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Original Article

Optimization of L-shaped Corner Dowel Joint in Modified Poplar using Finite Element Analysis with Taguchi Method[1]

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ABSTRACT

Modified poplar has emerged as a potential raw material for furniture production. Lack of specific modified poplar strength information; however, restricts applications in the furniture industry especially as related to strength in corner-joints. Optimization of strength in L-shaped corner dowel modified poplar joints under compression loads utilizing finite element analysis (FEA) by Taguchi method with the focus of this study. Four experiment factors (*i.e., Structure Style, Tenon Length, Tenon Diameter, and Tenon Gap*), each at three levels, were conducted by adopting a L_9-3^4 Taguchi orthodoxy array (OA) to determine the optimal combination of factors and levels for the von Mises stress utilizing ANSYS software. Results of Signal-to-Noise ratio (S/N) analysis and the analysis of variance (ANOVA) revealed the optimal L-shaped corner dowel joint in modified poplar is 45° Bevel Butt in structure style, 24 mm in tenon length, 6 mm in tenon diameter, and 20 mm in tenon gap. Tenon length and tenon gap are determined to be significant design factors for affecting von Mises Stress. Confirmation tests with optimal levels and experimental test indicated the predicted optimal condition is comparable to the actual experimental optimal condition.

Keywords : finite element analysis, modified poplar, furniture joint, Taguchi method

1. INTRODUCTION

High quality wood resources are increasingly scarce as long-term population growth has impacted forestlands. The poplar is a vital fast-growing wood, widely utilized as an environmentally friendly and sustainable raw material for paper and plywood as it features acceptable strength and working properties including light weight, rapidly-growing, low density, simple processing, and soft texture. Compared to other traditional solid wood species utilized in furniture; however, disadvantages of poplar related to strength, stiffness, physical and mechanical properties, and surface appearance have limited its broader application in furniture production.

In order to solve the various defects of fast-growing poplar and enlarge its application scope, poplar wood is commonly modified to

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resolve various defects utilizing chemical, physical, and biological methods to improve dimensional stability against moisture and bio-deterioration, mechanical properties, and weathering resistance (Hill *et al*., 2011). Evaluation of furniture structure performance quality assesses these properties. Furniture corner-joints are deemed the weakest points against heavy weights in furniture construction technology (Cetin Yerlikaya, 2012), thus improved design for strengthening methods in modified poplar furniture corner joints is vital. The L-shaped corner-joint is a significant furniture structure type manufactured and employed for connecting legs, transoms, and handrails. A joint style typically utilized in the L-shaped corner-joint is referred to as a butt joint with dowels with the dowel as a solid cylindrical rod typically composed of wood. The dowel joint is employed in numerous, diverse applications in furniture structure including structural reinforcements in cabinet making and furniture shelf supports and applies aligned bored holes in both receiving objects for insertion of a conjoining dowel pin. Applications are either currently minimal or may not exist for the L-shaped dowel furniture corner joint composed of modified poplar.

Several studies of L-shaped furniture corner-joint consisting of hard wood or wood-based panel have been conducted experimentally and by numerical simulations including the ANSYS Finite Element analysis. The joints were examined for diagonal tension and compression (Tankut and Tankut, 2009; 2010). Diagonal tensile strength of the L-shaped corner-joint was reported to be greater than the diagonal compressive strength. Atar *et al*. (2009) investigated tensile and compressive performance of corner-joints constructed with solid wood biscuits for case furniture. Best performance was achieved with melamine-coated fiberboards and Desmodur Vinil Trie Ketonol Acetate (DVTKA) adhesive. Studies conducted on Dowel-welded L-shaped joints (Segovia *et al*., 2010) indicated considerable difference only in mortise and tenon L-shaped joints between tension and compression test results on the same L-joint, with such joints yielding higher strength in compression than in tension. Tankut, A. N. *et al*. (2005) discovered that rectangular end mortise and tenons are approximately 15% stronger than both round end mortise and tenons and rectangular end tenons designed to fit into round end mortise joints while joint geometry significantly affects strength of those particular joints. Oktaee *et al*. (2014) reported that optimum results of simple and haunched mortise and tenon furniture joints under tension and compression loads were obtained with joints constructed utilizing 10 mm thick tenons that were 37.5 mm wide by 30 mm long. Tenon length was revealed to exert a superior effect on joint capacity while tenon width was found to exert a much less significant effect. Dalvand *et al*. (2014) investigated the bending moment resistance under diagonal compression load of corner doweled joints with plywood members. Experimental results indicated that bending moment resistance under diagonal compressive load was increased by increasing the dowel’s depth of penetration. Joints constructed with dowels of beech wood featured higher resistance than dowels of hornbeam wood.

Finite Element method is widely applied in biomechanics and bioengineering to determine the stresses and strains in complicated mechanical systems (Dar *et al.*, 2002). Finite Element analysis (FEA) is proven to assist in identification of areas prone to weakness and failure and researchers have demonstrated that FEA is an effective technique for analyzing furniture construction (Eckelman *et al.*, 1984; Cai *et al.*, 1993; Smardzewski, 1998; Colakoglu *et al.*, 2012).

Studies on L-shaped furniture corner- joint utilizing the Finite Element method often focus on the enhancement of strength and stiffness by enlarging furniture components and parts. Investigation of the optimal methods has improved configuration properties; however, an increase in the cost of materials and variance of structure performance characteristics has produced a setback. Efficient control of design factors utilizing an appropriate optimization method, such as the Taguchi Method, is critical during corner joint furniture manufacturing.

Taguchi method was developed by Taguchi and Konishi (Taguchi *et al.*, 1987) and has been widely applied in engineering to optimize performance characteristics within a combination of design parameters and in design of quality systems. The method has been proven as a simple and effective solution for experimental design (Taguchi *et al.*, 1987; Taguchi, 1990; Ross, 1996). An orthogonal array (OA) with a minimum set of test data was applied in the Taguchi Method application to also reduce the time and cost. The method typically applies loss function to measure the performance characteristic deviation from the target value. Loss function is further transformed into a Signal-to-Noise ratio (S/N) to determine the quality of characteristics that are insensitive to noise factors. The combination of factor level with the higher S/N ratio indicates a better performance characteristic and the design project consistent with the highest S/N ratio consistently yields optimal quality characteristics with minimum variance. Signal-to-Noise ratio may be categorized into three types for the Taguchi Method: 1) the lower the better; 2) the higher the better; and 3) the more nominal the better (Gu *et al.*, 2014; Wu *et al.*, 2000). The S/N ratio featuring 1) the lower the better characteristic, may be expressed as:

$$\mathrm{S/N} = -10\lg\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \cdots\cdots\cdots\cdots\cdots (1)$$

The S/N ratio featuring 2) the higher the better characteristic, may be expressed as:

$$\mathrm{S/N} = -10\lg\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \cdots\cdots\cdots\cdots\cdots (2)$$

The S/N ratio featuring 3) the more nominal the better characteristic, may be expressed as:

$$\mathrm{S/N} = -10\lg\left(\frac{1}{ns}\sum_{i=1}^{n} y_i^2\right) \cdots\cdots\cdots\cdots\cdots (3)$$

Table 1. Physical and Mechanical Properties of Modified Poplar utilized in FEM

Density (g/cm³)	Moisture content (%)	Bending strength (MPa)	Modulus of rigidity (MPa)			Modulus of elasticity (MPa)			Poisson's ratio		
ρ	MC	MOR	G_{LR}	G_{LT}	G_{RT}	E_L	E_R	E_T	μ_{LR}	μ_{LT}	μ_{RT}
0.56	7.6	115.8	1355	75	120	3397	252	253	0.28	0.67	0.04

*L, R and T are the longitudinal, radial and tangential directions of wood

Where y_i is the ith experiment at the test, n is the total number of trials in the test, and s is the standard deviation of y_i.

The goal of FEA utilizing ANSYS software in this study is to optimize design factor levels to obtain the lowest von Mises stress in the weakest point of L-shaped corner dowel joint in modified poplar. The lower the von Mises stress is, the safer the L-shaped corner-joint is, thus the S/N ratio for von Mises stress with the lower the better characteristic equation (Eq.(3)) was chosen to obtain an optimal design parameter and factor of L-shaped corner dowel joint in modified poplar. Analysis of variance (ANOVA) was then performed to identify the significant contribution of each design factor to the variability in product performance (Gijo *et al.*, 2010). The most significant design factor effecting structure strength through ANOVA will be optimized in the Taguchi Method. A confirmation test may then be conducted to verify optimal design factors obtained from the parameter design. If the S/N ratio obtained in the optimal set is similar to predicted values with the experimental results, the additive model utilized in L_9 (3^4) OA is assumed to be the actual approximation model.

The effect of structure design factors on the von Mises stress of L-shaped corner dowel joints in modified poplar was investigated in this study utilizing Finite Element Analysis and the Taguchi method to optimize the factor combination of furniture structure and to reduce cost while strengthening modified poplar furniture structure to achieve a more robust response to external disturbance factors.

2. MATERIALS and METHODS

The modified poplar (*populous euromericana* Cv.) samples in this study were obtained from Beijing, China and featured moisture content of approximately 7.6% with density of 0.56 g/cm^3. In this study, fast-growing poplar was modified with urea-formaldehyde prepolymer, which was synthesized in the laboratory. The physical and mechanical properties tests were conducted in accordance with GB/T 15777-1995 and GB/T 1928-2009 of Technical Institute of Physics and Chemistry, CAS. The physical and mechanical properties of modified poplar utilized for the Finite Element Analysis (FEA) were tested and are displayed in Table 1. Test equipment included: SANS CMT5000 MTS series microcomputer control electronic universal testing machine and the CryoLab system at temperature (4.2 K - 200 K).

Two types of numerical models in 40 mm ×

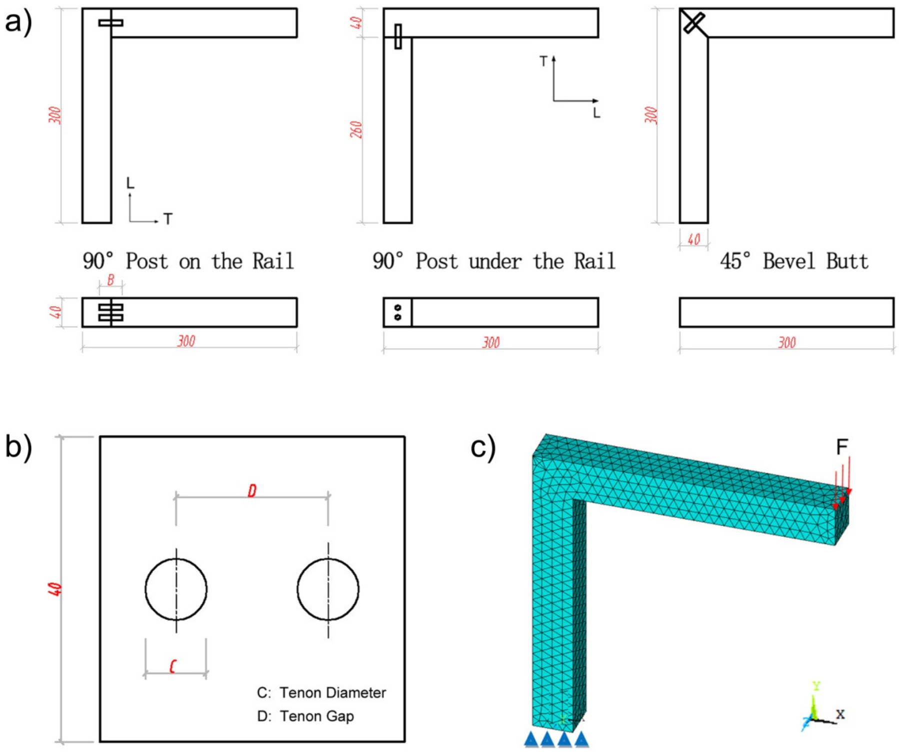

Fig. 1. Numerical Models: a) Size Sketch of Modified Poplar L-shaped Corner dowel Joint with Three Different Structure Styles; b) Size Sketch of Tenon Diameter and Tenon Gap; c) Size Sketch of Load and Constraint.

40 mm × 300 mm (radial × tangential × longitudinal) and 40 mm × 40 mm × 260 mm (radial × tangential × longitudinal) dimensions of L-shaped corner wooden dowel joint were constructed with three different joint styles (90° Post on the Rail, 90° Post under the Rail, 45° Bevel Butt) in the PROE 5.0 software (Beijing, Shuohe Technology Co., Ltd.) (Fig. 1a). Each test sample consists of the two elements, post and rail. Modified poplar wood dowels were employed to connect two portions of L-shaped corners. The joint was simplified to benefit analysis time by utilizing an interference fit joint without glue. Hole diameter was nearly equal to the tenon diameter for the joints without glue and the hole depth was approximately equal to half of the tenon length. Dowels were drilled to center sections of post and rail (Fig. 1b) with the tenon gap as the distance between the two dowels axes.

Simulation analysis of L-shaped corner wooden dowel joint in modified poplar was conducted utilizing ANSYS 10.0 software (China, Aonesoft Inc). The Finite Element model, according to the previous researches, was built with ANSYS 8 node 185 element type and meshed in 8 mm wide triangle element. Material properties in Table 1 were defined in

Table 2. Factors and Values at Different Levels

Factor / Leve 1	Level 1	Level 2	Level 3
Structure Style	90° Post on the Rail	90° Post under the Rail	45° Bevel Butt
Tenon Length	24 mm	32 mm	40 mm
Tenon Diameter	6 mm	8 mm	10 mm
Tenon Gap	10 mm	15 mm	20 mm

Table 3. L_9 (3^4) Orthogonal Array Utilized in the Experiment

Factors / Trial No.	(A)	(B)	(C)	(D)	Von Mises Stress (MPa)	S/N (dB)
1	90° Post on the Rail (1)	24 (1)	6 (1)	10 (1)	67.045	-36.53
2	90° Post on the Rail (1)	32 (2)	8 (2)	15 (2)	73.487	-37.32
3	90° Post on the Rail (1)	40 (3)	10 (3)	20 (3)	66.055	-36.40
4	90° Post under the Rail (2)	24 (1)	8 (2)	20 (3)	46.161	-33.29
5	90° Post under the Rail (2)	32 (2)	10 (3)	10 (1)	172.606	-44.74
6	90° Post under the Rail (2)	40 (3)	6 (1)	15 (2)	50.734	-34.11
7	45° Bevel Butt (3)	24 (1)	10 (3)	15 (2)	54.048	-34.66
8	45° Bevel Butt (3)	32 (2)	6 (1)	20 (3)	55.038	-34.81
9	45° Bevel Butt (3)	40 (3)	8 (2)	10 (1)	62.338	-35.90

Total mean of Von Mises Stress = 71.946

Total mean of S/N = -36.416

Preprocessor Element Type, for analysis of the von Mises stress of the corner-joint, to simulate the orthotropic characteristic of wood in three perpendicular directions. External load value on the corner-joint was determined during the experiments from actual usage, ergonomic factors, and the furniture mechanics performance test of the China national standard (GB/T 10357.2-2013). Degree of freedom UX, UY, and UZ at the post bottom was totally constrained and the vertical static load (1500 N) along the Y axis direction was applied to the end of middle node in the rail as displayed in (Fig. 1c).

Analysis of the selected design factors, including values of the von Mises stress, allowed the deviation level to be calculated to identify significant changing factors for the experiment. The full experimental design, with four factors and three levels on each, requires $3^4 = 81$ possible combinations of tests. Conducting this excessive number of experiments for all combinations is impractical, thus the Taguchi method employs an orthogonal array (OA) to examine quality properties by reducing the number of experiments. Structure style, tenon length, tenon diameter, and tenon gap were selected as four controllable design factors, each at three levels, in this study (Table 2). L_9 (3^4) Taguchi OA (Table 3) was then selected to study the four structural design factors of L-shaped corner wooden modified poplar dowel joint. Each trial

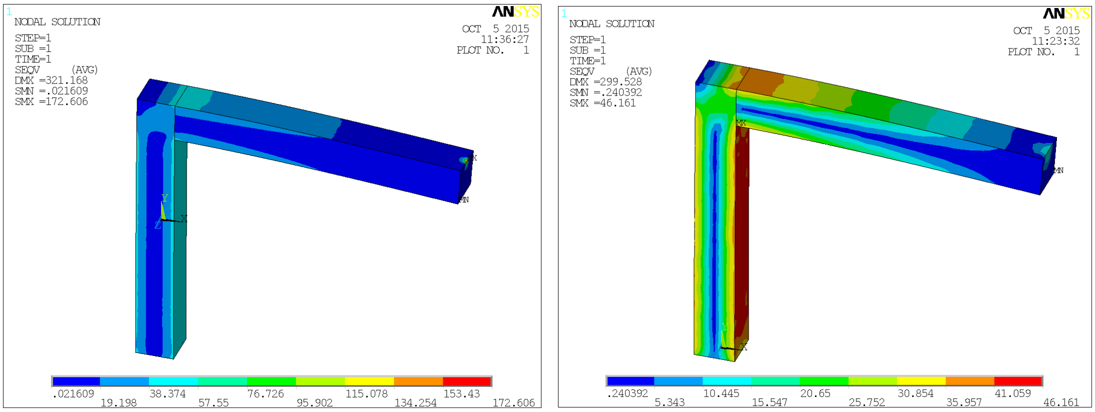

Fig. 2. Analysis of the Finite Element Software: a) Von Mises Stress of Modified poplar L-shaped Corner Dowel Joint (No. 5); b) Von Mises Stress of Modified Poplar L-shaped Corner Dowel Joint (No. 4).

was repeated 5 times to gain average.

3. RESULTS and DISCUSSION

3.1. Analysis of the Finite Element Software

Significant effects of varying design factors appear on the von Mises stress according to the ANSYS software analytical results (Table 3). From Fig. 2a) and 2b) we learn that the highest von Mises stress (172.606 MPa) of the modified poplar L-shaped corner dowel joint was obtained in No. 5 trial, while the lowest (46.161 Mpa) was acquired in No. 4 trial. Maximum von Mises joints stress in the No. 5 trial was approximately 273.9 % higher than joints stress in the No. 4 trial, substantially below the bending strength value of Modified poplar. The structure in the No. 5 trial gets more possibilities of damage in reality. Furthermore, the simulation we obtained clearly showed that von Mises stress reached the highest values at the place where the loading force was applied and tenon components in trial No. 5, while for the joint in trial No. 4, maximum Von Mises stress value was obtained in the joint of the horizontal rail and vertical post for the joint. Von Mises stress in trial No. 4 additionally features significantly more gradually varied distribution than in trial No. 5. In addition, the total mean of von Mises stress and S/N ratio for the nine experiments is also calculated and listed in Table 3.

3.2. Analysis of the S/N ratio

Results of the robustness for von Mises stress obtained from the Finite element analysis for each trial were statistically analyzed in this study utilizing Signal-to-Noise ratio (S/N) equations based on the lower the better characteristic displayed in Eq.(1). The S/N ratio for von Mises stress of structure style, tenon length, te-

Table 4. Mean S/N Ratio for Von Mises Stress at Each Level

Symbol	Design factor	Level 1	Level 2	Level 3	Max-min
(A)	Structure Style	-36.75	-37.38	-35.12	2.26
(B)	Tenon Length	-34.83	-38.96	-35.47	4.13
(C)	Tenon Diameter	-35.15	-35.50	-38.60	3.45
(D)	Tenon Gap	-39.06	-35.36	-34.83	4.23

Total mean S/N ratio = -36.42

non diameter, and tenon gap for all nine trials are summarized in Table 3.

The largest S/N ratio is approximately -33.29 dB in the No. 4 trial, while the lowest S/N ratio is nearly -44.74 dB in the No. 5 trial. The mean S/N ratio of 9 trials is approximately -36.416 dB.

Experimental design for the von Mises stress and S/N ratio is orthogonal, thus it is possible to separate each design factor effect at different levels. The mean S/N ratios for structure style at three different levels, for example, may be calculated by averaging the S/N ratios for experiments 1 to 3, 4 to 6, 7 to 9, respectively displayed in Eqs.(4), (5) and (6).

$$mA1=\frac{1}{3}(\eta_1+\eta_2+\eta_3) \cdots\cdots\cdots\cdots (4)$$

$$mA2=\frac{1}{3}(\eta_4+\eta_5+\eta_6) \cdots\cdots\cdots\cdots (5)$$

$$mA3=\frac{1}{3}(\eta_7+\eta_8+\eta_9) \cdots\cdots\cdots\cdots (6)$$

Based on the equation above, the η(dB) response table for each design factor level (structure style, tenon length, tenon diameter, and tenon gap) is created in an integrated manner with the η(dB) response values for von Mises stress at each level displayed in Table 4 and a total mean S/N ratio of approximately -36.42 dB.

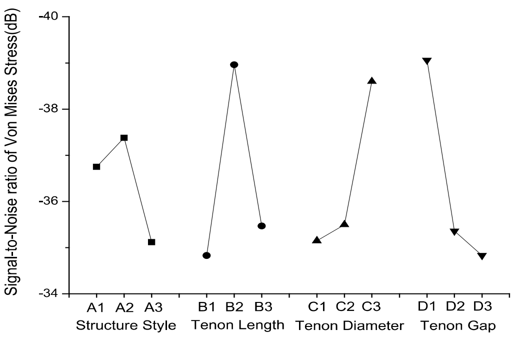

Fig. 3. Analysis of Means (ANOM) of Signal-to-Noise Ratio for Von Mises stress.

Results for the ANOM of the S/N ratio for von Mises stress at each level are illustrated in Fig. 3 with the conclusion that any alteration in the four design factors would manifest as either improvement or degradation of the von Mises stress. The difference among ratio values is minimal for the three levels of factor A with the S/N ratio value of A3 as the largest. The S/N ratio value initially decreases with design factors increase for the three levels of factor A and B, followed by an increasing trend with further increases in design factors. The S/N ratio value decreases with tenon diameter de-

Table 5. ANOVA of S/N Ratio for von Mises Stress

Factor	Sum of Squares (SS)	Degree of Freedom (DOF)	Mean of Squares (MS)	Variance Ratio (F-Value)	Percentage (%)
(A)	2.71	2	1.36	1.00	8.92%
(B)	9.88	2	4.94	3.65	32.51%
(C)	7.21	2	3.61	2.66	23.72%
(D)	10.59	2	5.30	3.91	34.85%
Error	0	0	0		
Total	30.39	8			
(Error)	(2.71)	(2)	(1.36)		

crease for the three levels of factor C with ratio value of C1 as the largest. The S/N ratio value increases with tenon gap increase for the three levels of factor D with ratio value of D3 as the largest. Structure design factors with the highest S/N ratio indicate a lower value of von Mises Stress thus the optimal set of L-shaped corner dowel joints for von Mises stress is acknowledged as A3, B1, C1, and D3, indicating that structure style is 45° bevel butt, tenon length is 24 mm, tenon diameter is 6 mm and tenon gap is 20 mm.

3.3. Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) purpose is identification of each factor's contribution to performance variability of the product (Gijo *et al.*, 2010).

Sum of Square (SS) from the total mean S/N ratio η_m may first be calculated as Eq.(7):

$$\mathrm{SS} = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \quad \cdots\cdots\cdots\cdots (7)$$

Where n is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the i-th experiment.

Each design factor features the mean of square (MS) calculated as:

$$\mathrm{MS} = \frac{SS}{DOF} \quad \cdots\cdots\cdots\cdots (8)$$

Where DOF represents the degree of freedom related to congruency in design factors. As a result of Freedom is non-existent in this study as a result of the orthostichous orthogonal array utilized in estimating error variation. Factors A features lower squares and is selected with the “Capture Method” to estimate average error variation in the analysis of variance. Variance ratio (F-value) is obtained from the ratio of mean square (MS) to mean square error (SSe) and may be interpreted as greater structure performance characteristics effects are due to major design factors change. The F-value is traditionally applied to determine the significance of each factor and the contribution percentage (%) is defined as the significance rate of design factors on the von Mises stress.

Table 5 displays the ANOVA of S/N ratio for von Mises stress revealing that contribution percentage for Factor A (structure style) is the

Table 6. Result of Confirmation Test for optimal precept

Quality characteristic	Initial condition	Optimal condition		Improvement	IR
	ANSYS	Prediction	ANSYS		
von Mises stress (MPa)	56.571	-	49.385	7.19	12.70%
S/N ratio (dB)	-35.05	-31.97	-33.87	1.18	3.37%

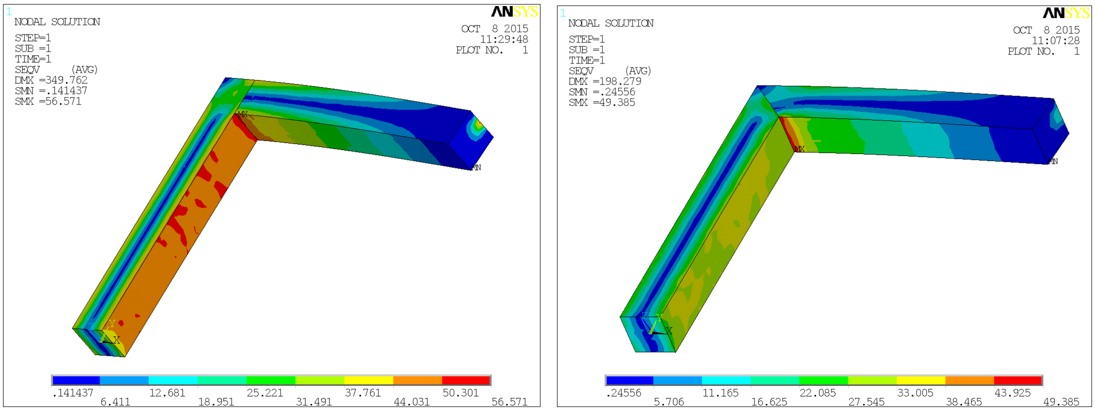

Fig. 4. a) Initial Condition of Von Mises Stress; b) Optimal Condition of Von Mises Stress.

lowest at 8.92% while contribution percentages for Factor D (tenon gap) is the highest at 34.85%. Factor D (tenon gap) then was concluded to exert the most significant effect on the von Mises stress in the focus area while the effect of Factor A (structure style) is negligible. Typically design factors changes exert a significant effect on structure quality characteristics when F > 4. The analysis of variance reveals that Factor B (tenon length) and Factor C (tenon gap) are the significant design factors for affecting von Mises stress. Variance ratio for Factor A is no more than 1; however, indicating structure style exerts a minimal effect on structure performance characteristics for von Mises stress.

3.4. Confirmation Test

Confirmation test is the final and most crucial step of the Taguchi method and is applied to verifying whether optimal results obtained in the experiment is expected to improve. Optimal design factors listed in Table 6 were applied to conduct the test.

Fig. 4a) and 4b) present the simulative experimental results of initial condition and optimal condition for von Mises stress utilizing finite element software analysis. The highest von Mises stress (56.571 MPa) of L-shaped corner dowel joint in modified poplar appears in the top connection portion of the corner. The post part of L-shaped corner appears large area of stress concentration which leads to material damage easily (Fig. 4a). Fig. 4b reveals that Von Mises stress (49.385 MPa) is located in the bottom of the corner commissure, substantially below the value of bending strength of modified poplar. The decrement of the von Mises stress from initial joint structure to the optimal joint structure is 7.186 dB while the improvement of S/N ratio for von Mises stress is about 1.18 dB. Improvement ratio (IR) is applied to calculate the proportional ratio of Taguchi optimization results compared to the initial condition presented as Eq.(9).

$$\mathrm{IR} = \frac{P_{initial} - P_{optimal}}{P_{optimal}} \times 100\% \quad \cdots\cdots\cdots\cdots\cdots (9)$$

Improvement ratio results are displayed in Table 6, indicating that IR for the von Mises stress and the S/N ratio from the initial condition to the optimal condition is approximately 12.70% and 3.37%, respectively. The improvement ratio result for the von Mises stress is also much higher from mean value of 9 trials to the optimal condition which is almost one third. The Taguchi method utilizing FEM, as revealed in the above result, may not only obviously reduce the von Mises stress to improve strength of the L-shaped corner dowel joint, but also effectively increase the S/N ratio to optimize robustness of structure performance characteristics. The optimal condition owns better strength and robustness in L-shaped corner structure in modified poplar.

The confirmation experiment purpose in this study is to validate optimal conditions (A3, B1, C1, D3) suggested by the experiment as corresponding with the predicted values calculated by Eq.(10):

$$\eta_{\mathrm{opt}} = \eta_{\mathrm{m}} + \sum_{i=1}^{o} (\eta_{\mathrm{i}} - \eta_{\mathrm{m}}) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (10)$$

Where η_{m} is the total mean S/N ratio, η_{i} is the mean S/N ratio at the optimal level, and o is the number of main design parameters affecting the quality characteristic. The S/N ratio for predicted optimal condition is calculated as:

$$\begin{aligned} \eta_{\mathrm{opt}} &= \mathrm{m} + (\mathrm{m}_{\mathrm{Ai}} - \mathrm{m}) + (\mathrm{m}_{\mathrm{Bi}} - \mathrm{m}) + \\ &\quad (\mathrm{m}_{\mathrm{Ci}} - \mathrm{m}) + (\mathrm{m}_{\mathrm{Di}} - \mathrm{m}) = \mathrm{m}_{\mathrm{A3}} + \\ &\quad \mathrm{m}_{\mathrm{B1}} + \mathrm{m}_{\mathrm{C1}} + \mathrm{m}_{\mathrm{D3}} - 3\mathrm{m} \qquad \cdots\cdots (11) \\ &= -35.12 - 34.83 - 35.15 - 34.83 + 3 \\ &\quad \times 36.42 = -30.67\mathrm{dB} \end{aligned}$$

The predicted optimal condition; however, is commonly calculated utilizing the η-value with high percentage (%) to avoid producing higher improvement of predicted optimal condition than actual experimental optimization, leading to high-end prediction. Factor B, factor C and factor D are then chosen to predict the S/N ratio of optimal condition with the S/N ratio for predicted optimal condition calculated as:

$$\begin{aligned} \eta_{\mathrm{opt}} &= \mathrm{m} + (\mathrm{m}_{\mathrm{B1}} - \mathrm{m}) + (\mathrm{m}_{\mathrm{C1}} - \mathrm{m}) + \\ &\quad (\mathrm{m}_{\mathrm{D3}} - \mathrm{m}) = \mathrm{m}_{\mathrm{B1}} + \mathrm{m}_{\mathrm{C1}} + \mathrm{m}_{\mathrm{D3}} - 2\mathrm{m} \quad \cdots\cdots (12) \\ &= -34.83 - 35.15 - 34.83 + 2 \times 36.42 \\ &= -31.97\mathrm{dB} \end{aligned}$$

Table 7. Comparison of experimental testing with numerical simulation

Experiment test			ANSYS simulation		
Quality characteristic	Initial condition	Optimal condition	Quality characteristic	Initial condition	Optimal condition
Ultimate load P_{max} (N)	1220	1450	Von Mises stress (MPa)	56.571	49.385

Predicted value for the S/N ratio is -31.97 dB and the experimental result by Finite Element Analysis for S/N ratio is -33.87 dB. Results of the predicted optimal condition approximately align with the actual experimental optimal condition indicating the additive model applied in the Taguchi orthogonal test for prediction closely approximates the practical model. The orthogonal test and the design factors analyzed in this study then are reasonable and effective.

Results obtained from the ANSYS Finite Element Simulation Analysis were also compared with the results obtained from the experimental test (Table 7). The ultimate load in the L-shaped corner dowel Joint under optimal conditions was greater than under initial conditions indicating the optimal structure of the modified poplar L-shaped corner joint yields superior strength and robustness over initial conditions.

From the above experiment we can come to the conclusion that the finite element method with the Taguchi Method was determined to be a general and suitable method when exact numerical calculations are employed to check loads imposed on structures and may be utilized as a suitable, non-destructive technique for calculating structural strength at various times.

4. CONCLUSION

1) Overall, an optimized joint based on FEM simulations with Taguchi method for the L-shaped corner dowel in modified poplar, consisting of structure style (A) of 45° Bevel Butt, tenon length (B) of 24 mm, tenon diameter (C) of 6 mm, and tenon gap (D) of 20 mm, was partly predicted to show a better robustness compared to the initial test sample. As a result of the ANOVA, tenon gap (D) and tenon length (B) were identified as the important factors for improving strength and robustness of the modified poplar L-shaped corner dowel joint.
2) Confirmation test results validate the effectiveness and efficiency of the Taguchi Method utilizing FEA for optimizing the structure design factor with multiple performance characteristics. The orthogonal test and the design factors analyzed in this study then were determined to be mainly reasonable and effective.
3) Finite element analysis with Taguchi method were revealed in the study as effective in applications to optimize the combination of structure design factors to attain maximum structure performance and minimize quality variation of L-shaped corner dowel

joints in modified poplar, contributing to cost savings and time efficiency compared to traditional methodologies. The optimization approach for structure strength and robustness of L-shaped corner dowel joint in modified poplar utilizing the Finite Element and Taguchi orthogonal experimental method may be applied in the future to additional fast-growing wood and classical corner joints in furniture structure.

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REFERENCES

Atar, M., Ozcifci, A., Altinok, M., Celiket, U. 2009. Determination of diagonal compression and tension performance for case furniture corner joints constructed with wood biscuits. Material & Design 30(3): 665～670.

Cai, L.P., Wang, F.H. 1993. Influence of the stiffness of corner joint on case furniture deflection. Holz als Roh-und Werkstoff 51(6): 406～408.

Cetin, Y.N. 2012. Effects of glass-fiber composite, dowel, and minifix fasteners on the failure load of corner joints in particleboard case-type furniture. Material & Design 39: 63～71.

Colakoglu, M.H., Apay, A.C. 2012. Finite Element analysis of wooden chair strength in free drop. International Journal of Physical Sciences 7(7): 1105～1114.

Dalvand, M., Ebrahimi, G., Tajvidi, M., Layeghi, M. 2014. Bending moment resistance of dowel corner joints in case-type furniture under diagonal compression load. Journal of Forestry Research 25(4): 981～984.

Dar, F.H., Meakin, J. R., Aspden, R.M. 2002. Statistical methods in Finite Element analysis. Journal of Biomechanics 35(9): 1155～1161.

Eckelman, C.A., Rabiej, R. 1984. A comprehensive method of analysis of case furniture. Forest Products Journal 35(4): 62～68.

GB/T 15777-1995 (1995) Method for determination of the modulus of elasticity in compressive parallel to grain of wood. Chinese National Standard.

GB/T 1928-2009 (2009) General requirements for physical and mechanical tests of wood. Chinese National Standard, Beijing, China.

GB/T 10357.2-2013 (2013) Test of mechanical properties of furniture—Part 2: Stability of chairs and stools. Chinese National Standard, Beijing, China.

Gu, F., Hall, P., Miles, N.J., Ding, Q.W., Wu, T. 2014. Improvement of mechanical properties of recycled plastic blends via optimizing processing parameters using the Taguchi method and principal component analysis. Material & Design 62: 189～198.

Gijo, E.V., Scaria, J. 2010. Reducing rejection and rework by application of Six Sigma methodology in manufacturing process. International Journal of Six Sigma and Competitive Advantage 6(1/2): 77～90.

Hill, A.S., Callum, A.S. 2011. Wood Modification. Bioresources 6(2): 918～919.

Oktaee, J., Ebrahimi, G., Layeghi, M., Ghofrani, M., Eckelman, C.A. 2014. Bending moment capacity of simple and haunched mortise and tenon furniture joints under tension and compression loads. Turkish Journal of Agriculture and Forestry 38(2): 291～297.

Ross, P.J. 1996. Taguchi techniques for quality engineering New York: McGraw-Hill.

Segovia, C., Renaud, A., Pizzi, A. 2011. Performance of Dowel-Welded L-Joints for Wood Furniture. Journal of Adhesion Science and Technology 25(15): 1829～1837.

Smardzewski, J. 1998. Numerical analysis of furniture constructions. Wood Science and Technology 32(4): 273～286.

Tankut, A.N., Tankut, N. 2005. The effects of joint forms (shape) and dimensions on the strengths of mortise and tenon joints. Turkish Journal of Agriculture and Forestry 29(6): 493～498.

Tankut, A.N., Tankut, N. 2009. Investigations the effects of fastener, glue, and composite material types on the strength of corner joints in case-type furniture construction. Material & Design 30(10): 4175～4182.

Tankut, A.N., Tankut, N. 2010. Evaluation the effects of edge banding type and thickness on the strength of corner joints in case-type furniture construction. Material & Design 31(6): 2956～2963.

Taguchi, G., Konishi, S. 1987. Taguchi Methods Orthogonal Arrays and Linear Graphs: Tools for Quality Engineering. Dearborn, Michigan: American Supplier Institute.

Taguchi, G. 1990. Introduction to Quality Engineering, Asian Productivity, Tokyo, Japan.

Wu, Y., Wu, A. 2000. Taguchi methods for robust design. New York: The American Society of Mechanical Engineers.