Mechanical Properties Evaluation of Two Wood Species of Ancient Timber Structure with Nondestructive Testing Methods

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Mechanical properties of wood were evaluated using nondestructive test methods. The tests were conducted using the stress wave timing and resistance drilling machine, while static mechanical tests were conducted by an Instron universal testing machine. Both nondestructive and static mechanical tests were performed on wood specimens for Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) and elm (*Ulmus rubra*). There were strong linear correlations between density (ρ) and resistance amplitude (F), static modulus of elasticity (MOE) and dynamic modulus of elasticity (E_D), modulus of rupture (MOR) and E_D, and ultimate compressive strength (UCS) and E_D. Additionally, an algorithm of the reliability index was developed with the first-order second-moment method. The reliability analysis indicated that the reliability index increased with the decreased design value for both Chinese fir and elm, but it increased as the live-to-dead load ratio (ρ) increased. To achieve the reliability index requirements of the Chinese national code, the MOR design value should be set to 12.6 and 21.7 MPa, while the UCS design value should be set to 10.2 and 13.4 MPa for Chinese fir and elm, respectively.

Keywords: Mechanical properties; Wood; Nondestructive test methods; Stress wave time; Resistance drilling

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INTRODUCTION

Chinese fir (*Cunninghamia lanceolata* Lamb. Hook) and elm (*Ulmus rubra*) are widely used in Chinese ancient timber structures. It is thus important to investigate the mechanical properties of these wood products. Due to the historical value of ancient timber structures, neither local nor whole destructive tests are allowed because these tests can lead to the loss of structural integrity. To evaluate the mechanical properties and residual load capacity of the existing wood members, nondestructive tests (NDT) are effective (Riggio *et al*. 2014). The common NDT tools are stress wave timing and resistance drilling methods, which can provide qualitative and quantitative evaluations of the stiffness and strength of existing wood members.

Most preliminary studies of NDT have evaluated material properties and the effective section by stress wave tests. The findings of Yin *et al*. (2010) and Cheng and Hu (2011) showed that different acoustic-based nondestructive methods could provide good prediction for bending modulus of elasticity, modulus of rupture, and compressive strength parallel to grain. Longitudinal vibration is regarded as the most precise and reliable source of such information. Wang *et al*. (2004) and Dackermann *et al*. (2014) used the stress wave timing nondestructive method to assess the decay in standing timber and the health state of the inspected timber member. However, it is difficult to determine the green density of the whole or local section of an existing structural member by traditional testing methods, and destructive tests cannot be performed. Thus, a nondestructive method with the resistograph test technology has been explored for the prediction of density. Drilling resistance tests provide good predictions of wood density (Rinn *et al*. 1996; Kahl *et al*. 2009; Acuna *et al*. 2011). Drilling resistance tests also detect the size and location of internal defects, cracks, and decay (Jasieńko *et al*. 2013; Tannert *et al*. 2014; Zhang *et al*. 2015). However, there has been little research on the prediction of mechanical properties by drilling resistance combined with stress wave tests.

The objective of this study was to evaluate the mechanical properties of wood based on nondestructive test methods (stress wave timing combined with resistance drilling tests). The relationships between nondestructive and static mechanical tests were also investigated. The design value of mechanical strength was determined based on a reliability analysis.

EXPERIMENTAL

Preparation of Test Pieces

Sample logs were collected from old temples located in Anhui and Shanxi, China. According to the Chinese Academy of Forestry in Beijing, the wood species of all logs were Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) and elm (*Ulmus rubra*).

Figure 1 shows the flow chart for processing and testing small wood specimens. A total of 300 small rough specimens (40 × 40 × 500 mm) were sawn from the logs, and small rough specimens were then planed and cut into 20 × 20 × 450 mm pieces. Due to the limited log diameter and the presence of knots, a total of 107 pieces of Chinese fir and 91 pieces of elm were selected for nondestructive testing (Fig. 1(b), (c)). All specimens were stored under constant temperature (20 ± 2 °C) and relative humidity (65%) until an equilibrium moisture content of 12% was achieved.

An average mean value from two testing points was assumed to represent the resistance amplitude of each small wood specimen. After nondestructive measurements were completed, each small specimen was divided into two parts: one 30-mm section for the compressive test and one 300-mm section for the bending test (Fig. 1(d)).

Nondestructive Tests

The stress wave equipment (Fakopp, Microsecond Timber, Ágfalva, Hungary) has two spikes, which were nailed into the xylem at a 45° angle with the log axis (Fig. 1(b)). The head of a spike with an accelerometer was hit by a hammer, and the stress wave signal was detected by another accelerometer after wave propagation in the specimen. The dynamic modulus of elasticity, E_D, of the specimen was determined with Eq. 1,

$$E_{\mathrm{D}} = \rho \upsilon^2 \tag{1}$$

where E_D is the dynamic modulus of elasticity of the wood specimen (GPa) based on stress wave testing results, ρ is the green density of the wood specimen (g/cm^3), and υ is the stress wave velocity propagated in the wood specimen (m/s).

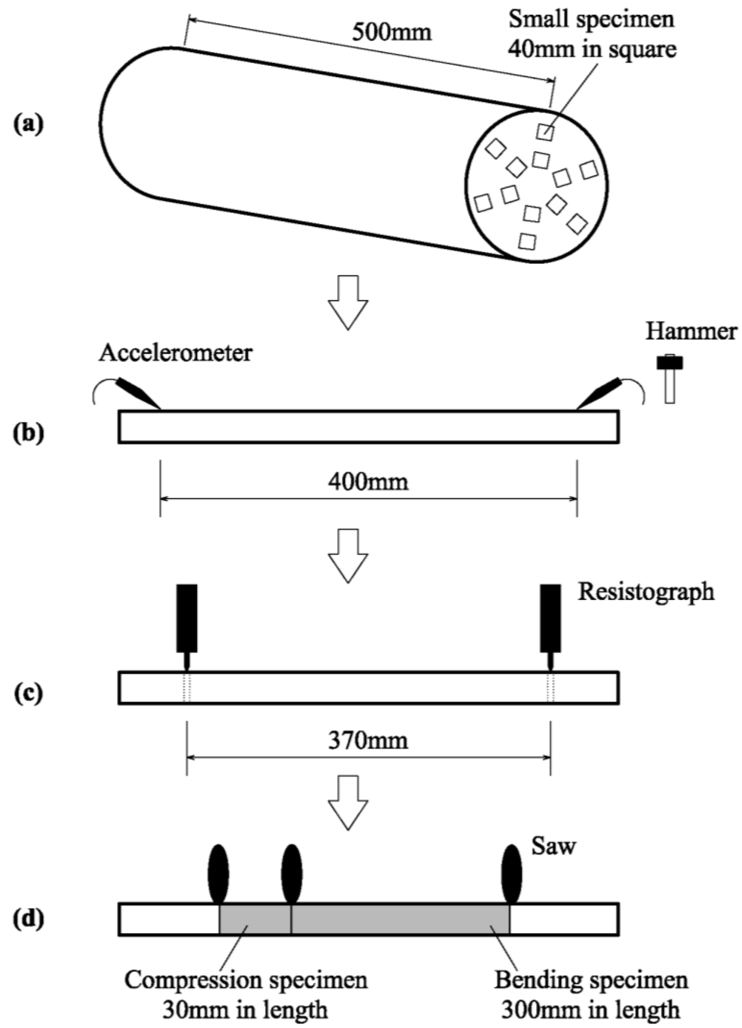

Fig. 1. Processing and testing of small specimens: (a) sawing pattern for extracting small specimens; (b) stress wave velocity measurement; (c) resistance amplitude measurement; (d) cutting small specimens for static mechanical tests

In order to predict exactly the green density of the whole or local section of an existing structural member, the resistograph test technology thus has been developed (Rinn *et al*. 1996; Kahl *et al*. 2009; Acuna *et al*. 2011). A drill bit with a 1.5- to 3-mm diameter in the resistograph equipment (IML-RESI, PD, Heidelberg, Germany) was driven into the xylem perpendicular to the tangential plane (Fig. 1(c)), with a constant feed speed of 2000 mm/min and needle speed of 5000 r/min. The obtained resistance amplitude curves reflected the change in green density along the drill path and detected internal defects, cracks, and decay. The average value of resistance amplitude curves from the first peak to the last peak was used to represent the density of the wood specimen, as shown in Fig. 2. Therefore, the dynamic modulus of elasticity of wood specimens was expressed as,

$$E_{\mathrm{D}} = F\upsilon^2 \tag{2}$$

where F is the average value of resistance amplitude (%), as determined by resistograph testing.

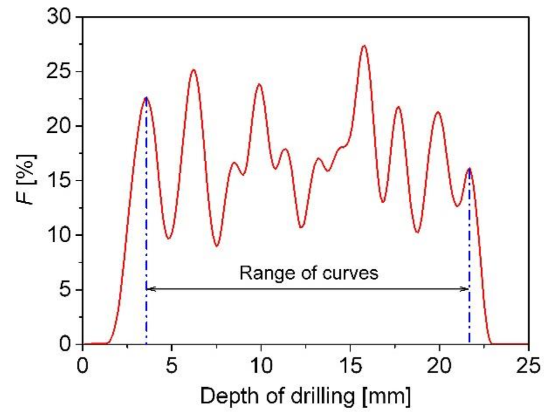

Fig. 2 Typical resistance amplitude curve

Static Mechanical Tests

Both static compressive tests parallel to grain and bending tests were conducted according to the Chinese national standards (Table 1) using an Instron 5582 Universal Test Machine (Boston, USA). Third point loading was conducted for the static MOE test. However, central point loading, *i.e.*, three-point loading, was applied for the MOR test. Compressive strength was measured in parallel to grain. The static MOE, MOR, and UCS were calculated as follows,

$$\mathrm{MOE} = 23Pl^3 \big/ (108bh^3w) \tag{3}$$

$$\mathrm{MOR} = 3F_{\max} l \big/ (2bh^2) \tag{4}$$

$$\mathrm{UCS} = F_{\max} \big/ (bt) \tag{5}$$

where MOE is the static modulus of elasticity (GPa); MOR is the static modulus of rupture (MPa); UCS is the ultimate compressive strength parallel to the grain of wood (MPa); P is an increment of load (N); l is the distance between two support points (mm); b is the specimen width (mm); h is the specimen height (mm); w is the increment of deformation corresponding to P (mm); F_{max} is the maximum load (N); and t is the specimen thickness (mm).

Table 1. Summary of Static Mechanical Test Conditions for Wood Specimens

Test	Standard	Dimension (mm)	Loading	Span (mm)	Velocity (mm/min)
ρ	GB 1933 (2009)	20 × 20 × 20	—	—	—
MOE	GB 1936.2 (2009)	20 × 20 × 300	Third point	240	1.5
MOR	GB 1936.1 (2009)	20 × 20 × 300	Central point	240	3.0
UCS	GB 1935 (2009)	20 × 20 × 30	End face	30	1.0

Statistical Analysis

Statistical significance analysis between Chinese fir and elm was conducted by SPSS 19.0 software (IBM SPSS Corporation, Chicago, USA). The comparisons for each mechanical property were calculated by LSD and Tamhane methods with the ANOVA test results (Yu and He 2006). The significance level was set to $p < 0.05$. Graphics were generated with Origin 9.0 software (OriginLab Corporation, Northampton, USA). The coefficient of determination was also calculated to determine the relationships between nondestructive test and static mechanical test results.

RESULTS AND DISCUSSION

Mechanical Tests

The nondestructive and static mechanical test results are summarized in Table 2. Mechanical properties obtained by both the nondestructive and static test for elm were larger than those for Chinese fir, and the mean values of ρ, v, F, E_D MOE, MOR, and UCS for elm were 1.83, 1.22, 3.47, 2.29, 1.22, 1.65, and 1.28 times those for Chinese fir, respectively. By the ANOVA test, the p-values for each mechanical property between Chinese fir and elm were less than 0.05, which indicated that there are significant differences between Chinese fir and elm for each mechanical property.

Relationships between Nondestructive and Static Mechanical Tests

To obtain the relationships between nondestructive and static mechanical tests, regression analysis was performed on each mechanical test result for both Chinese fir and elm (Fig. 3), including the relationships between ρ and F, MOE and E_D, MOR and E_D, and UCS and E_D, respectively. The linear regression formulas and coefficients are presented in Table 3. The test of significance of regression's correlation coefficient was analyzed by t-test method at the significance level of 0.001.

Table 2. Nondestructive and Static Mechanical Test Results of Wood Specimens

Group	Number of Specimens	Properties	Mean	SD	COV	Max	Min
Chinese fir	107	ρ (g/cm^3)	0.356	0.033	9.27 %	0.437	0.293
		v (m/s)	4939	293	5.93 %	5936	3982
		F (%)	17.345	5.313	30.6 %	33.404	9.350
		E_D (GPa)	4.179	1.113	26.6 %	7.615	2.421
		MOE (GPa)	11.040	1.303	11.8 %	7.615	2.421
		MOR MPa)	62.170	10.787	11.3%	83.945	29.718
		UCS (MPa)	34.386	5.215	15.2 %	48.774	20.393
Elm	91	ρ (g/cm3)	0.653	0.039	5.97 %	0.755	0.569
		v (m/s)	6048	236	3.90 %	6521	4398
		F (%)	60.210	5.949	9.88 %	75.125	49.059
		E_D (GPa)	9.562	1.566	16.4 %	13.819	6.254
		MOE (GPa)	13.464	1.863	13.8 %	18.214	8.468
		MOR MPa)	102.393	11.463	11.2 %	123.037	70.044
		UCS (MPa)	44.063	5.346	12.1 %	55.994	32.521

SD, standard deviation; COV, coefficient of variation; v, the stress wave velocity; F, the resistance amplitude of resistograph; E_D, the dynamic modulus of elasticity

Figure 3(a) shows the relationships between ρ and F. The developed regression model between the ρ and F of wood specimens was significant at the 0.001 confidence level, with a determination of coefficient 0.745 and 0.575 for Chinese fir and elm, respectively. The regression results indicated that the resistance amplitude based on the resistograph test method provides a good prediction of the green density of wood specimens. The findings of Rinn *et al.* (1996) showed that there is a significant correlation between the gross density of dry wood obtained from the mean resistance amplitude and the X-ray density profile. There is also reported a good correlation between drilling resistance and density (Rinn *et al*. 1996; Kahl *et al*. 2009; Acuna *et al*. 2011).

Figure 3(b) shows the relationships between MOE and E_D. The developed regression model between the MOE and E_D was significant at the 0.001 confidence level, with a determination of variation 0.502 and 0.633 for Chinese fir and elm, respectively. Similar results were obtained in a previous study on the prediction of MOE of old beams using the E_D value (Cavalli and Togni 2013).

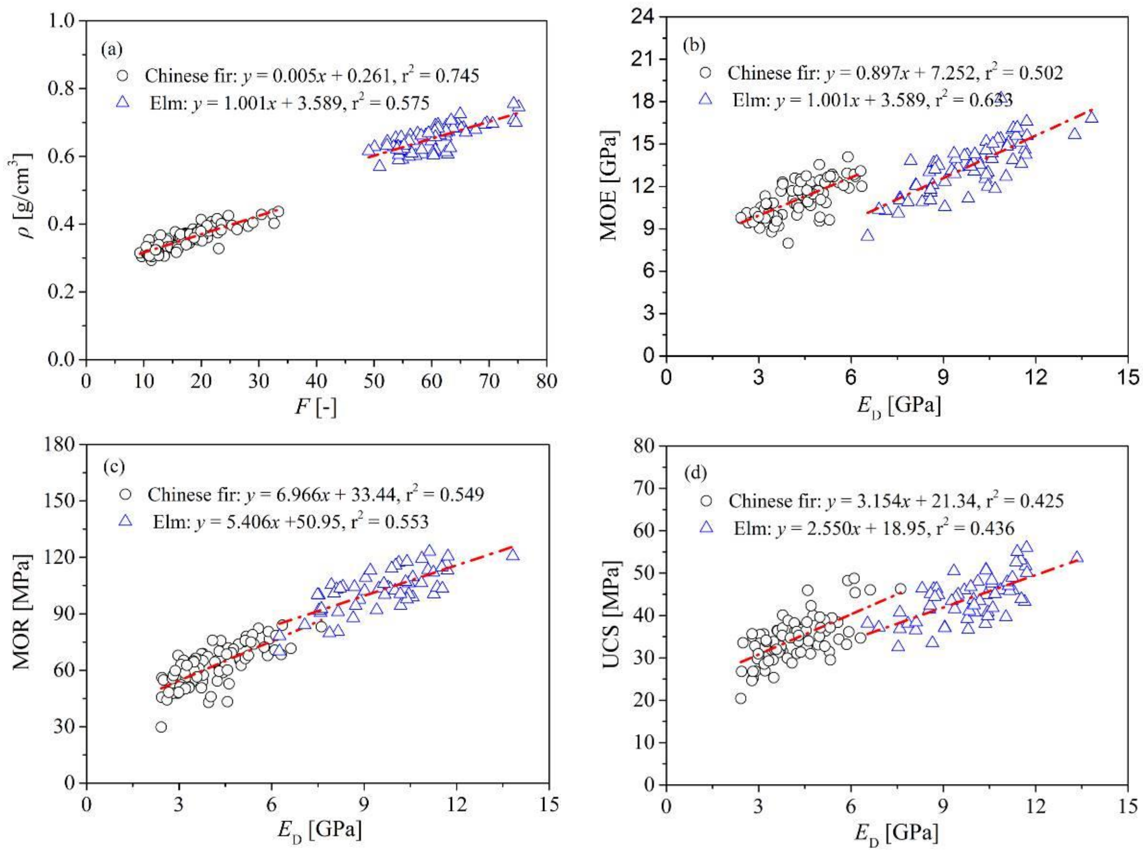

Fig. 3 Predicted static mechanical properties of wood by a nondestructive test method: (a) ρ; (b) MOE; (c) MOR; (d) UCS

Table 3. Linear Regression Formula and Coefficient for Each Static Mechanical Property Based on Nondestructive Test Results

Group	Properties	Linear Regression Formula	r^2
Chinese fir	ρ	ρ = 0.005F+0.261	0.745 (**)
	MOE	MOE = 0.897E_D+7.252	0.502 (**)
	MOR	MOR = 6.966E_D+33.44	0.549 (**)
	UCS	UCS = 3.154E_D+21.34	0.425 (**)
Elm	ρ	ρ = 0.005F+0.350	0.575 (**)
	MOE	MOE = 1.001E_D+3.589	0.633 (**)
	MOR	MOR = 5.406E_D+50.95	0.553 (**)
	UCS	UCS= 2.550E_D+18.95	0.436 (**)

** significant at 0.001 level.

Figure 3(c) shows the relationship between MOR and E_D. The developed regression model between the MOR and E_D of small specimens was significant at the 0.001 confidence level, with a determination of variation 0.549 and 0.553 for Chinese fir and elm, respectively. For Chinese fir, the MOR and E_D relationship was stronger than the MOE and E_D; however, it showed the reverse results for elm. There was no obvious pattern.

Figure 3(d) shows the relationship between UCS and E_D. The developed regression model between the UCS and E_D was significant at the 0.001 confidence level, with a determination of variation 0.425 and 0.436 for Chinese fir and elm, respectively. The UCS can be directly determined by resistograph tests, with a high coefficient of determination between the UCS and resistance amplitude in the longitudinal direction (Calderoni *et al*. 2010; Zhang *et al*. 2015).

Moreover, the significant differences of correlation coefficient between Chinese fir and elm were investigated. The results indicated that the regression correlation coefficients of MOR, MOE, and UCS for elm were all significantly greater than those for Chinese fir. However, for ρ, there was no difference at the significant level of 0.05.

Reliability Analysis

The design values of MOR and UCS were determined based on the reliability analysis (GB 50005 2003). In reliability analysis, the test results (Table 2) were obtained based on the small clear wood specimen rather than the full size wood specimen. Therefore, the effects of the equation precision (k_1), the geometric character (k_2), the long-term load (k_3), the natural defect (k_4) (such as knot, crack and oblique grain, the drying defects (k_5), the dimensions (k_6), and the predicted precision of nondestructive method (k_7) should be considered in the process of reliability analysis. According to the Chinese national design code of timber structures (GB 50005 2003), both the bending and compressive resistance (R) of wood could be calculated using Eq. 6. And the mean value (μ_R) and coefficient of variance (δ_R) of R were determined by Eq. 7 and 8, respectively (Wang 2002; Zhong *et al*. 2014; Zhong and Ren 2014),

$$R = k_1 k_2 k_3 k_4 k_5 k_6 k_7 f_{\mathrm{N}} \tag{6}$$

$$\mu_{\mathrm{R}} = \mu_{\mathrm{k1}}\mu_{\mathrm{k2}}\mu_{\mathrm{k3}}\mu_{\mathrm{k4}}\mu_{\mathrm{k5}}\mu_{\mathrm{k6}}\mu_{\mathrm{k7}}\mu_{\mathrm{fN}} \tag{7}$$

$$\delta_{\mathrm{R}} = \sqrt{\delta_{\mathrm{k1}}^2 + \delta_{\mathrm{k2}}^2 + \delta_{\mathrm{k3}}^2 + \delta_{\mathrm{k4}}^2 + \delta_{\mathrm{k5}}^2 + \delta_{\mathrm{k6}}^2 + \delta_{\mathrm{k7}}^2 + \delta_{\mathrm{fN}}^2} \tag{8}$$

where f_N is the predicted value of mechanical strength by nondestructive test results (Table 3), with its mean value and COV shown in Table 4. The statistical parameters of adjusting factors are shown in Table 5.

Two types of load, the dead load (G) and live load (L), were applied to the timber structure. The dead loads include the self-weight of structural members and other materials, while the live loads include the office occupancy load (L_O), residential occupancy load (L_R), wind load (L_W), and snow load (L_S).

According to the requirements of standard GB 50009 (2012), the dead load data follows a normal distribution, while the live load data is fitted to the extreme type-I. The statistical parameters of the loads are shown in Table 6.

Table 4. Statistical Parameters of f_N and R (GB 50005 2003)

Parameters	f_N				R			
	Chinese Fir		Elm		Chinese Fir		Elm	
	MOR	UCS	MOR	UCS	MOR	UCS	MOR	UCS
Mean value	62.042	34.376	101.545	44.053	24.599	18.761	40.261	24.043
SD	7.962	3.403	8.527	3.529	6.942	4.877	10.670	6.092
COV (%)	12.8	9.9	8.4	8.0	28.2	26.0	26.5	25.3

Table 5. Statistical Parameters of Adjusting Factors (GB 50005 2003)

Properties	Parameters	k_1	k_2	k_3	k_4	k_5	k_6	k_7
MOR	Mean value	1.000	0.960	0.720	0.750	0.850	0.890	1.011
	SD	0.050	0.058	0.086	0.120	0.034	0.053	0.110
	COV (%)	5.0	6.0	12.0	16.0	4.0	6.0	10.9
UCS	Mean value	1.000	0.940	0.720	0.800	-	-	1.008
	SD	0.050	0.075	0.086	0.112	-	-	0.123
	COV (%)	5.0	8.0	12.0	14.0	-	-	12.2

The limit state design equation for bending and compressive resistance is described by Eq. 9. Two load combinations, including G+L_O, G+L_R, G+L_W, and G+L_S, were then used in the reliability analysis,

$$a_D D_K + a_L L_K = K_S f_d \tag{9}$$

where a_D is the dead load factor and is equal to 1.2; a_L is the live load factor and is equal to 1.4; D_K is the nominal dead load; L_K is the nominal live load; K_S is an adjusting factor for the service life and keeps to 1.0 for 50 years; and f_d is the design value of mechanical strength predicted by nondestructive test methods (GB 50009 2012).

Table 6. Statistical Parameters of the Loads (GB 50009 2012)

Statistical parameters	Load types				
	G	L_O	L_R	L_W	L_S
Mean/nominal	1.060	0.524	0.644	1.000	1.040
COV (%)	7.0	28.8	23.3	19.0	22.0
Distribution types	Normal	Extreme-I	Extreme-I	Extreme-I	Extreme-I

The performance function, developed to determine the design value of MOR and UCS for first-order second-moment reliability analysis, is as follows (Kimiaeifar *et al*. 2013; Zhong *et al*. 2014; Zhong and Ren 2014),

$$Z = R - (D + L) \tag{10}$$

where R, D, and L are random variables representing the resistance, dead load (G), and live load (L_O, L_R, L_W, or L_S), respectively. The random variable R was assumed to be a lognormal distribution according to standard GB 50005 (2003).

By substitution of Eq. 9 into Eq. 10, the failure function was rewritten as,

$$Z = R - \frac{k_s f_d}{a_D + \rho a_L}(g + \rho l) \tag{11}$$

where ρ, g, and l are the equivalents of L_K/D_K, D/D_K, and L/L_K, respectively.

Based on the investigation on the timber structure in China (GB 50005 2003; GB50009 2012), the live-to-dead load ratio (ρ) was specified as 0.25, 0.5, 1.0, and 2.0, respectively. An algorithm for reliability index (β) was developed by use of Matlab 7 software (MathWorks, Natick, USA). First-order second-moment reliability analyses were performed for all the data and simulation cases, including G+L_O, G+L_R, G+L_W, and G+L_S (Zhuang 2004; Zhong *et al*. 2014; Zhong and Ren 2014). For example, the relationships between β and the design value of bending strength, and between β and the design value of compressive strength of Chinese fir, for different load combinations, are shown in Figs. 4 and 5.

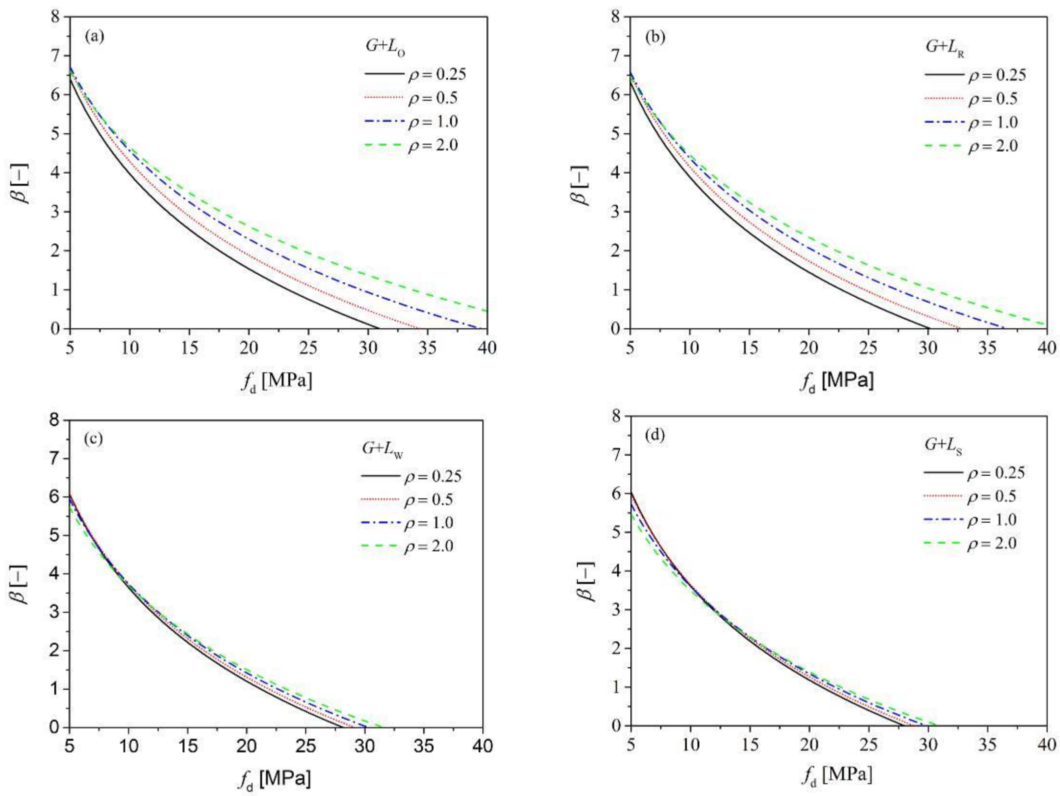

Fig. 4 Reliability index (β) versus the design value of bending strength (f_d) of Chinese fir under different load combinations: (a) G+L_O; (b) G+L_R; (c) G+L_W; (d) G+L_S

The reliability analysis indicated that the reliability index (β) increased with the decrease in design value for both Chinese fir and elm. In addition, the β increased as the live-to-dead load ratio (ρ) increased. This result was consistent with previous findings (Folz and Foschi 1989; Zhuang 2004; Zhong *et al*. 2014; Zhong and Ren 2014). The reliability level was calculated by taking the average of the reliability index under each load combination, which needed to achieve the target reliability level ($\beta_0 = 3.2$) (GB50068 2001).

To meet the requirements for the minimum reliability index ($\beta > \beta_0$) (GB50068 2001), the average of the reliability index (Table 7) for all load combinations was 3.206 for MOR and 3.229 for UCS of Chinese fir, and 3.207 for MOR and 3.216 for UCS of elm.

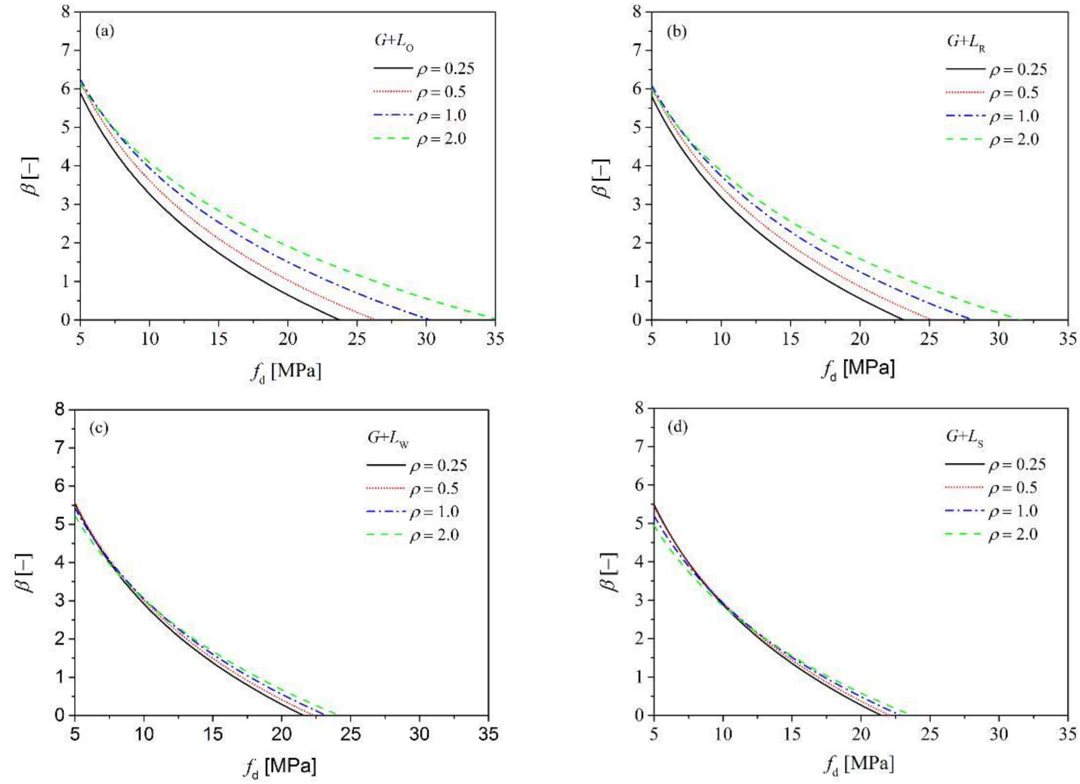

Fig. 5 Reliability index (β) versus the design value of compressive strength (f_d) of Chinese fir under different load combinations: (a) $G+L_O$; (b) $G+L_R$; (c) $G+L_W$; (d) $G+L_S$

Table 7. Reliability Index (β) for Different Load Combinations

Load Combinations	ρ	β			
		Chinese fir		Elm	
		MOR (12.6 MPa)	UCS (10.2 MPa)	MOR (21.7 MPa)	UCS (13.4 MPa)
$G+L_O$	0.25	3.158	3.195	3.168	3.185
	0.5	3.487	3.544	3.513	3.542
	1.0	3.818	3.875	3.845	3.873
	2.0	3.990	4.024	4.002	4.017
$G+L_R$	0.25	3.074	3.105	3.080	3.093
	0.5	3.343	3.391	3.361	3.385
	1.0	3.615	3.666	3.637	3.662
	2.0	3.769	3.801	3.779	3.792
$G+L_S$	0.25	2.801	2.810	2.790	2.791
	0.5	2.855	2.863	2.844	2.844
	1.0	2.859	2.855	2.840	2.832
	2.0	2.811	2.791	2.781	2.765
$G+L_W$	0.25	2.832	2.844	2.823	2.826
	0.5	2.921	2.936	2.915	2.919
	1.0	2.979	2.988	2.969	2.970
	2.0	2.979	2.976	2.961	2.954
Average (all)	—	3.206	3.229	3.207	3.216

Then, the design value corresponding to the target reliability level could be determined based on the relationship between the reliability index and the reliability index. Therefore, the design value of bending strength was set to 12.6 and 21.7 MPa for Chinese fir and elm, respectively, while the design value of compressive strength was 10.2 and 13.4 MPa for Chinese fir and elm, respectively.

Table 7 also shows that the simulated load cases of the maximum and minimum β were G+L_O and G+L_S, for the same ratio of live-to-dead load (ρ), respectively. This result is consistent with previous findings (Zhuang 2004; Zhong *et al*. 2014; Zhong and Ren 2014).

CONCLUSIONS

1. Both the nondestructive and static mechanical test results showed that the properties of elm were greater than those of Chinese fir.
2. There were good linear correlations between ρ and F, MOE and E_D, MOR and E_D, and UCS and E_D, which suggested that the nondestructive method by stress wave timing combined with resistance drilling tests was effective in evaluating the mechanical properties of wood.
3. The reliability analysis indicated that the reliability index (β) increased with the decrease of design value for both Chinese fir and elm. In addition, the reliability index (β) increased as the live-to-dead load ratio (ρ) increased.
4. To achieve the reliability index requirements of the Chinese national code, it is suggested that the MOR design value be set to 12.6 and 21.7 MPa for Chinese fir and elm, respectively, while the UCS design value should be set to 10.2 and 13.4 MPa for Chinese fir and elm, respectively.

ACKNOWLEDGMENTS

The authors received financial support from the National Natural Science Foundation of China (31570711) and the Grant for the Palace Museum of China (KT2015-06).

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Article submitted: March 5, 2016; Peer review completed: May 9, 2016; Revised version received and accepted: June 12, 2016; Published: June 27, 2016.
DOI: 10.15376/biores.11.3.6600-6612