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Process Optimization of Large-Size Bamboo Bundle Laminated Veneer Lumber (BLVL) by Box-Behnken Design

Xiaoyi Niu, Jiuyin Pang, Hanzhong Cai, Shan Li, Lei Le, and Junhua Wu*

This work focuses on optimization of the laminated lap-joint lengthening technology that is used to produce large-size bamboo bundle laminated veneer lumber (BLVL). A three-factor Box-Behnken design was developed in which lap-joint length (x_1), board density (x_2), and thickness of lap veneer (x_3) were the three factors. Multi-objective optimization of response surface model was used to obtain 17 optimum Pareto solutions by a genetic algorithms method. The mechanical properties of BLVL predicted using the model had a strong correlation with the experimental values (R^2 = 0.925 for the elastic modulus (MOE), R^2 = 0.972 for the modulus of rupture (MOR), R^2 = 0.973 for the shearing strength (SS)). The interaction of the x_1 and x_3 factors had a significant effect on MOE. The MOR and shearing SS were significantly influenced by the interaction of x_2 and x_3 factors. The optimum conditions for maximizing the mechanical properties of BLVL lap-joint lengthening process were established at x_1 = 16.10 mm, x_2 = 1.01 g/cm^3, and x_3 = 7.00 mm. A large-size of BLVL with a length of 14.1 m was produced with the above conditions. Strong mechanical properties and dimensional stability were observed.

Keywords: Bamboo bundles; Lap-joint; Laminated veneer lumber (LVL); Box-Behnken design; Response surface methodology; Mechanical properties

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INTRODUCTION

The development of energy efficient buildings made from green building materials has the potential to initiate a paradigm shift leading to a huge demand for environmentally friendly construction materials. It follows that large-size bamboo-based engineered products will become a valid alternative to traditional construction materials due to their abundance as a raw material, good structural integrity, aesthetic pleasance, effective seismic resistance, and ease of manufacturing (Nugroho and Ando 2001; Lugt *et al*. 2005; Huang *et al*. 2015; Yu *et al*. 2015). A variety of bamboo-based products, including bamboo-strip laminates, mat and curtain ply bamboo, glue-laminated bamboo, and bamboo scrimber have been developed and successfully applied in buildings, bridges, floors, transportation, and other fields (Hu and Pizzi 2013; Sharma *et al*. 2015; Chen *et al*. 2016; Yanjun *et al*. 2016). However, the dimensions of artificial bamboo boards developed to this point have been small with sizes of 1.22 m to 2.44 m, which severely hinders further applications in larger-span structural applications. Components such as double beam bamboo bundle laminated veneer lumber have limited use because of the scarcity of continuous hot pressing machinery (Li *et al*. 2014; Chen *et al*. 2016).

Bamboo bundle laminated veneer lumber (BLVL) is manufactured by arranging broomed bamboo bundle fibers impregnated with phenol-formaldehyde resin (PF) in a parallel lay-up, which was then hot pressed. Bamboo bundle laminated veneer lumber as a potential construction material has a favorable uniform density, dimensional stability, and stability of mechanical performance (Chen *et al*. 2013, 2014). The effects of scarf-joint and finger-joint forms on the mechanical properties of large-scale BLVL have been compared (Yeh and Lin 2012; Deng *et al*. 2014). Zhang *et al*. (2014) evaluated the effects of the four veneer-joint forms (*i.e.*, button joint, lap joint, toe joint, and tape joint) on the mechanical properties of BLVL and found that the best veneer-joint form was the lap joint laminate. Recently, large span BLVL (length > 2.44 m) was successfully manufactured by combining the prepress densification process and the intermittent hot-press method (Sharma *et al*. 2015). According to the intermittent hot-press process, research is required on the parallel lap-joint and assembly technology of bamboo bundle veneer in order to allow for effective production of large-span BLVL. Additionally, broomed bamboo bundle fibrosis veneer is a loosely laminated reticulate sheet and is much harder than wood, which makes it inconvenient to mill. Based on the lap-joint method used in laminated veneer lumber (LVL) (Zhang *et al*. 2014), loose bamboo bundle fibers are laminated in a crisscross overlap with each other at the lap-joint. The local density and stress distribution at the lap-joint have a large variation caused by the technological parameters of the process such as the thickness of lap veneer, lap-joint length, and board density. The variance of density and stress distribution is of key importance for the mechanical behavior and dimensional stability of large-span BLVL. Therefore, the lap-joint process and lay-up method of bamboo bundle veneer would have a great influence on the mechanical properties of board, especially at the lap-joint.

Once a certain mechanical index of board needs to be satisfied for the engineering design requirements, manufacturing processes parameters should be adjusted accordingly. Typical methods are based on conducting a large amount of destructive testing, which is repetitive, labor-intensive, inefficient, blind, and a waste of resources. If the inner mathematical relationships between process parameters and the mechanical properties of a board could be developed using numerical simulation, then a predetermined regard for the lap-joint assembly pattern could effectively be obtained with the optimization process parameters. Based on this, the parameters and model are then corrected and reconfirmed by the re-experimental data, which improves the work efficiency and saves resources. Response surface methodology (RSM) is an accurate and effective tool which is a kind of statistical and mathematical method used for optimizing experimental processes (Bezerra *et al*. 2008; Jiang *et al*. 2013; Subramonian *et al*. 2015). By designing a series of experiments for adequate and reliable data for the response of variables of interest, a mathematical model of the second order response surfaces with the best fittings is developed. The best finite-parameter solutions with a maximum or minimum value of interest and the interactive effects of process parameters in 3-D contour plots could be observed (Aslan and Cebeci 2007; Lai *et al.* 2013; Yuan *et al*. 2015).

There are few studies available in literature about the optimization of lap-joint assembly process for large-span bamboo bundle laminated veneer lumber (BLVL) using RSM. Therefore, the focus of this study is to optimize the laminated lap-joint lengthening technology using RSM on a three-level three-factorial Box-Behnken experimental design. The Functional relationship between the three factors (x_1: lap-joint length, x_2: board density, x_3: veneer thickness) on the mechanical properties of lap-joint BLVL were investigated.

EXPERIMENTAL

Manufacture Process of BLVL

Cizhu bamboo (*Neosinocalamus affinis*) bundle veneers were immersed in phenol formaldehyde (PF) resin (solid content of 12%) for 5 to 7 min and then dried to a moisture content of 10% to 12% under an ambient environment. The resin soaked veneers were layered symmetrically along their grain direction with the outer layer of bamboo bundle facing upward. The overlap joint in each bamboo bundle layer was set on a 1/6 to 1/2 position along the length of the board. The lap-joints in adjacent layers were designed with horizontal separation. A pressure, temperature, and time of 3.5 MPa, 150 °C, and 30 min, respectively, were applied to the BLVL during the hot press. The dimensions of BLVL were 300mm × 150 mm × 12.5 mm (length*width* thickness).

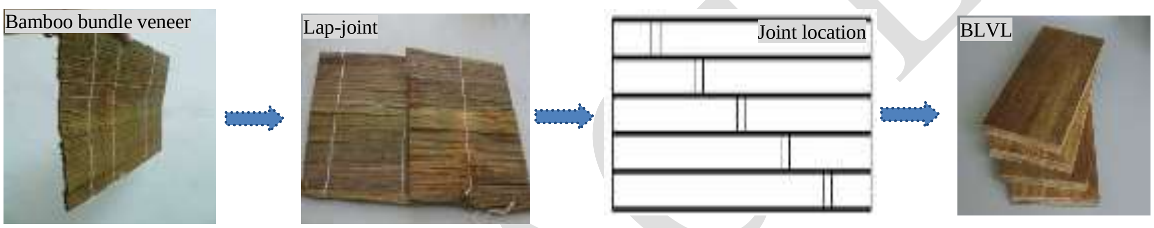


Fig. 1. Production of bamboo bundle veneer and lap-joint allocation on BLVL

Mechanical Properties

The BLVL were tested for modulus of elasticity (MOE), modulus of rupture (MOR), and shearing strength (SS) under perpendicular loading to the glue line. Seventeen coded groups were used for each test with seven replicates per group (Table 1) for a total of 357 samples prepared for testing. The testing procedures to determine the MOE, MOR, and SS were in accordance with the ASTM standards D1037 (2006), D3500 type A (2003), and D2344 (2006), respectively.

Response Surface Methodology and Box-Behnken Experimental Design

Response variables (y_1, y_2, y_3, …, y_m) reflected the results of interest, independent variables (x_1, x_2, x_3, …, x_k) were those which affected the response variables, and variables *m* and *k* were the number of response variables and independent variables, respectively. Equation 1 is an empirical expression for response variables and independent variables.

$$y = f(x_1, x_2, x_3 ......, x_k) \quad (1)$$

The objective was to find a functional relationship between the independent variables (x) and response variables (y), as well as what independent variable (x) would optimize the response variables (y). A second-order polynomial model was utilized according to the following equation,

$$y = \eta_0 + \sum_{i=1}^{k} \eta_i x_i + \sum_{i=1}^{k} \eta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \eta_{ij} x_i x_j \quad (2)$$

where η_0, η_i, η_{ii}, and η_{ij} were the regression coefficients of constant, linear, quadratic, and interactions terms, respectively.

The independent variables (x_1: lap-joint length (mm), x_2: board density(g/cm^3), x_3: veneer thickness (mm)) were at three levels (x_1: 10 mm (-1), 20 mm (0), 30 mm (1); x_2: 0.8 g/cm^3 (-1), 0.95 g/cm^3(0), 1.1 g/cm^3 (1); x_3: 4.0 mm (-1), 5.5 mm (0), 7.0 mm (1)). For the three-level three-factorial Box-Behnken experimental design (BBD), a total of 17 experimental runs were made in random order (Table 1). Response variables of (y_1: MOE, y_2: MOR, y_3: SS) were expressed by means of seven measurements. The specific model for three-level three-factorial is as follows,

$$y = \eta_0 + \eta_1 x_1 + \eta_2 x_2 + \eta_3 x_3 + \eta_{11} x_1^2 + \eta_{22} x_2^2 + +\eta_{33} x_3^2 + \eta_{12} x_1 x_2 + \eta_{13} x_1 x_3 + \eta_{23} x_2 x_3 \quad (3)$$

where y (y_1, y_2, y_3) represents the predicted response of interest; η_0 was the constant regression coefficients; η_1, η_2, and η_3 were the linear regression coefficients; η_{11}, η_{22}, and η_{33} were the quadratic coefficients, and η_{12}, η_{13}, and η_{23} were the interaction coefficients. These coefficients were determined in the second-order model by computer simulation programming that applied the least square method. The data analyses were undertaken using the Design-Expert V.8.0.6 (Stat-Ease, Inc., Minneapolis, MN, USA).

Table 1. Experiment Design by BBD, Experimental and Predicted Values of Mechanical Properties of BLVL

Group No.	Independent Factors			MOE (GPa)		MOR (MPa)		SS (MPa)	
	x_1	x_2	x_3	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.
1	-1	-1	0	15.82	14.70	115.35	119.46	8.00	8.69
2	1	-1	0	18.24	18.66	142.51	144.76	8.87	9.19
3	-1	1	0	15.73	15.81	100.75	98.50	15.26	14.94
4	1	1	0	13.04	14.67	140.13	136.02	17.71	17.01
5	-1	0	-1	12.46	12.97	141.94	141.01	13.60	13.14
6	1	0	-1	20.72	19.69	178.75	179.68	15.31	15.22
7	-1	0	1	22.60	23.12	143.67	142.74	18.03	18.11
8	1	0	1	20.24	19.21	165.98	166.91	18.14	18.60
9	0	-1	-1	19.22	19.88	154.49	151.31	10.57	10.33
10	0	1	-1	19.62	18.45	96.77	99.95	14.51	15.29
11	0	-1	1	18.36	18.40	155.74	152.56	13.22	12.44
12	0	1	1	17.50	16.96	171.04	174.22	21.29	21.53
13	0	0	0	20.83	21.21	166.14	170.14	11.79	12.00
14	0	0	0	21.27	21.21	176.09	170.14	12.31	12.00
15	0	0	0	21.78	21.21	163.56	170.14	12.56	12.00
16	0	0	0	20.13	21.21	174.76	170.14	11.37	12.00
17	0	0	0	21.00	21.21	170.14	170.14	12.00	12.00

Exp., Experimental; Pred., Predicted

RESULTS AND DISCUSSION

Results of Response Surface Methodology Experiments

The effects of three independent variables(x_1: lap-joint length, x_2: board density, and x_3: veneer thickness) with the three-coded level on the mechanical properties of BLVL (y_1: MOE, y_2: MOR, and y_3: SS) using BBD are reported in Table 1. The predicted values for the response variables matched well with the experimental data, indicating a strong correlation (Table 2). The low coefficient of variation (CV) values indicated good stability in the mechanical behavior of BLVL, which was adequate and suitable for the mathematical model as a function Eq. 3.

Table 2. Model Adequacy Indicators for Each Modeled Response of BLVL

Response Variables	R^2-value	Adj-R^2	Pred-R^2	CV (%)
MOE	0.925	0.850	0.977	6.12
MOR	0.972	0.943	0.761	4.05
SS	0.973	0.952	0.847	5.57

After fitting the mechanical properties data to the experimental results using Eq. 3, the following quadratic response functions representing y_1, y_2, and y_3 were be expressed as a function of lap-joint length (x_1), board density (x_2), and veneer thickness (x_3), respectively. Adj-R^2 represents the adjusted value of R^2 after removing the effect of the number of independent factors on the response variables. The coefficients in the model equations are rounded.

For the y_1 MOE model equation,

$$Y_{MOE} = -176.47 + 7.47X_1 + 247.49X_2 + 11.47X_3 - 0.85X_1X_2 - 1.02X_1X_3 - 0.14X_1^2 - 123.83X_2^2 + 0.02X_1^2X_3 \quad (4)$$

For y_2 MOR model equation:

$$Y_{MOR} = -397.35 - 22.44X_1 + 1959.27X_2 - 117.36X_3 + 5.53X_1X_3 + 81.13X_2X_3 + 0.63X_1^2 - 1292.09X_2^2 - 0.14X_1^2X_3 \quad (5)$$

For y3 SS model equation:

$$Y_{SS} = 49.93 - 0.15X_1 - 1.78X_2 - 18.70X_3 - 0.027X_1X_3 + 4.58X_2X_3 + 0.0088X_1^2 + 1.48X_3^2 \quad (6)$$

Analysis of variance for the response surface second-order model of the MOE, MOR, and SS show the values of "Prob > F" less than 0.05 indicated that the model had a strong significance (Tables 3, 4, and 5).

Table 3. Analysis of Variance for MOE Regression Equation

Source	Sum of Squares	DF	Mean Square	F-value	Prob > F	Significance
Model	130.07	8	16.26	12.35	0.0009	Significant
x_1	3.97	1	3.97	3.02	0.1207	
x_2	4.14	1	4.14	3.14	0.1141	
x_3	2.22	1	2.22	1.68	0.2307	
$x_1 x_2$	6.51	1	6.51	4.95	0.0568	Not significant
$x_1 x_3$	28.22	1	28.22	21.44	0.0017	Significant
x_1^2	25.51	1	25.51	19.39	0.0023	

x_2^2	32.77	1	32.77	24.90	0.0011	
$x_1^2 x_3$	19.96	1	19.96	15.16	0.0046	
Residual	10.53	8	1.32			
Lack of Fit	9.06	4	2.26	6.16	0.0531	Not significant
Pure Error	1.47	4	0.37			
Cor Total	140.60	16				

Table 4. Analysis of Variance for MOR Regression Equation

Source	Sum of Squares	DF	Mean Square	F-value	Prob > F	Significance
Model	10139.14	8	1267.39	34.16	< 0.0001	Significant
x_1	1973.70	1	1973.70	53.19	< 0.0001	
x_2	440.95	1	440.95	11.88	0.0087	
x_3	1426.20	1	1426.20	38.44	0.0003	
$x_1 x_3$	52.56	1	52.56	1.42	0.2681	Not significant
$x_2 x_3$	1332.86	1	1332.86	35.92	0.0003	Significant
x_1^2	1080.61	1	1080.61	29.12	0.0006	
x_2^2	3568.57	1	3568.57	96.17	< 0.0001	
$x_1^2 x_3$	936.65	1	936.65	25.24	0.0010	
Residual	296.85	8	37.11			
Lack of Fit	180.82	4	45.20	1.56	0.3389	Not significant
Pure Error	116.04	4	29.01			
Cor Total	10435.99	16				

Table 5. Analysis of Variance for Shearing Strength (SS) Regression Equation

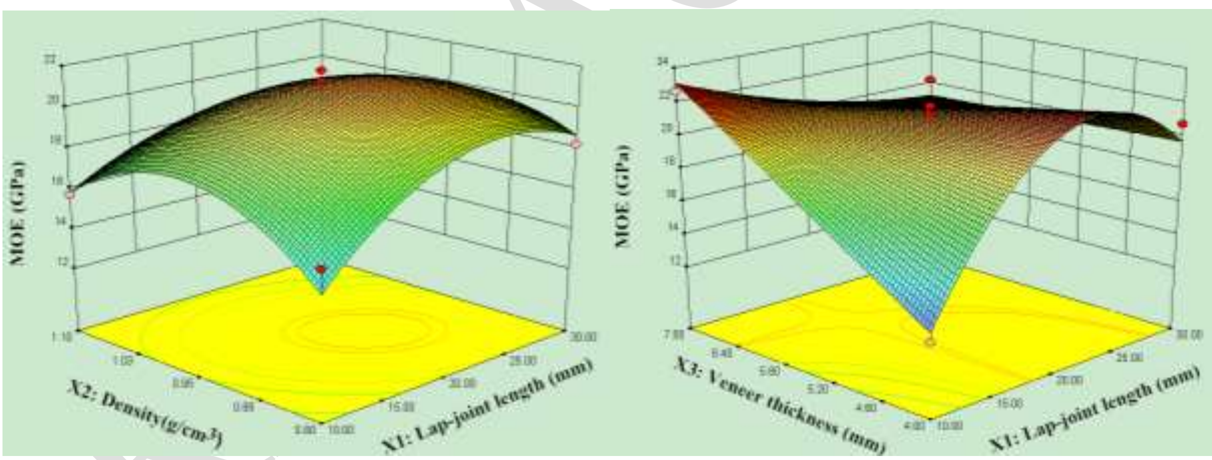
Source	Sum of Squares	DF	Mean Square	F-value	Prob > F	Significance
Model	193.49	7	27.64	46.77	< 0.0001	significant
x_1	3.30	1	3.30	5.58	0.0425	
x_2	98.84	1	98.84	167.25	< 0.0001	
x_3	34.84	1	34.84	58.95	< 0.0001	
$x_1 x_3$	0.63	1	0.63	1.07	0.3281	Not significant
$x_2 x_3$	4.25	1	4.25	7.20	0.0251	significant
x_1^2	3.33	1	3.33	5.63	0.0417	
x_3^2	46.76	1	46.76	79.12	< 0.0001	
Residual	5.32	9	0.59			
Lack of Fit	4.47	5	0.89	4.22	0.0941	Not significant
Pure Error	0.85	4	0.21			
Cor Total	198.81	16				

The model F-values for MOE, MOR, and SS regression equation indicated that the models were all significant. In addition, the lack of fit values of “Prob > F” were all more than 0.05, which implies the models fitted the MOE, MOR, and SS well.

Effect of Lap-Joint Variables on the Mechanical Properties of BLVL

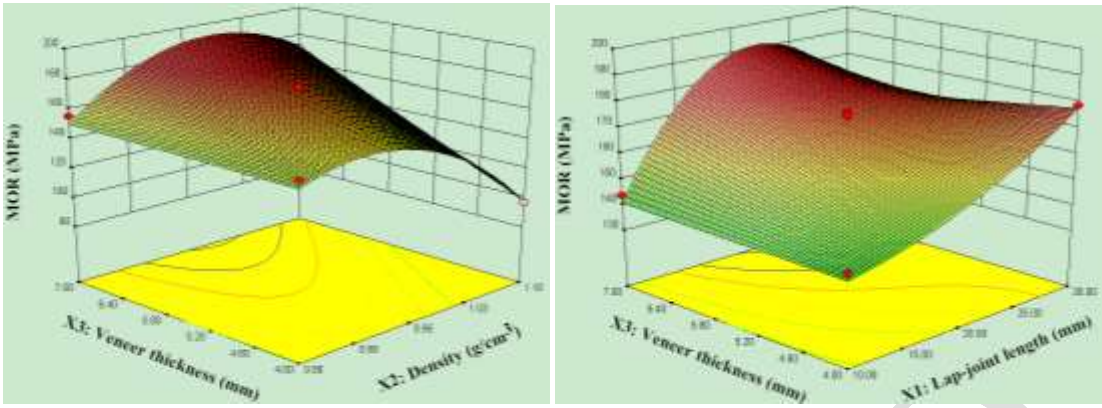
A serials 3-D response surface contour plots were drawn to clarify the effect of the variables on the mechanical properties of BLVL (Figs. 2 through 4). The interactive effect of independent variables can be observed directly from the 3-D response surface contour plots. The contour plots’ oval shape (at the bottom of 3-D response surface plots) indicated the interactive effect between the response variables was significant. The contour plot representing the interaction between lap-joint length (x_1) and board density (x_2) was flat which affected the MOE of the BLVL (Fig. 2). Similarly, the elliptical shape of the contour plots in Figs. 3 and 4 indicated the interactive effect of board density (x_2) and veneer thickness (x_3) on MOR, while the board density (x_2) and veneer thickness (x_3) had a larger effect on the SS. The round contour plots in Figs. 2(a) and 4(b) and the line contour plot of Figure 3(b) showed there was a minimum interactive effect between the lap-joint length (x_1) and board density (x_2) on the MOE, lap-joint length (x_1) and veneer thickness (x_3) on the MOR, lap-joint length (x_1) and veneer thickness (x_3) on the SS, respectively.

From the variance of the MOE, MOR, and SS that the results were verified to their strong Prob > F values (Tables 3 to 5). The Prob>F values for MOE model x_1x_3, MOR model x_2x_3, and SS model x_2x_3 were all lower than 0.05 which indicates that the results were significant at the 95% confidence level. The Prob>F values of MOE model x_1x_2,, MOR model x_1x_3, and SS model $x_1x_3$were confirmed to have no significant effect on the BLVL. It was observed from the contour plots that the BLVL had stronger mechanical properties when the board was manufactured with a middle level of lap-joint length, board density, and upper level of the veneer thickness. An appropriate lap-joint length and board density was beneficial for strong interfacial bonding between the layers of the BLVL. Based on the manufacturing conditions, bamboo bundle veneer thickness had a positive contribution to the interactive influence on mechanical properties. The main effect of these positive contributions was namely the larger the veneer thickness, the better MOR and SS obtained.



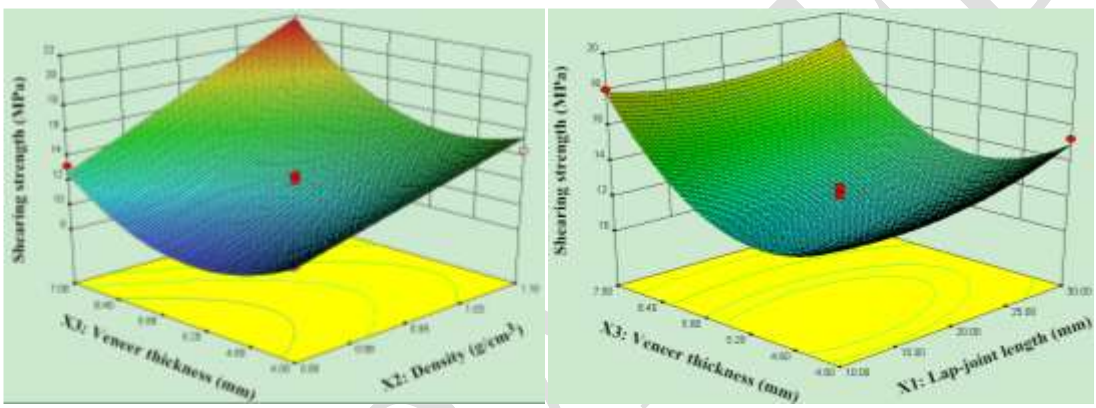
(a) **(b)**

Fig. 2. Response surfaces plots showing the effect of lap-joint length (x_1) and (a) board density (x_2) or (b) veneer thickness (x_3) on MOE



(a) (b)

Fig. 3. Response surfaces plots showing the effect of veneer thickness (x_3) and (a) board density (x_2) or (b) lap-joint length (x_1) on MOR



(a) (b)

Fig. 4. Response surfaces plots showing the effect of veneer thickness (x_3) and (a) board density (x_2) or (b) lap-joint length (x_1) on SS

Optimization of Lap-Joint Process and Its Application in Large-Span BLVL

Multi-objective optimization was based on the response surface model by using a genetic algorithm (GA) due to its common used to generate high-quality solutions to optimization. In a GA, a population of candidate solutions of lap-joint parameters to an optimization problem is evolved toward better solutions.

Table 6. The 17 Pareto Solutions for Multi-Objective Optimization

No.	Independent Variables			Mechanical Properties			Desirability Factor
	x_1 (mm)	x_2 (g/mm^3)	x_3 (mm)	MOE (GPa)	MOR (MPa)	SS (MPa)	
1*	16.10	1.01	7.00	20.84	180.00	19.00	0.852
2	16.08	1.01	7.00	20.86	180.00	18.96	0.852
3	16.05	1.00	7.00	20.90	180.00	18.91	0.852
4	15.97	1.00	7.00	21.00	180.00	18.76	0.851
5	15.61	1.01	7.00	21.00	177.94	19.00	0.851
6	15.42	0.99	7.00	21.23	177.85	18.61	0.848
7	16.29	1.01	6.99	20.65	180.00	19.18	0.846
8	15.53	1.02	7.00	20.86	176.67	19.32	0.841
9	16.73	1.03	7.00	20.21	180.00	19.68	0.830
10	14.34	0.97	7.00	21.72	172.64	18.09	0.830
11	21.14	1.01	7.00	19.51	191.34	19.00	0.805
12	27.35	0.99	7.00	18.82	180.00	19.02	0.777
13	28.82	0.93	4.00	20.72	176.70	14.38	0.698
14	28.93	0.93	4.00	20.65	177.06	14.40	0.698
15	28.69	0.93	4.00	20.80	176.47	14.33	0.698
16	28.98	0.93	4.00	20.63	177.42	14.39	0.698
17	28.68	0.95	4.00	20.65	173.95	14.60	0.696

*indicates selected design

Optimal parameters for obtaining the maximum object value set were determined to be control population of 30, aberration ratio of 0.1, number of iterations of 80, and crossover probability of 0.2. The 180 E_b level superior products of bamboo scrimber standard required the lower limit values of BLVL to be 18 GPa for MOE, 160 MPa for MOR, and 12 MPa for SS. The upper limit values for the 180E_b were 26 GPa for MOE, 180 MPa for MOR, and 19 MPa for SS. The optimized global Pareto solutions for group 17 were obtained using iterative computation with the initial values of x_1, x_2, and x_3 equal to 17 mm, 1.06 g/cm^3, and 6.0 mm (Table 6). The initial parameters of the mechanical properties of the manufactured BLVL were a MOE of 16.4 GPa, MOR of 175.6 MPa, and SS of 14.7 MPa.

The 17 groups of Pareto solutions were higher than the special requirements of the 180 E_b level superior products of bamboo scrimber standard (Table 6). In addition, all sets of 17 Pareto solutions had increased at different degrees when compared with the experimental results of BLVL processed with initial parameters. The first group selected by the computer system had the best solutions with a lap-joint length of 16.1 mm, board density of 1.01 g/cm^3, and veneer thickness of 7 mm, which resulted in strong response values. The desirability factor for group 1 was 0.852, which indicates that the experimental design possessed a strong feasibility (Fig. 8). Mechanical tests and aging treatment experimental results showed that the long-size BLVL possessed good strength, stiffness, and durability (Chen *et al*. 2016). The BLVL with a length of 14.1 m was developed based on the laminated lap-joint lengthening technology (Fig. 5).

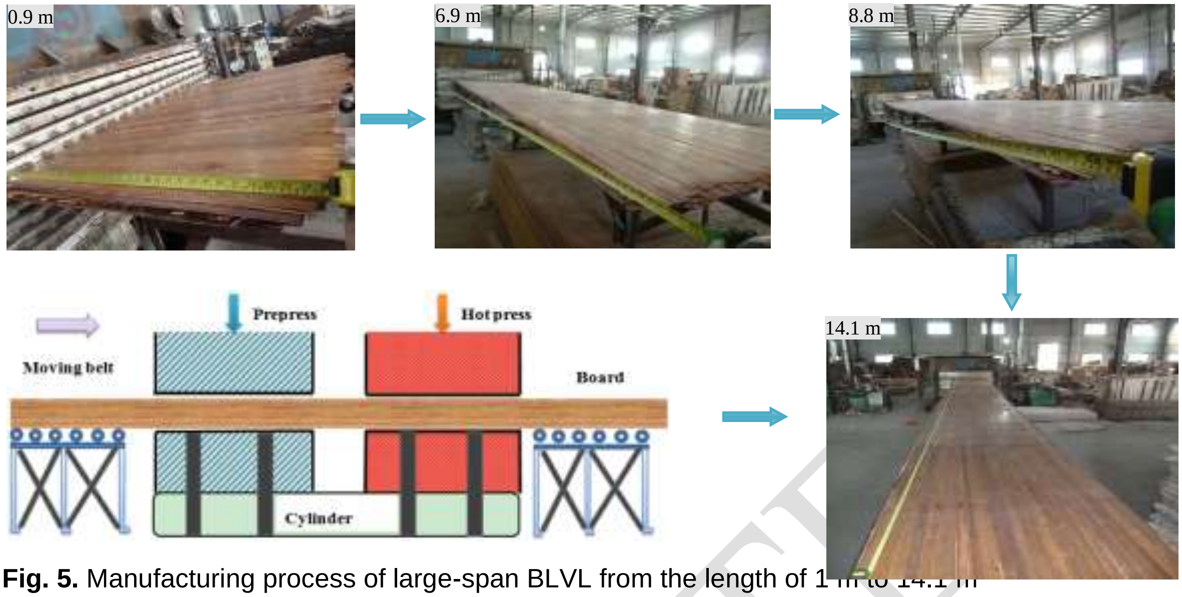


Fig. 5. Manufacturing process of large-span BLVL from the length of 1 m to 14.1 m

CONCLUSIONS

1. The 3-D response surface contour plots were developed in order to better understand the interactive effect of the independent variables on the mechanical properties of BLVL. A significant interactive effect between lap-joint length (x_1) and veneer thickness (x_3) on elastic modulus (MOE) was observed. Similarly, modulus of rupture (MOR) and shearing strength (SS) were significantly affected by the board density (x_2) and veneer thickness (x_3).
2. Seventeen optimum Pareto solutions for determining the maximum mechanical properties of BLVL were obtained using a genetic algorithms method. This method determined that the best process combination was a lap-joint length (x_1) of 16.10 mm, board density (x_2) of 1.01 g/cm^3, and veneer thickness (x_3) of 7.00 mm.
3. The efficiency of Box-Behnken design and response surface methodology for modeling was able to optimize the fabrication of engineered bamboo-based materials, in an economical way that maximized the process parameters in the least amount of experiments as possible.

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