Using Non-Destructive Testing to Determine the Correlation between Dynamic Mechanical Properties and Bonding Strength of Wood-Plastic Composite Adhesive Joints

Mei He and Mingwei Di*

Wood-plastic composites (WPC) have been developed into new and important wood-based composites because of their benefits for the environment, economy, and recyclability. When combined with structural adhesives, WPCs will have a greatly broadened application in the construction field. In this work, epoxy resin and acrylic ester were used to bond WPC adhesive joints. The shear strength of the adhesive joints was determined and investigated. Resonant frequency and dynamic modulus of elasticity (MOE) of the WPC adhesive joints were measured using the longitudinal vibration method. The correlation between different vibration parameters and shear strength of WPC adhesive joints was also investigated. Results showed that the epoxy resin had a better bonding quality than the acrylic ester on the bonding of WPC adhesive joints. The resonant frequency, dynamic MOE, and the dynamic MOE ratio of the WPC adhesive joints had close correlations with their shear strength for the samples bonded with epoxy resin.

Keywords: Wood-plastic composites; Adhesive joint; Nondestructive testing; Bonding strength; Correlation

*Contact information: Key Laboratory of Bio-Based Material Science & Technology (Ministry of Education), Northeast Forestry University, Harbin, China; *Corresponding author: dimingwei@126.com*

INTRODUCTION

Wood-plastic composites (WPC), which contain plant fiber and thermosets or thermoplastics, are very promising and sustainable green materials to achieve durability without using toxic chemicals (Ashori 2008). The utilizations of WPC in decking, fencing, railing, siding, and paneling can be effectively extended by adding WPC to structures (Cheng *et al.* 2012). During the manufacturing of WPC structures, adhesive bonding of WPC can achieve a seamless connection of product, overcome the limitations of the molding process, and enrich the varieties of the wood-plastic composite materials (Liu *et al.* 2010). The bonding quality of WPC joints critically affects the strength and life expectancy of the structure (Gramlich *et al.* 2006). Because of the low surface energy (30 mJ/m^2), hydrophobic smooth surface and limited functional groups of polyolefins, it is notoriously difficult to achieve a firm adhesion of WPC (Gupta *et al.* 2007). Additionally, the additives (*e.g.*, paraffin) used during the manufacture of WPC further hinder the formation of excellent WPC adhesion interface. To solve this problem, many works have investigated many surface modification methods to improve WPC adhesion including physical methods, chemical methods, and combined methods (Oporto *et al.* 2007; 2009; Laborie and Gupta 2008; Wolkenhauer *et al.* 2008; Liu *et al.* 2010; Moghadamzadeh *et al.* 2011).

Nondestructive testing has been used in the wood industry to sort and grade wood products over the last few decades, and it has been shown to correlate with standard evaluation techniques of wood strength (Nzokou *et al.* 2006). Wood-plastic composites, as a wood-based composite, have also been evaluated by nondestructive testing (Yu *et al.* 2012). Although tensile and compression shear testing is widely employed as the conventional method to determine the bonding quality of WPC joints, nondestructive testing provides an efficient, rapid, and economic way to determine the bonding quality (Schroeder *et al.* 2002). For bonding joint evaluation, many works on nondestructive testing of adhesively bonded joints using ultrasonic techniques have been carried out mainly on metal-to-metal joints (Brotherhood *et al.* 2003; Michaloudaki *et al.* 2005). Few attempts, however, have been made to inspect composite-to-composite adhesive joints (Vijaya Kumar *et al.* 2013), especially the WPC adhesive joint.

In the present study, epoxy resin and acrylic ester were used to bond WPC adhesive joints. The shear strength of the adhesive joints was determined and investigated. The resonant frequency and dynamic modulus of elasticity (MOE) of the WPC adhesive joints were measured using the longitudinal vibration method. Meanwhile, the correlations between the different vibration parameters and shear strength of the WPC adhesive joints were also investigated to explore the dynamic parameters that may reflect the bonding quality of the WPC joints.

EXPERIMENTAL

Materials

The WPC materials were provided by the Material Science and Engineering College of Northeast Forestry University (China). The weight percent of the poplar flour was 60%, and its particle size was in the range of 0.4 to 0.8 mm. High-density polyethylene (HDPE) was used and the weight percent of it was 30%. HDPE used in this study (5000S resin, density 0.954 g/cm^3, melt flow index 0.7 g/10 min) was purchased from Daqing Petrochemical Co., China. The other 10% in the WPC was maleic anhydride polyethylene coupling agent. The mean value of WPC density in this study was 1.175 g/cm^3, and the COV of WPC density was 1.4%. Figure 1 shows the distribution of WPC density in this study. The WPC was sanded using 180-mesh sandpaper. The dimensions of the WPC used as lap plates were 180 mm × 40 mm × 4 mm. Two lap plates were adhered together with epoxy resin and acrylic ester adhesives, and the bonding area was 40 mm × 15 mm. The bonded samples were pressed with a clamp. Afterward, the bonded samples were cured at room temperature for 24 h and then at 50 °C for 4 h. Ten samples were bonded with an epoxy resin adhesive, and ten samples were bonded with acrylic ester.

Methods

Nondestructive testing

Nondestructive testing was carried out using a longitudinal vibration method with an ONO SOKKI CF-5220Z Fast Fourier Transform (FFT) analyzer (Yokohama, Japan), as shown in Fig. 2. The specimen was supported lightly by the fingers at the center of the specimen and was tapped by a small hammer at the end of the specimen. The tap tone was detected by a microphone at the other end of the beam. The resonance frequencies of the tap tone were identified by a FFT analyzer.

The Young's modulus of free-free longitudinal vibration E_p was calculated using Eq. 1 (Hu 2004),

$$E_p = \rho\left(\frac{2lf_n}{n}\right)^2, n = 1,2,3...... \qquad (1)$$

where, n is the order of resonance mode, f_n is resonance frequency of the n-th (first, second and third…) resonance mode, L is length of the specimen, and ρ is density of the specimen.

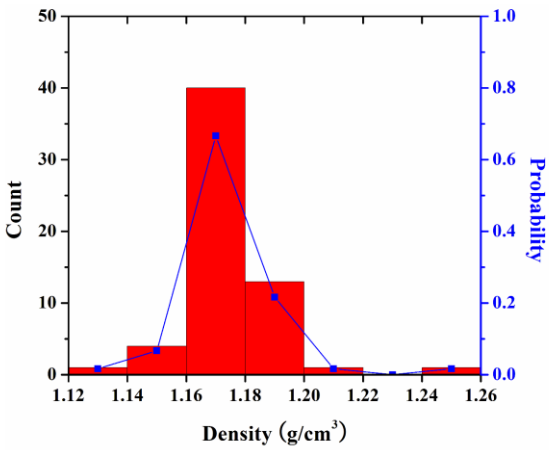

Fig. 1 The distribution of WPC density

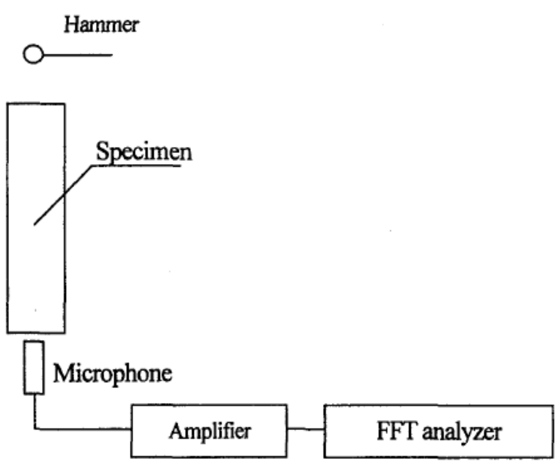

Fig. 2. Schematic diagram of the longitudinal vibration test

Shear strength testing

The shear bonding strengths of the WPC were tested according to the Chinese Standard (GB-T 17517 1998) in a CMT 5504 Universal Mechanical Testing Machine provided by Shenzhen Xinsansi Co., Ltd. (China).

Statistical Analysis

The linear regression analysis between nondestructive parameters and bonding properties of WPC joints was performed with Microsoft Excel, and the linear regression equations and corresponding correlation coefficient (R) were obtained with the software. To determine the significance of the correlation between nondestructive parameters and bonding properties of WPC joints, the obtained correlation coefficient was compared to the critical value of Pearson product-moment correlation coefficient under the confidence level of 0.05 ($R_{n,0.05}$) (Sigle 2015). In $R_{n,0.05}$, "n" stands for the degree of freedom, which is equal to 2 less than the number of samples, and 0.05 is the confidence level, which means the confidence interval is 95%. If the absolute value of the correlation coefficient was above $R_{n,0.05}$, there was a significant relationship between nondestructive parameters and bonding properties. On the contrary, there was no significant relationship between them.

RESULTS AND DISCUSSION

Bonding Strength

Figure 3 shows the shear strength of the WPC samples bonded with acrylic ester and epoxy adhesives, respectively. Results indicate that the WPC samples bonded with epoxy resin had better shear strength than those bonded with acrylic ester. Meanwhile, the coefficient of variation (COV) of shear strength for the epoxy samples was lower than that for the acrylic ester samples (11.9% and 16.9%, respectively). Thus, in these adhesives, epoxy is more suitable for bonding WPC, and it can provide bonding interface with more stability than acrylic ester.

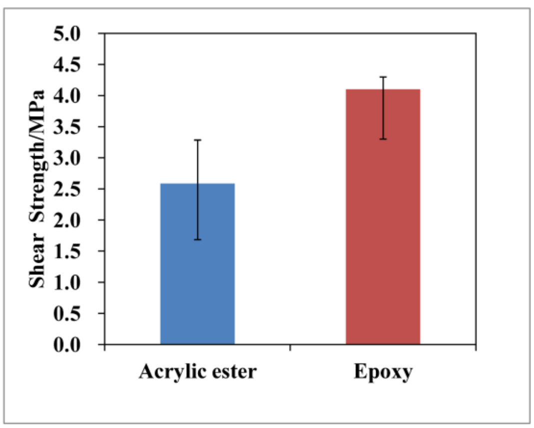

Fig. 3. Shear strength of the WPC bonded with acrylic ester and epoxy resin adhesives

Results of Nondestructive Tests

The resonant frequency and dynamic MOE of the WPC samples bonded with the acrylic ester and epoxy adhesives are shown in Figs. 4a and 4b. Results indicate that the resonant frequency and dynamic MOE of both the epoxy resin and acrylic ester samples were almost identical. WPC joint samples had varied bonding properties with the COV of 11.9 to 16.9%. And the resonant frequency and dynamic MOE of epoxy samples varied more greatly than those of the acrylic ester samples, which may reflect the variation of bonding properties better. Thus, the WPC samples boned with epoxy resin had better vibration response than those bonded with acrylic ester.

To analyze the influence of the epoxy adhesive on the dynamic properties of the WPC joint samples, the dynamic MOE of the WPC lap plates before bonding with epoxy adhesive were also determined as shown in Fig. 4c. It has been reported that the dynamic MOE of laminiated composites can be calculated according to the following equation (Hu 2004; Chauhan *et al*. 2005),

$$E = E_a V_a + E_b V_b + E_c V_c \tag{2}$$

where E, E_a, E_b, and E_c stand for the MOE of the entire composites, laminate a, laminate b, and laminate c, respectively, and V_a, V_b, V_c stand for the volume percentages of laminate a, b, and c, respectively. The dynamic MOE of two lap of WPC joint sample (E_a and E_b), and the dynamic MOE of the entire joint (E) were obtained as mentioned above. According to the Eq. 2, the effective MOE of the WPC joint can be expressed as (E_a + E_b)/2 when ignoring the influence of bondline. The dynamic MOE ratio of the WPC samples before and after the bonding process were caculated according to Eq. 3:

$$R_1 = \frac{\frac{E_a + E_b}{2}}{E} \tag{3}$$

In Eq. 3, R_1 represents the influence of bondline on the dynamic MOE of the WPC joint, as shown in Fig. 4d. It can be seen that the dynamic MOE values of the WPC joint samples were lower than those of the WPC lap plates, which may be caused by the larger dimensions of the joint sample. And the dynamic MOE ratios were all larger than 1, and ranged from 1.00 to 1.12.

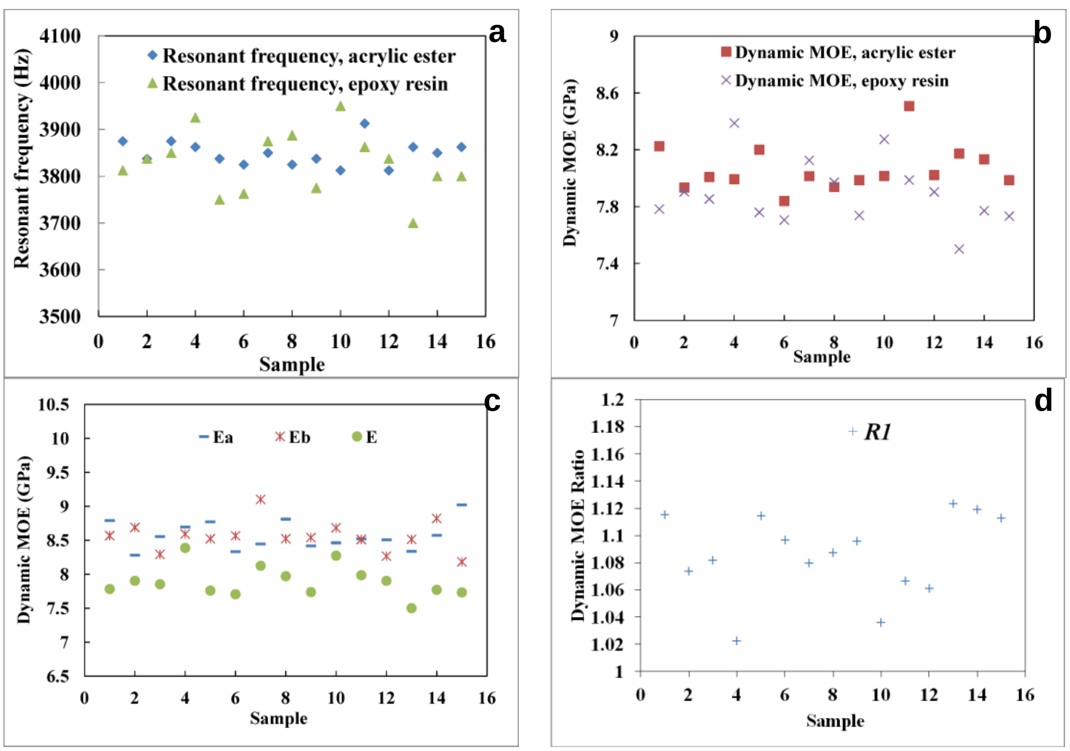

Fig. 4. Nondestructive testing results of the WPC samples: (a) resonant frequency of WPC samples, (b) dynamic MOE of WPC samples, (c) dynamic MOE of lap plates, and (d) dynamic MOE ratio

Correlation between Dynamic Parameter and Shear Strength

To investigate the correlation between the dynamic mechanical properties and the bonding properties of the WPC samples, regression analysis was conducted between the different dynamic parameters and shear strength. From the regression analysis between dynamic mechanical properties (f for resonant frequency, E for dynamic MOE) and shear strength (S) of the WPC samples bonded with acrylic ester, the following linear regression formulas were obtained: S = -0.002f + 12.68, R = 0.161 < $R_{13,\,0.05}$ = 0.514; S = -0.949E + 10.24, R = 0.352 < $R_{13,\,0.05}$ = 0.514. The regression curves between f (or E) and S are shown in Fig. 5. Results indicate there was no correlation between f (or E) and S for the acrylic ester samples.

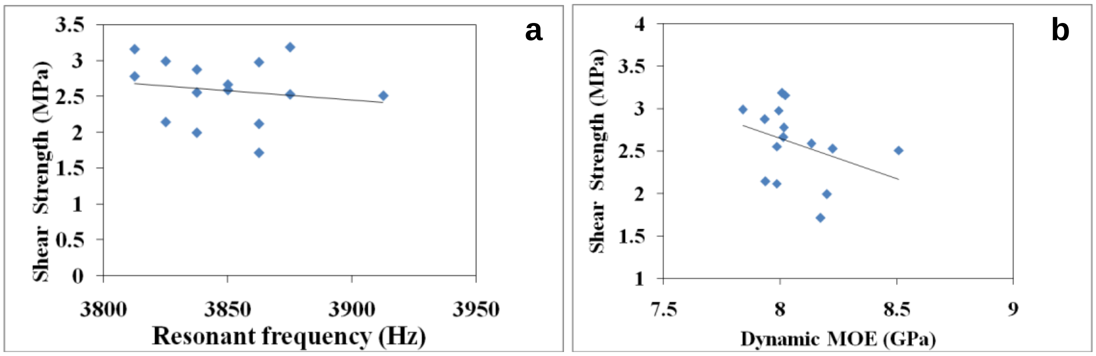

Fig. 5. Regression curves between (a) f and S and (b) E and S for the samples bonded with acrylic ester adhesive

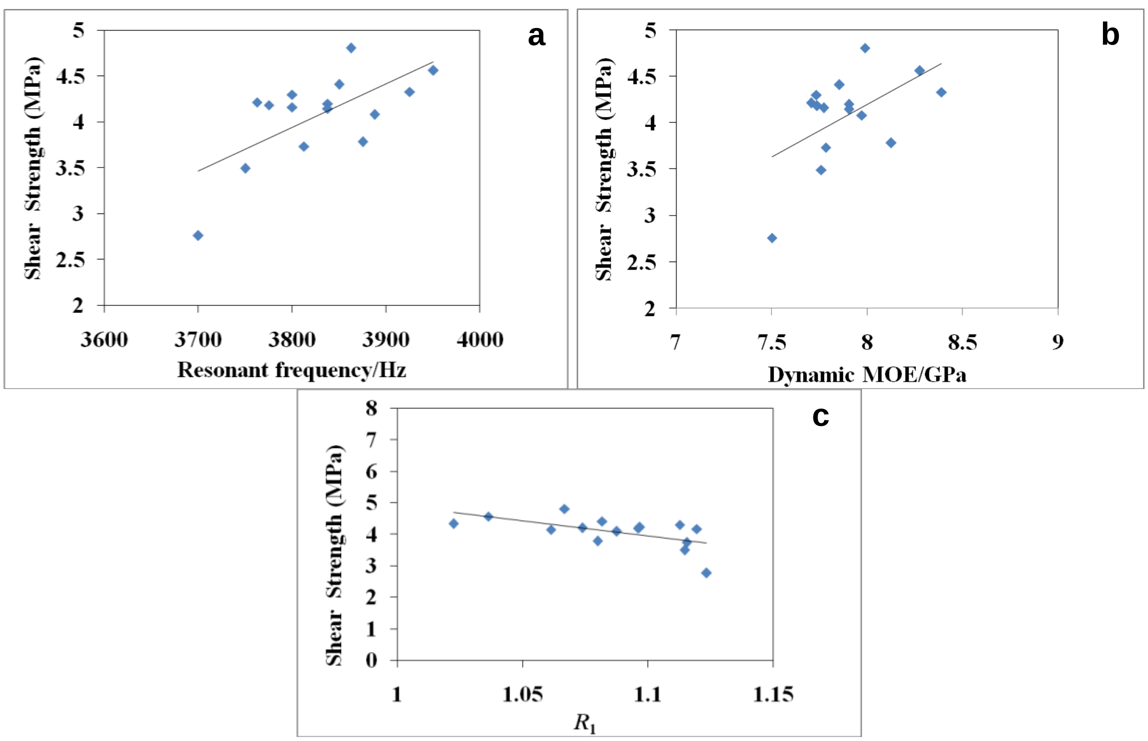

Fig. 6. Regression curves between (a) f and S, (b) E and S, and (c) R_1 and S for the samples bonded with epoxy adhesive

From the regression analysis between dynamic mechanical properties and shear strength of the WPC samples bonded with the epoxy adhesive, the following linear regression formulas were obtained: S = 0.004f - 14.09, R = 0.654 > $R_{13,\,0.05}$ = 0.514; S = 1.131E – 4.850, R = 0.534 > $R_{13,\,0.05}$ = 0.514. The regression curves between f (or E) and S are shown in Fig. 6.

From the regression analysis between the dynamic MOE ratio and shear strength of the WPC samples bonded with epoxy adhesive (Fig. 6), the following linear regression formula was obtained: S = -9.485R_1 + 14.378, R = 0.589 > $R_{13,\ 0.05}$ = 0.514. Results indicate that the dynamic MOE and dynamic MOE ratio had strong correlation with bonding strength for the samples bonded with epoxy adhesive. Compared with the samples bonded with acrylic ester, the samples bonded with epoxy adhesive had better correlations between the dynamic parameters and the shear strength. The reason may be that the cured epoxy adhesive led to a higher adhesion of the WPC than the cured acrylic ester, which will give better adhering behaviors of the samples bonded with epoxy adhesive on stress and vibration transfer (Yamini and Young 1980; Slone 2002). In this case, the dynamic parameters of the samples bonded with epoxy adhesive can reflect the bonding properties more profitably; thus closer correlations between dynamic parameters and the shear strength can be achieved using the epoxy adhesive. Additionally, it's known that the density and stiffness of polymers will influence their vibration behaviors (Schuyer 1959; Davidse *et al.* 1962), and the differences between these two adhesives on density and stiffness will also have an effect on the vibration properties of WPC joints.

For WPC joints bonded with epoxy, it can be seen that all the dynamic parameters (resonance frequency, dynamic MOE, dynamic MOE ratio) had significant correlation with the shear strength of them, which may provide a way to predict the bonding quality of WPC joints with a nondestructive method. However, it is difficult to directly establish a prediction theory using the resonance frequency or dynamic MOE of WPC joints. The future study will focus on the calculation of dynamic MOE of bondline based on the dynamic MOE ratio.

CONCLUSIONS

1. The epoxy resin adhesive had a better bonding quality than the acrylic ester adhesive on the bonding of WPC adhesive joints. It can also provide bonding interface with more stability than acrylic ester.
2. The WPC samples bonded with epoxy adhesive had better vibration response than those bonded with acrylic ester.
3. The resonant frequency, dynamic MOE and dynamic MOE ratio of the WPC adhesive joints had strong correlation with the shear strength of the WPC joints bonded with epoxy resin.

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