	Screw sketch
Single-start thread screw	3.5	5	2.8	40	
Double-start thread screw	3.5	5	1.4	40	

The screw was driven into the sample at a constant speed up to a depth of 18 mm. The screw was pulled out by using INSTRON 5582 with a speed of 2 mm·min^{-1}. The maximum load was recorded as F_{max}. The screw withdrawal forces were calculated by Eq. 4. The critical displacement was determined by continuing the test until the load until it decreased to 0.85*F_{max} (shown in Fig. 3).

$$f = \frac{F_{max}}{d \times l_p} \tag{4}$$

where: f - the screw withdrawal force (N·mm^{-2}),
F_{max} - the maximum loading (N),
d - the screw diameter (mm),
l_p - the depth of screw in sample (mm).

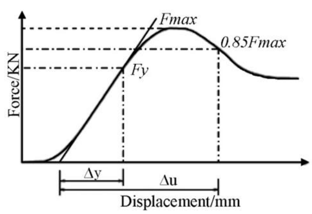


Fig. 3: Load-displacement curve (Ni and Li 1994).

The ductility coefficient was calculated by Eq.5 (Chopra 2005). The rigidity was determined by the slope of curve between 10 % Fmax and 40 % Fmax
(EN 26891 2001).The rigidity was calculated by Eq. 6.

$$\mu = \frac{\Delta u}{\Delta y} \tag{5}$$

where: μ - ductility coefficient (mm),
Δu - the critical displacement (mm),
Δy - the displacement corresponding with the maximum yield loading (mm).

$$K = (F_{0.4} - F_{0.1})/(S_{0.4} - S_{0.1}) \tag{6}$$

where: K - screw connection rigidity ($N \cdot mm^{-1}$),
$F_{0.4}$ - 40 % of F_{max} (N),
$F_{0.1}$ - 10 % of F_{max} (N),
$S_{0.4}$ - corresponding displacement of $F_{0.4}$,
$S_{0.1}$ - corresponding displacement of $F_{0.1}$.

RESULTS AND DISCUSSION

The correlation of density with RM and screw withdrawal force

Fig. 4 shows the regression model of density with RM and screw withdrawal force. Diagrams (a), (b) and (c) exhibit the relationships between density and single-start screw withdrawal, double-start screw withdrawal, and RM, respectively.

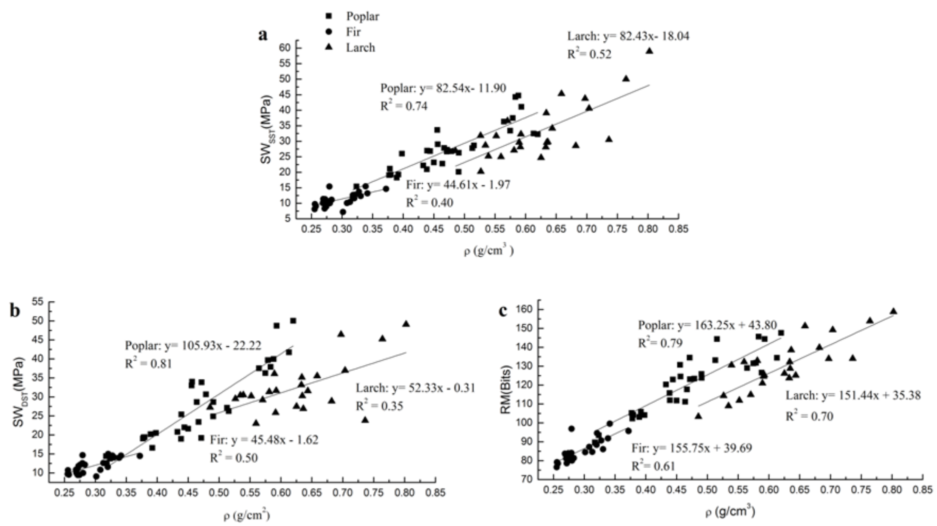


Fig. 4: The regression model of density with RM and screw withdrawal force, (a) the relationship of density and single-start screw withdrawal force (SW_{SST}), (b) the relationship of density and double-start screw withdrawal force (SW_{DST}), (c) the relationship of density and RM.

The results showed that RM represented a high correlation coefficient with a range of 0.6~0.8 in all three species. The correlation coefficient for screw withdrawal was in a range of 0.35~0.85. Different species had significant influence on the testing results, but overall the resistograph testing method is prior to screw withdrawal testing. The correlation coefficients between density of Chinese larch and screw withdrawal force with two methods (single- and double- start) were only 0.35 and 0.52, respectively, while the correlation coefficient of density and RM reached to 0.70.

The reason was the different testing mechanism used by resistograph and screw withdrawal. The max pulling force was recorded in screw withdrawal testing, while an average value was collected during the driving screw in resistograph test (Mclain 1997, Lechner et al. 2014). The correlation coefficient between density of poplar and single-, double- start screw withdrawal force and RMs were 0.74, 0.81and 0.79, respectively, which show a much tighter correlation than those of larch and fir. It was due to the different microstructure of softwood and hardwood (Chen 1985). Considerable research had shown that the correlation coefficients between density and results with screw-withdrawal test, microdrilling and pin penetration were mainly in a range of 0.35~0.85 (Kloiber et al. 2014, Feio 2007). The results in this study, therefore, were comparable. Resistograph testing was comparable as the optimal method to predict the density of wood.

The correlation of UCS with RM and screw withdrawal force

Tab. 3 shows the average density, UCS, single- and double- start screw withdrawal force of three species and their resultant variable coefficient. Fig. 5 shows the regression model of UCS with RM and screw withdrawal force, (a) (b), (c), exhibits the relationship of UCS and single-start screw withdrawal, UCS and double-start screw withdrawal, UCS and RM, respectively. Due to the differences in the microstructure of different species, such as fiber size and cell type (Tollefson 2017, Zhang et al. 2015, Zhong et al. 2013), the correlation coefficient between testing method and UCS is affected by different tree species. Strong relations have been found between UCS and the results of some of the testing methods, the correlation coefficient reaches 0.70 for Chinese fir, 0.60 for Chinese larch and 0.65 for poplar.

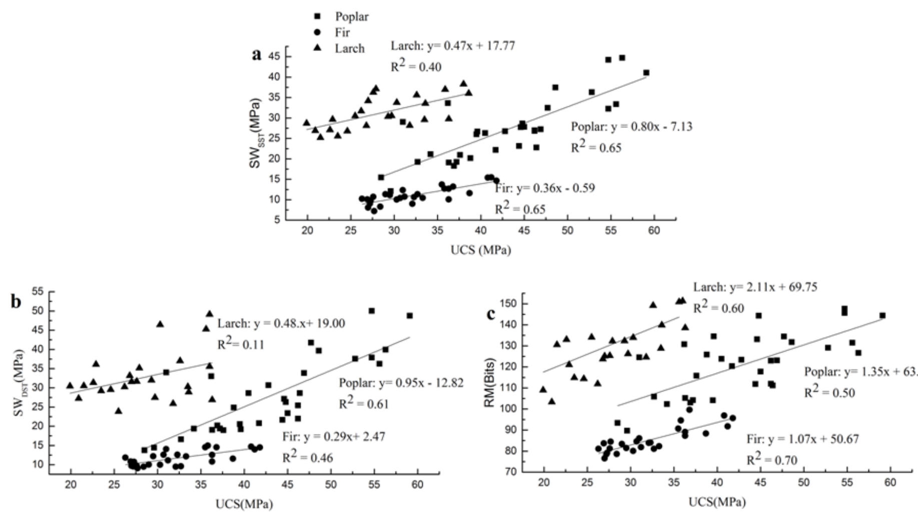


Fig. 5: The regression model of UCS with RM and screw withdrawal force, (a) the relationship of UCS and single-start screw withdrawal force (SW_{SST}), (b) the relationship of UCS and double-start screw withdrawal strength (SW_{SST}), (c) the relationship of UCS and RM.

The coefficient distribution of UCS of three species samples and RM were all in a range of 0.5~0.7, the coefficient of UCS of samples and single-start screw withdrawal force distributed in 0.4~0.65, while that of with double-start screw withdrawal force was in a range of 0.10~0.61. Therefore, resistograph and single-start screw withdrawal testing were considered as the optimal choice. For the species, the correlation coefficient with the two screws withdrawal to predict density and UCS was: poplar > fir and larch. RM is generally more reliable, but because of the expenses involved, SW should also be considered as a much cheaper alternative. The common correlation coefficients of UCS with NDT were in range of 0.3~0.7 (Bai et al. 2009, Zhang et al. 2015, Ceraldi et al. 2001). It illustrated that both methods were used to determine the UCS with a generally acceptable coefficient. Further research needs be done to ensure the effect of screw pitch on the correlation coefficient of the predicting model. The results of the experiment are shown in Tab. 3.

Tab. 3: Experimental results.

	Poplar	Chinese fir	Chinese larch
Density ($g \cdot cm^{-3}$)	0.473(17.54)	0.293(10.41)	0.620(12.81)
UCS (MPa)	43.034(18.83)	32.171(14.85)	28.412(17.82)
SW_{SST} (MPa)	27.176(29.15)	11.155(18.64)	33.067(26.89)
SW_{DST} (MPa)	27.937(34.83)	11.953(18.77)	31.728(22.71)
RM	121.088(12.54)	85.460(6.99)	129.298(10.93)

Note: Values in parentheses are coefficients of variation (%); UCS is the ultimate compression strength parallel to grain; SW_{SST} is the single-start screw withdrawal force; SW_{DST} is the double-start screw withdrawal force; RM is average drill resistance.

Fig. 6 shows the average value curves of screw withdrawal force-replacement of three species with two screw withdrawal testing: (a), (b) and (c) show poplar, fir and larch diagrams, respectively. Small screw pitched resulted in a breakage of wood fiber, affecting the pulling strength (Liu and Zhao 2012). A partial of tracheid and wood fiber underwent the shear force to break when the screw was pulling. The broken fibers were absorbed in screw gap with scatter distribution; integral fibers were warped along with the pulling force. The degree of warping gradually increased from the inner to surface, owning to the shear times increasing from inner to surface. Large screw pitch led to a large connecting area with stronger shear force and friction force.

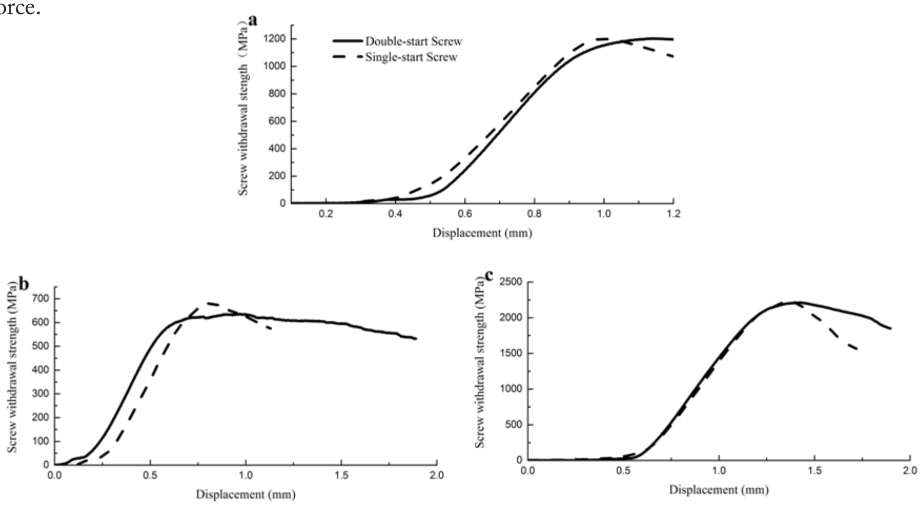


Fig. 6: Screw withdrawal force – displacement curves of three species of wood: (a) poplar, (b) Chinese fir, (c) Chinese larch.

As shown in Fig. 5, the correlation coefficients of UCS of three species and single-start screw withdrawal force were higher than those of with double-start screw withdrawal force. Ductility coefficient referred to the max replacement of wood divided to yield replacement, reflecting the plastic deformation capacity before breakage. A high ductility coefficient implied an excellent plastic deformation capacity, leading to a high correlation coefficient of UCS and screw withdrawal force. Double-start screw had a small pitch, increasing the force acting on the wood fiber, which was prone to decline the plastic strength (Li 2013), leading to the correlation coefficient was smaller than that of single-start screw withdrawal. Fig. 7 shows the ductility distribution of three species.

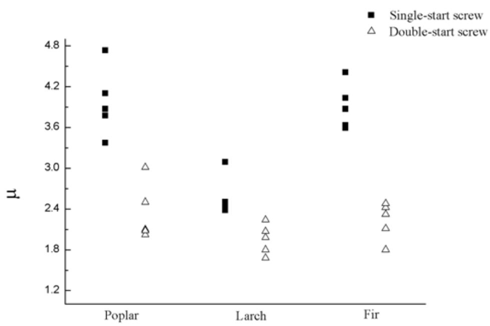


Fig. 7: Ductility coefficient distribution.

The results presented that the ductility coefficient of poplar obtained from single- or double-start screw withdrawal was higher than those of larch and fir. The linear relationship between density, UCS, and the screw withdrawal force in three species presented the similar values, implying that ductility was a key factor that affected the results.

Fig. 8 shows the rigidity distribution of three species. The rigidity reflected the resistance deformation capacity of wood under the external force.

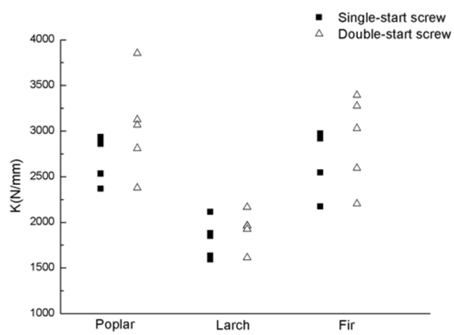


Fig. 8: Rigidity distribution.

Higher rigidity indicated stronger capacity of resisting the deformation. For one species, the rigidity determined by single- and double- start screw withdrawal were similar, the rigidity of larch was higher than that of fir, the rigidity of fir and poplar were almost the same. Combined with Figs. 3 and 4, the correlation coefficient of fir between density, UCS, and screw withdrawal force were higher than those of larch, while lower than those of poplar. Therefore, the rigidity of wood was not considered as a valued parameter to predict the density and UCS.

CONCLUSIONS

Wood species determined the correlation coefficient between density and RM, and between density and screw withdrawal force. The correlation coefficient values were higher in poplar than in fir and larch. Resistograph method was able to investigate the correlation coefficient in a high fitting rate, leading to modeling the relationship of density and UCS well. Compared with the screw withdrawal method, resistograph method is generally more reliable. In the screw withdrawal method, the screw pitch affected the test results, greater pitch resulting in higher correlation coefficients.

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