Optimization of Tensile Shear Strength of Linear Mechanically Welded Outer-to-Inner Flattened Moso Bamboo (*Phyllostachys pubescens*)

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Mechanical welding technology has been widely employed in the making of bonding joints with wood. Moso bamboo, a lignocellulosic biomaterial, can also be bonded using mechanical welding technology. The surface response methodology was used to define welding parameters yielding optimal joint strength. In the range of this experiment, it was found that the vibration amplitude and the welding pressure both had a significant influence on the performance of the joint, while the welding time did not. The quadratic model was able to significantly fit the actual results and could be used to determine and optimize the bonding strength.

Keywords: Mechanical welding; Moso bamboo; Shear strength; Surface response methodology; Quadratic model

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INTRODUCTION

Moso bamboo (*Phyllostachys pubescens*) is the primary type of bamboo used for industrial purposes in China. The most important of all the industrial processing methods of moso bamboo is glued and laminated bamboo, which can be used to manufacture flooring, paneling, furniture, construction materials, kitchen utensils, and so on. Figure 1 (b) shows that the height of the transverse section of a glued and laminated beam is mainly composed of bamboo that is glued on both its inner and outer sides. Therefore, the optimization of the glue strength on the outer and inner sides of moso bamboo is necessary. The glue strength has the greatest effect on the properties of the final product (Jiang *et al*. 2005).

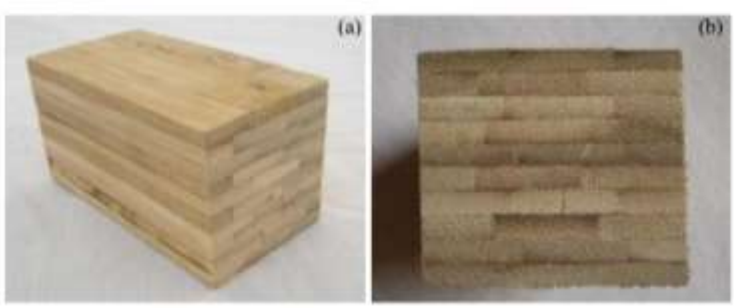

Fig. 1. Bamboo glued laminated beam: (a) side face and (b) transverse section

Improving the usable ratio of bamboo is a constant point of interest for many companies and independent researchers alike. The flattening is a very interesting method in that it can increase the usable amount of moso bamboo from its usual 50% up to 80%.

Figure 2 shows how the method can greatly improve the usable ratio. However, the traditional method of flattening requires the bamboo to be pretreated with chemicals that may pollute the environment and can be a health hazard to humans. A newly invented flattening method called "stressed flattening" (Liu *et al*. 2013) can solve this problem.

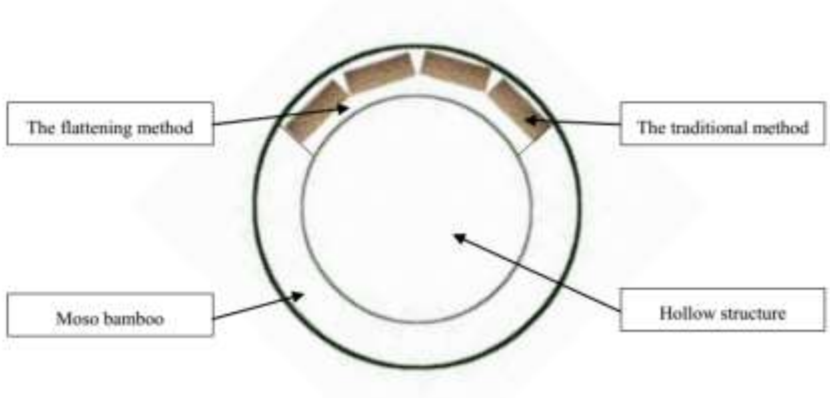

Fig. 2. The difference between the traditional wood processing method and the method of flattening is shown. The gray bamboo shows the portion that can be used, and the part between the two lines shows the usable, flattened bamboo.

Mechanically induced, linear vibration friction welding, which has mostly been used in thermoplastics and metals, has been utilized for the bonding of wood for more than a decade (Gfeller *et al*. 2003). During this time, some other new technologies have also been employed, such as rotational wood dowel welding, ultrasonic welding, and microfriction stir welding (Pizzi *et al*. 2004; Tondi *et al*. 2007). However, most research has been predominantly focused on the understanding and improvement of the welded bond, new types of wood to employ, and new products that may be manufactured by welding (Leban *et al*. 2004; Ganne-Chedeville *et al*. 2005; Stamm *et al*. 2005; Omrani *et al*. 2009 and 2010; Belleville *et al*. 2011; Martins *et al*. 2013). Bamboo is also a lignocellulosic material; however, due to its round structure, bamboo-on-bamboo welding has not been studied so far.

In this paper, the welded bonding strength between the inner and outer sides of stressed moso bamboo were optimized *via* response surface methodology. The welding time, welding pressure, and welding amplitude were considered in the experiment.

EXPERIMENTAL

A four-year-old sample of moso bamboo was chosen for this experiment, as this is an age at which moso bamboo is considered mature and is normally harvested for industrial usage. The bamboo was collected from a bamboo plantation in Anhui province, China. The bamboo was stress flattened, as prescribed by Liu *et al* (2013), and only the middle section of the flattened bamboo was studied to limit the effects of extraneous factors (Fig. 3). The outer green skin and the inner yellow skin of the bamboo were not removed, as can be seen from Fig. 3, which can simplify the welding bonding process. Our previous study has proved that the green and yellow skin of bamboo have no significant influence on the final bonding strength of the welded joints Because the green and yellow skin of the bamboo can be expelled out from the edge during the welding process. The flattened bamboo was cut into sections of 200 mm × 20 mm × 8 mm, and two of them were welded together *via* linear vibration to form a bonded joint of 200 mm × 20 mm × 16 mm. The samples were welded parallel to the longitudinal bamboo fibers.

The bonding strength samples were cut and tested according to EN 302-1 (2004) after they were kept for an obligatory 7 days in a 20 ˚C and 65% environment to research a constant weight. Total length, width and the length of overlap of the test pieces were 150 mm, 20 mm, and 10 mm, respectively. The loading speed of the Instron universal testing machine was 2 mm/min, and the time required to reach failure is between 30 s and 90 s. Every group had six replicates. The standard deviations of each group were in the range of 10% to 20% and Grubbs Criterion was applied to reject the results.

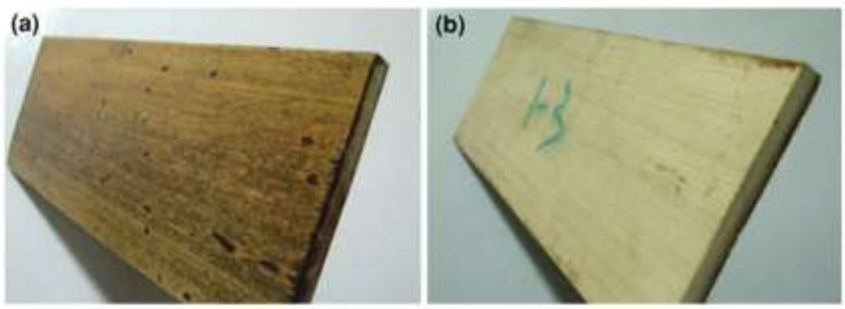

Fig. 3. Flattened, 1/3 round moso bamboo: (a) external skin and (b) internal surface

A KLN Ultraschall LVW-2261 (Mecasonic, Crest group, Annemasse, France), which was designed for welding thermoplastics and complete process control, was used. The vibration welding frequency was 150 Hz. According to Gfeller *et al*. (2003), welding pressure (W.P.), vibration amplitude (V.A.), and welding time (W.T.) are the three most important parameters that influence the tensile bonding strength. A three-phase welding process was chosen to produce the bonding joints. The first phase of welding is the cleaning and preheating phase, so 0.5 MPa (W.P.), 1 s (W.T.), and 1 mm (V.A.) are good parameters for this stage. The last phase is the holding phase, during which there is no vibration amplitude. According to previous research, holding time and holding pressure can be 10 s and 2.5 MPa, respectively. The most important phase is the second phase. To optimize the second phase, a steepest ascent experiment was used to find the central value (Table 1); then, the Box-Behnken experimental design was employed to optimize the results. The Box-Behnken method is one of the surface response analysis methods that have frequently been used in all kinds of process optimization (Myers *et al*. 2004, Wongprot *et al*. 2012, Teh *et al*. 2013, Duret *et al*. 2013). The parameters chosen for the steepest ascent experiment are shown in Table 1. Because the maximum vibration amplitude of the machine is 22 mm, the V.A. of No. 4 was set to 2 mm, the same as No. 3, for safety purposes.

Table 1. Steepest Ascent Experimental Design and Results

No.	W.T. (s)	W.P. (MPa)	V.A. (mm)	Tensile shear Strength (MPa)
1	3	1.25	1.5	No
2	4	1.5	1.75	5.08
3	5	1.75	2	5.93
4	6	2	2	5.31

According to the results in Table 1, the tensile shear strength reached its maximum value in the third experiment. In light of this, the parameters of No. 3 (W.T. = 5 s; W.P. = 1.75 MPa, and V.A. = 2 mm) were selected as the central points with which to design the Box-Behnken experiment shown in Table 2. The statistical software package Design-Expert 6.0.1, StatEase, Inc., (Minneapolis, MN,USA) was applied to analysis the data.

Table 2. Design of Levels and Factors

Level	W.T. (s)	W.P. (MPa)	V.A. (mm)
-1	4	1.25	1.5
0	5	1.75	1.75
+1	6	2.25	2

RESULTS AND DISCUSSION

There were 17 experimental points in the design of the Box-Behnken experiment, constituting three parameters and three levels. Among them, 12 were factorial points and the other five were zero points that were used to estimate the experimental margin of error (Table 3). The tensile shear results are shown in Table 3.

Table 3. Box-Behnken Experimental Design and the Tensile Shear Results

No.	W.T. (s)		W.P. (MPa)		V.A. (mm)		Strength (MPa)
	A	Code	B	Code	C	Code	
1	6	1	1.75	0	1.5	-1	4.15
2	4	-1	1.25	-1	1.75	0	4.09
3	6	1	1.75	0	2	1	5.72
4	6	1	2.25	1	1.75	0	5.31
5	5	0	2.25	1	2	1	5.88
6	5	0	1.75	0	1.75	0	5.63
7	5	0	1.75	0	1.75	0	5.82
8	5	0	1.75	0	1.75	0	5.21
9	5	0	1.25	-1	2	1	5.57
10	5	0	1.25	-1	1.5	-1	3.96
11	4	-1	1.75	0	2	1	5.98
12	4	-1	1.75	0	1.5	-1	3.89
13	4	-1	2.25	1	1.75	0	5.01
14	5	0	2.25	1	1.5	-1	4.98
15	6	1	1.25	-1	1.75	0	4.22
16	5	0	1.75	0	1.75	0	5.38
17	5	0	1.75	0	1.75	0	5.75

Design-Experiment software was employed to regress the results, and the following equation was derived:

$$\text{Shear Strength} = 5.56 + 0.054A + 0.42B + 0.77C + 0.043AB - 0.13AC - 0.18BC - 0.53A^2 - 0.37B^2 - 0.091C^2 \quad (1)$$

Figure 4 shows the actual tensile shear strength *versus* the predicted strength based on Eq. 1. Significant parallels can be seen here. Variance analysis demonstrated that the model F-value is 12.69, which implies that the model is accurate and the regressed equation can be applied to guide optimization.

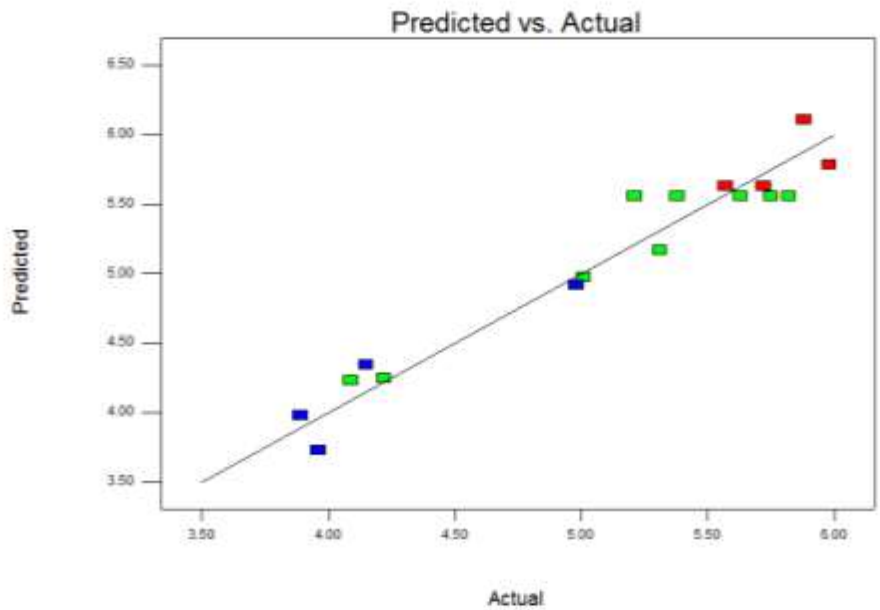

Fig. 4. Scatter plot for actual tensile shear strength *versus* predicted strength. Predicted values were calculated based on Eq. 1 of the model, with $R^2 = 0.93$.

That the values of "Probe > F" were less than 0.05 indicates that the model terms are accurate (Table 4). In the case shown in Table 4, B (W.P.), C (V.A.), A2 (W.T.2), and B2 (W.P.2) are accurate model parameters. Values greater than 0.1 indicate that the model terms are not accurate. The "Lack of Fit F-value" of 1.25 indicates the lack of fit is not significant relative to the pour error. A (W.T.) has no significant impact on the final results owing to that after 4 s of the welding, the temperature of the welding surface reach the maximum point and hold constant. The maximum temperature of the welding surface after 4 s, 5 s, and 6 s were the same.

Table 4. Results of Variance Analysis

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	8.32	9	0.93	12.69	0.0015
A	0.023	1	0.023	0.32	0.5907
B	1.39	1	1.39	19.15	0.0032
C	4.76	1	4.76	65.35	< 0.0001
AB	0.0072	1	0.0072	0.099	0.7169
AC	0.068	1	0.068	0.93	0.3674
BC	0.13	1	0.13	1.73	0.2298
A^2	1.19	1	1.19	16.34	0.0049
B^2	0.57	1	0.57	7.87	0.0263
C^2	0.035	1	0.035	0.48	0.5090
Residual	0.51	7	0.073		
Lack of fit	0.25	3	0.082	1.25	0.4039
Pure Error	0.26	4	0.066		
Cor Total	8.83	16			

Figure 5 visually indicates how two of the three parameters influenced the final tensile shear strength of inner to outer welding on moso bamboo. Comparing Fig. 5(a), (b), and (c), it can be noted that the interaction between W.P. and V.A. or V.A. and W.T. had a greater effect on the final results than interaction between W.T. and W.P. in the range of this experiment. The best parameters for welding strength were found to be W.P. = 0 (1.75 MPa), W.T. = 0 (5 s), and V.A. = 1 (2 mm). The calculated bonding strength was 6.23 MPa, which is only 2% stronger than the actual strength shown in Table 1.

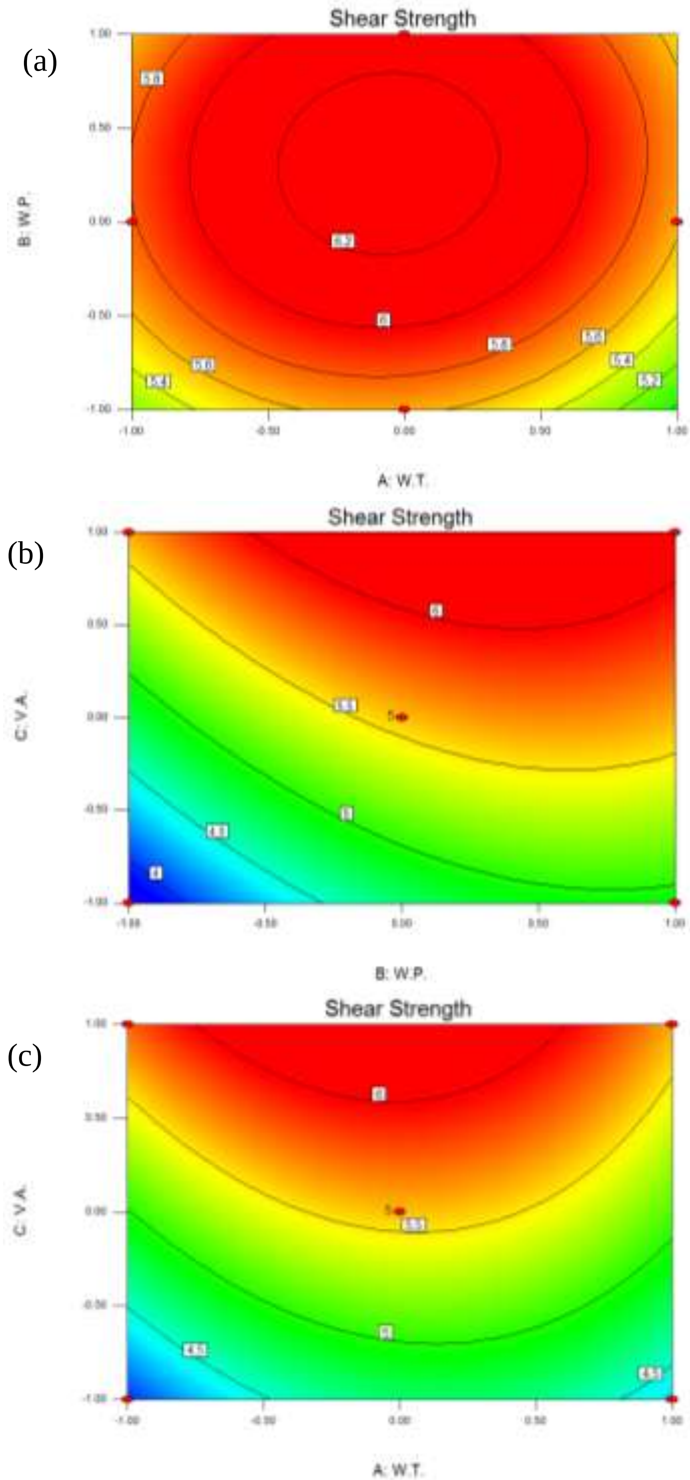

Fig. 5. The influence of welding time (W.T./s), welding pressure (W.P./MPa) and vibration amplitude (V.A./mm) on the tensile shear strength (MPa). The black lines are contours. (a) W.P. and W.T. with V.A. = 1 (2 mm), (b) V.A. and W.P. with W.T. = 0 (5 s), and (c) V.A. and W.T. with W.P. = 0 (1.75 MPa)

Ten experimental replications were done to verify the reliability of the optimized parameters. A modification of the parameters was also employed by changing the three phases to four by improving and decreasing the welding pressure shown in Table 5. The average tensile shear strength attained with four phases is slightly greater than what was attained with three phases.

Table 5. Results of the Verification and Improvement Experiment

Parameters of welding			Bonding strength	
Time(s)	Pressure (MPa)	Amplitude(mm)	Mean (MPa)	SD (MPa)
1/5/10	0.5/1.75/2.5	1/2/0	6.15	0.42
1/2/3/10	0.5/1.5/1.75/2.5	1/2/2/0	6.23	0.45
1/2/3/10	0.5/1.75/2/2.5	1/2/2/0	6.18	0.41

CONCLUSIONS

1. Linear vibration welding technology is not merely able to be used on wood but can also make glue joints with bamboo.
2. Welding pressure, welding time, and vibration amplitude are the main factors influencing the tensile shear strength of the welding joint between the inner and outer sides of moso bamboo. Among these factors, the vibration amplitude was the most important, welding pressure was less so, and welding time had no significant effect on the final results in the range of this experiment.
3. Better average results may be attained by increasing the three-phase weld to a four-phase weld.

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