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Research Article

Coefficient of Acceptability for Joints in Furniture Frame Analysis under Cyclic Loads

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Abstract

This study aimed to determine the coefficient of acceptability for furniture joints on chair frames. In doing so, three chair configurations made of soft maple and yellow poplar were defined. Chairs were subjected to a front-to-back cyclic load test until non-recoverable failure occurred. Ultimate failure loads for each chair frame were used to determine the moment capacity of critical joints. Likewise, according to American Library Association, acceptable light, medium and heavy-duty service loads were subjected to chairs in the structural analysis to obtain acceptable moment capacities of critical joints, using the stiffness method. Then, lines were drawn from the initial strength of the joint to the moment capacities of the joint at the load level imposed on the chair. Differentiating the slopes between lifeline and acceptable levels gave a coefficient of acceptability. This coefficient would provide insight into the serviceability and durability of joints and chair frames.

Keywords: Cyclic load, Chair frames, Round mortise and tenon joints, Acceptance level, Performance test.

1. Introduction

The rational design of furniture dictates that any member and joint could be designed if their moment capacities are known [1]. Besides, joint design is vital in the strength design of the furniture even though it is its last step [2]. Most of the failures on chairs are owing to failed or loose joints rather than members [3]. Reliability of the joints results in the reliability of the chair because the strength of the chair depends on the weakest joints [4]. Therefore, the initial strength of a joint and its moment under imposed load were taken into consideration in this study to estimate the coefficient of acceptability. This estimation should give insight into the serviceability of the chair frames` life.

The performance test of chairs is a realistic load model with cyclic loads to assess a typical utilization and mode of failure in their service. In initial life, a chair has full strength based on its member and joint design, but the initial strength will decrease in service due to fatigue. Therefore, it fails before it cannot reach its initial strength. The ratio between the static load capacity of a chair and stepwise cyclic load capacity is 56% [5]. In the case of constant cyclic load subjected to the chair, failure occurred at 20% and 30% of the initial strength [6,7]. On the contrary, to evaluate the cyclic load capacity of a chair, American Library Association (ALA) specifications is used. This specification sets acceptable light, medium and heavy-duty service loads according to the loading application [8]. However, benchmarking the load capacity of the structure with these load levels results in a pass/fail criterion.

Likos et al. [9] studied a relationship between static load and cyclic load capacity of chair frames and stated that the ratio between cyclic and static load was 2/3. In another study, the relationship between the cyclic load capacity of full-frame chairs and the static load capacity level of T- and L-shaped joints was studied to estimate the cyclic load capacity level of full-frame chairs from the static load level of joints [10]. In doing so, an equation was established from this approach, and the average difference between test results and estimated values of full-frame chairs was 13%. Kasal et al. [11] studied performance test results of chair frames made of different tenon sizes. In this study, the cyclic load capacity of full-frame joints was estimated by using the static load capacity of joints, and the average ratio between them was 1,04. Kılıç et al. [12] studied performance test results under cyclic load in the experiment and finite element analysis. The estimated test result was used to compare with the ALA specification. Kuşkun et al. [13] studied the cyclic load capacity level of the full-frame chair and resulted that larger tenon sizes provided a highly acceptable rate for chairs. These studies give an insight into whether a chair passes or fails the performance test. On the other hand, the acceptability rate should be an intermediate coefficient to estimate how much better quality a chair would acquire during service life.

In this study, acceptability coefficients for critical joints on chair frames were estimated by comparing the lifeline of the joints and their acceptable levels. In doing so, three chair frames with one, two, and three stretchers made of both soft maple and yellow poplar wood were defined. Front-to-back cyclic load tests were applied horizontally on chairs, and cyclic load capacity levels were obtained. By stiffness method, critical joints with the highest moment were considered. Then, differentiation between slopes of the initial strength-to-failure moment and initial strength-to-acceptable levels was used to estimate the coefficient of acceptability.

2. Material and Methods

2.1. Materials and Construction of Furniture Frames

In this study, soft maple (Acer macrophyllum) and yellow poplar (Liriodendron tulipifera) wood specimenswere used in furniture construction. All 1-m long boards were obtained from a local sawmill in Northern Indiana, USA. Table 1 indicates some mechanical properties of these wood species.

Table 1. Some mechanical properties of soft maple and yellow poplar [14]

Wood species	Specific gravity	Modulus of rupture (N/mm^2)	Modulus of elasticity (N/mm^2)	Compression parallel to grain (N/mm^2)	Shear parallel to grain (N/mm^2)	Tension perpendicular to grain (N/mm^2)
Sugar maple	0.48	74	10000	41.0	11.9	3.7
Yellow poplar	0.42	70	10900	38.2	8.7	3.7

All boards were conditioned at 7% moisture content at least one month and then subsequently machined to dimensions for each member given in Table 2. All components were sequentially numbered and taken from a material pool, and each furniture member was randomly selected from this material pool.

Table 2. Member sizes for chair frame

Member	Thickness (mm)	Width (mm)	Length (mm)
Front leg	38.10	38.10	431.80
Rear leg	38.10	38.10	863.60
Stretcher	22.22	22.22	431.80

Round tenons, 19.05 mm-diameter and 38.10 mm-long, were cut in the tenoning machine, and matching mortises were machined on the drill press with tolerances of 0.254 mm (Figure 1). Tolerances were such that a tenon could be inserted 2/3 of its length into a mortise without using force [15].

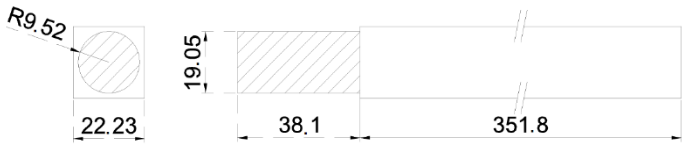


Figure 1. Configuration of the round mortise and tenon joints

40% solid content polyvinyl acetate (PVA) adhesive was used to coat the faces of the tenon and the mortise walls, and the full length of the tenon was inserted into the mortise and clamped in place. Specimens were clamped, remained at least 24 h and were stored in a conditioning room at 7% moisture content for at least one week before they were tested [16]. The side frame configurations of the chairs were given in Figure 2.

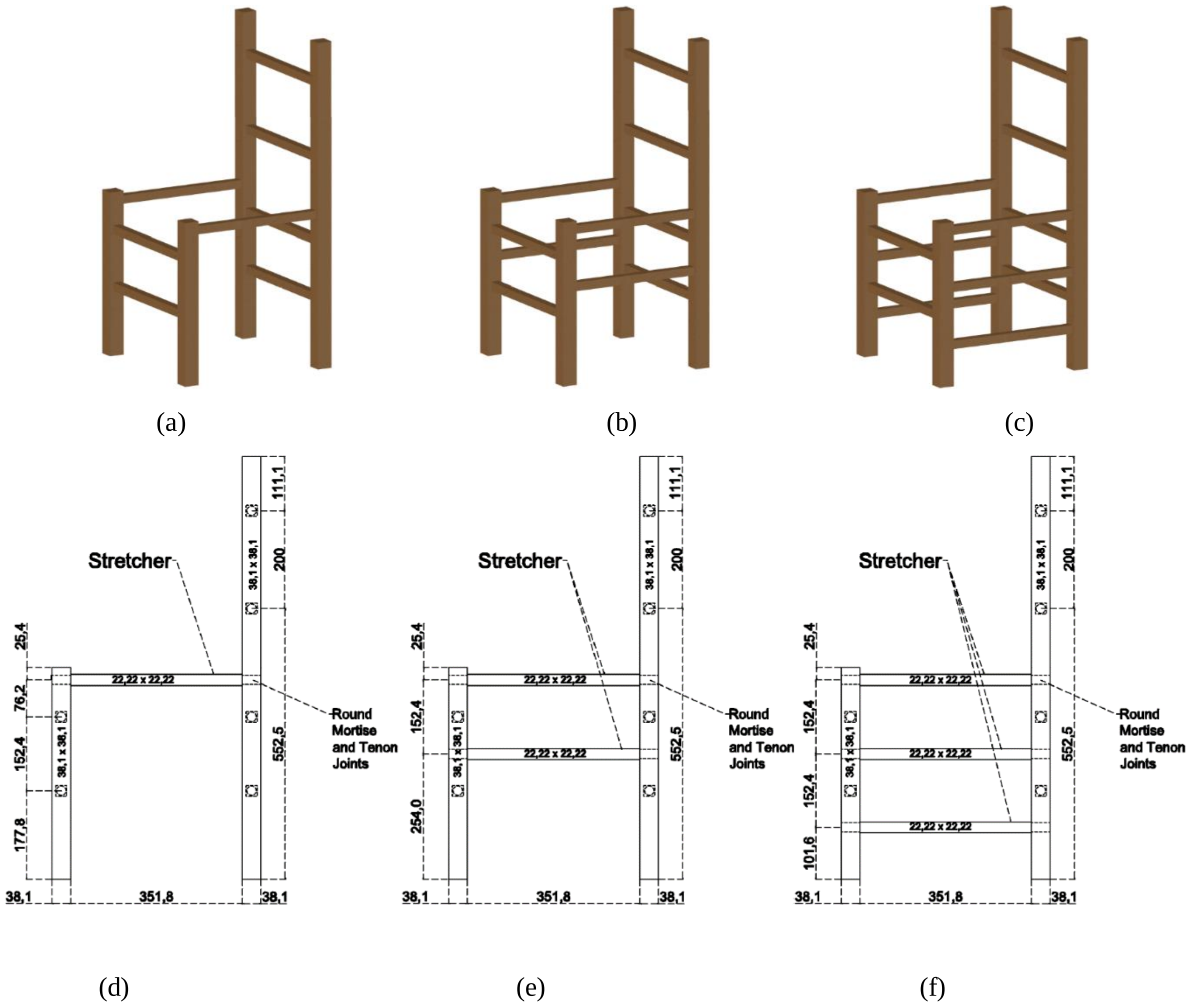


Figure 2. Configuration of the full-frame chair with a. one stretcher, b. two stretchers, and c. three stretchers, and dimensions and position of joints on side chair with d. one stretcher, e. two stretchers, and f. three stretchers

2.2. Performance Test of Chair Frames and Stiffness Method for Hyperstatic Frame Analysis

In the test procedure, a chair was mounted for the test shown in Figure 3. Reaction brackets were used to prevent chairs from sliding on the platform. A chain was passed over the front-to-back seat, connected to the load head on one end, and anchored to the platform on the other. In doing so, chairs were subjected to horizontal front-to-back load.

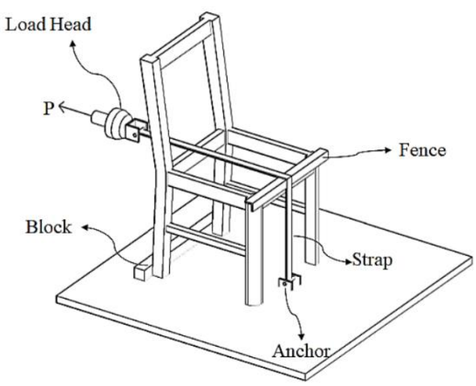


Figure 3. Configuration of the front-to-back cyclic load test set-up

Stepwise front-to-back cyclic load tests were imposed on the chair frames with an initial load of 222.50 N. Loads were applied on the chairs with a speed of 20 cycles/min. After 25000 cycles were completed, the load level was incremented to 111.25 N, and then the subsequent step started. Tests were continued until non-recoverable failure occurred or horizontal deflection exceeded 50 mm [8]. After the failure load level and cycle were obtained, the equation 1 was used to calculate the ultimate cyclic load level [17].

$$F_{C,ul} = (F_{C,fail} - F_i) + \left(F_i \times \frac{N_{C,fail}}{25000}\right) \quad (1)$$

where,

FC,ul: ultimate cyclic load level (N)
FC,fail: Cyclic failure load (N)
Fi: Incremental load (N)
NC,fail: Failure cycle.

In a structural analysis of the furniture frames, the degree of determinacy is significant to apply the structural analysis method. In the case of a side frame analysis, front and back legs were joined with a single member, rail, or stretcher. It is an isostatic structure (degree of determinacy is 0), so equilibrium equations can be used to get initial strength on joints. On the other hand, if one more stretcher is used in the side frame, the degree of determinacy is equal to 1, and the structure will be hyperstatic. Thus, equilibrium equations will not be enough in the structural analysis of the frame. Instead, the stiffness method is one of the intermediate procedures for the structural analysis of hyperstatic structures. The degree of determinacy is calculated by;

$$s = m + h - 3j \quad (2)$$

s: degree of indeterminacy
m: number of members
j: number of joint
h: number of degrees of freedom.

A structure contains members and joints called elements and nodes in the stiffness method, respectively. A node has 3 degrees of freedom and an element has 6 degrees of freedom (Figure 4). In the stiffness method, the structure is analyzed element by element, and an element stiffness matrix is used for each member. Afterward, each element stiffness matrix is accumulated to obtain a global stiffness matrix (for frame analysis). This global stiffness matrix relates global loadings and global displacements, resulting in internal forces and deflections on member ends. The stiffness method is applied as eq. 3 to eq. 9 [18].

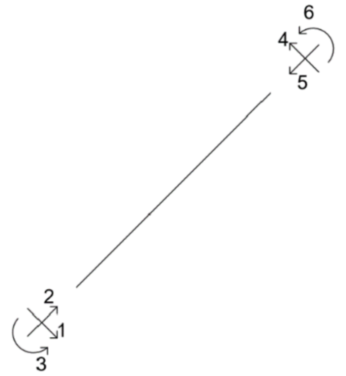


Figure 4. Degrees of freedom for element stiffness

$$\{Q\} = [K] \times \{D\} \tag{3}$$
$$[K] = \sum_{i=1}^{n} k_i \tag{4}$$
$$[k] = [T]^{T} \times [k'] \times [T] \tag{5}$$

$$k' = \begin{bmatrix} AE/L & 0 & 0 & -AE/L & 0 & 0 \\ 0 & 12EI/L^3 & 6EI/L^2 & 0 & -12EI/L^3 & 6EI/L^2 \\ 0 & 6EI/L^2 & 4EI/L & 0 & -6EI/L^2 & 2EI/L \\ -AE/L & 0 & 0 & AE/L & 0 & 0 \\ 0 & -12EI/L^3 & -6EI/L^2 & 0 & 12EI/L^3 & -6EI/L^2 \\ 0 & 6EI/L^2 & 2EI/L & 0 & -6EI/L^2 & 4EI/L \end{bmatrix} \tag{6}$$

$$T = \begin{bmatrix} \lambda_x & -\lambda_y & 0 & 0 & 0 & 0 \\ \lambda_y & \lambda_x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_x & -\lambda_y & 0 \\ 0 & 0 & 0 & \lambda_y & \lambda_x & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

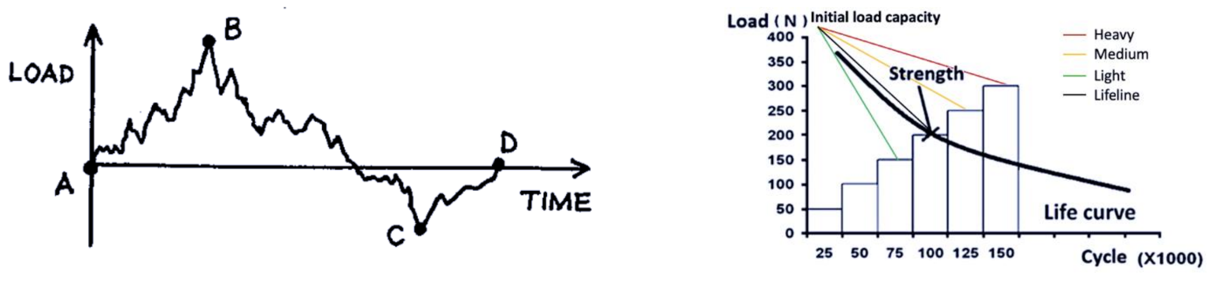
$$\lambda_x = cos\theta_x \tag{8}$$
$$\lambda_y = cos\theta_y \tag{9}$$

where,

Q: Global loadings for structure (N)
K: Global stiffness matrix for structure
D: Global displacements for structure (mm)
k_i: global stiffness matrix
n: number of elements
T: Force transformation matrix
k': element stiffness matrix
A: cross-section area of elements
E: Elasticity of material used in elements
L: Length of the element
I: Moment of inertia of the element
θ_x: angle of the element to the x-axis
θ_y: angle of the element to the y-axis.

2.3. Determination of the coefficient of acceptability

The overall strength of the structure reduces under dozens and hundreds of loadings in the course of its life span. Prediction of these loading in service is complicated (Figure 4.a). A furniture construction has an initial load capacity – ultimate load capacity – but it would be subjected to normal and abusive loads during its service life. The first crossing point is load level when imposed load and material strength cross each other. At this point, internal forces on joints or members initiate to exceed material strength capacity, so the structure itself is expected to fail. Load level at failure is compared to American Library Association (ALA) specifications to determine whether it passes or fails to light, medium, and heavy-duty acceptable load levels (Figure 4.b).



(a) (b)

Figure 4. a. Irregular load history in structure [19] and b. Relationship between load steps and product strength [20]

The bending moment capacity of RMT joints is calculated via eq. 10 and eq. 11, and then, it is multiplied by 3 to obtain its initial load capacity by considering the allowable bending capacity of wood in bending [2].

$$M_s = 0.97 \times \frac{W}{D^{1.5}} \times M \tag{10}$$

$$M = k \times \frac{\pi \times D^3}{32} \times \sigma_E \tag{11}$$

where,

M_s: The bending moment capacity of the tenon with shoulder
W: the width of the stretcher
D; Diameter of the tenon
M: Bending moment capacity of tenon without shoulder
k: coefficient (1.18)
σ_E: Modulus of rupture of materials used in the tenon.

The coefficient of acceptability (CoA) is calculated by differentiating the slope of the lifeline (m_L) and the slope of i^{th} acceptable load level (m_i) (i: light, medium, or heavy).

$$CoA = \frac{m_i - m_L}{m_L} \tag{12}$$

$$m = \frac{y_2 - y_1}{x_2 - x_1} \tag{13}$$

3. Results and Discussions

3.1. Front-to-Back Cyclic Load Capacity

Front-to-back cyclic load capacity determines the strength of the furniture construction because imposed load which is subjected during sitting and tilting on a chair in its service life is most likely to be encountered. According to the test results (Table 3 and Figure 5), the cyclic load capacity level increased by increasing the number of stretchers for chairs made of soft maple and yellow poplar wood. Cyclic load capacity for chairs made of soft maple wood with three stretchers was 76.56% and 771.87% higher than those of two stretchers and one stretcher, respectively. Likewise, chairs made of yellow poplar wood presented the same pattern; namely, chairs with three stretchers had 85.56% and 271.56% more strength than those of two stretchers and one stretcher, respectively.

Table 3. Results of front-to-back cyclic load test

Wood Species	# of Stretcher	Failure Load (N)	Failure Cycle	Ultimate Load (N)
Soft Maple	3	2002.50	11829	1943.76
	2	1112.50	22360	1100.93
	1	333.75	101	222.94
Yellow Poplar	3	2113.75	17829	2081.71
	2	1223.75	2063	1121.85
	1	667.50	817	560.26

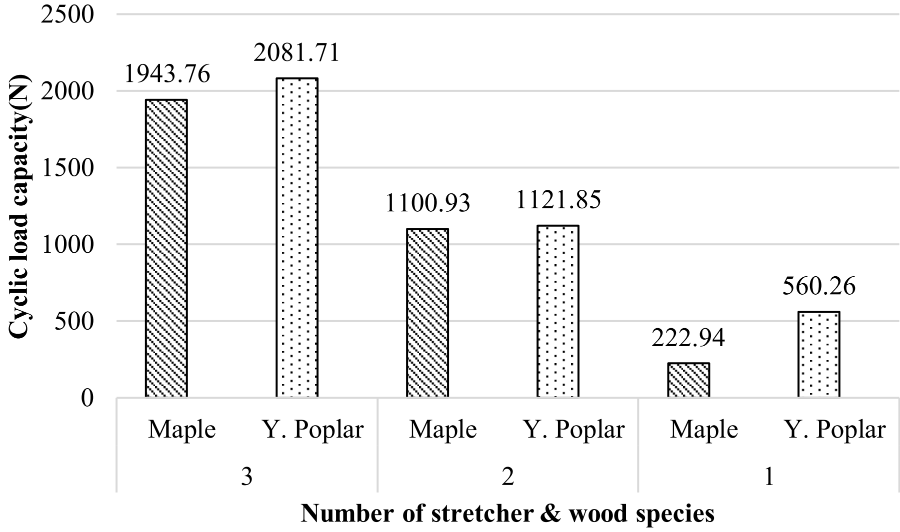


Figure 5. The ultimate cyclic load capacity of the chair frames

3.2. Structural Analysis of Chair Frame

Three chair configurations were defined, and each node on the chairs was numbered as Figure 6. Table 4 showed bending moment at the nodes where the cyclic failure load was subjected to node 3 horizontally. Chairs made of both soft maple and yellow poplar wood with one stretcher had a bending moment of 45.30 N.m and 113.83 N.m on node 2, respectively. Those of two and three stretchers had 84.69 N.m, 58.62 N.m, 86.43 N.m, and 62.58 N.m on node 4, respectively. As can be seen, an increasing number of stretchers in construction enhances the durability of the chair due to the fact that it causes a double-moment effect on members.

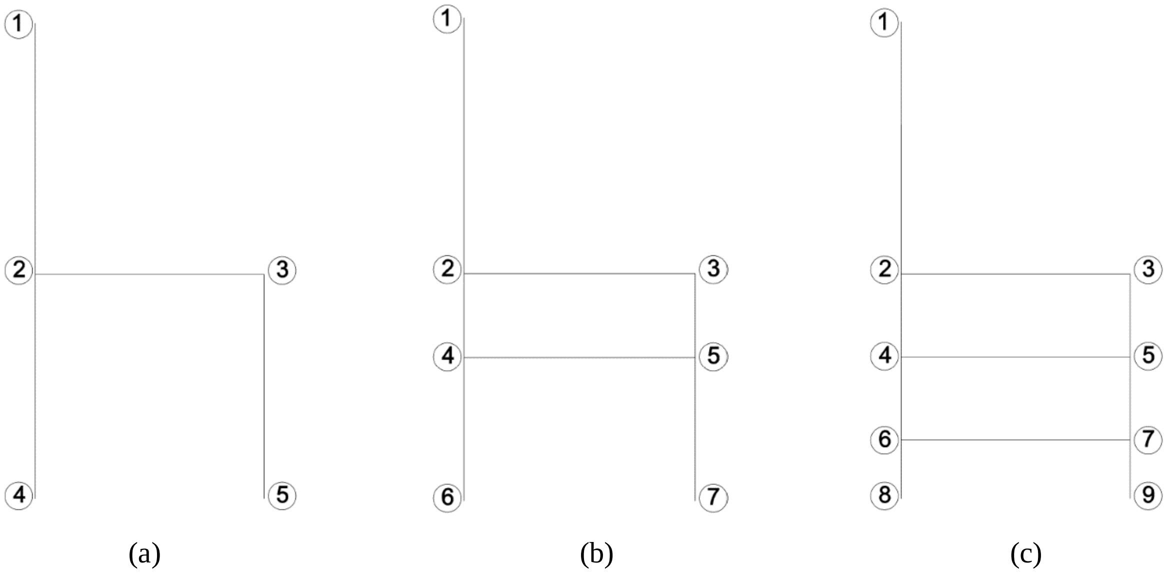


Figure 6. Nodes on chair frame for stiffness method

Table 4. Bending moment capacities on nodes at cyclic failure load (N.m)

Wood Species	# of stretchers	Nodes 1	2	3	4	5	6	7	8	9
Soft maple	1	0.00	**45.30**	0.00	0.00	0.00	-	-	-	-
	2	0.00	35.80	43.60	**84.70**	59.40	0.00	0.00	-	-
	3	0.00	44.81	43.90	**58.60**	58.40	43.90	43.10	0.00	0.00
Yellow poplar	1	0.00	**113.80**	0.00	0.00	0.00	-	-	-	-
	2	0.00	36.50	44.50	**86.40**	60.60	0.00	0.00	-	-
	3	0.00	47.10	46.90	**62.60**	62.50	47.00	46.00	0.00	0.00

*Note: The node having the highest moment capacity is shown in bold.

Table 5 demonstrates moment capacities on each node while acceptable load levels were imposed on chairs from node 3 horizontally. Likewise, the maximum moment occurred on node 2 for chairs with one stretcher, whereas on node 4 for chairs with two and three stretchers.

Table 5. Bending moment capacities on nodes at acceptable service load levels (N.m)

Load levels	# of stretchers	Nodes 1	2	3	4	5	6	7	8	9
Acceptable light-duty	1	0.00	**271.20**	0.00	0.00	0.00	-	-	-	-
	2	0.00	43.42	52.93	**102.78**	72.13	-	-	-	-
	3	0.00	30.21	30.12	**40.18**	40.07	30.15	29.51	-	-
Acceptable medium-duty	1	0.00	**317.50**	0.00	0.00	0.00	-	-	-	-
	2	0.00	50.66	61.76	**119.91**	84.15	-	-	-	-
	3	0.00	35.25	35.15	**46.88**	46.75	35.18	34.42	-	-
Acceptable heavy-duty	1	0.00	**406.91**	0.00	**0.00**	0.00	-	-	-	-
	2	0.00	65.13	79.40	**154.17**	108.19	0.00	0.00	-	-
	3	0.00	45.32	45.19	**60.27**	60.11	45.23	44.26	-	-

*Note: The node having the highest moment capacity is shown in bold.

3.3. The coefficient of acceptability for the critical joints

Figure 7 shows a trend from the initial life of the product to moments on critical joints at failure, acceptable light-duty service, acceptable medium-duty service, and acceptable heavy-duty service load. The initial moment capacity of the round mortise and tenon joints on chairs made of soft maple wood was 124.93 N.m, whereas those of yellow poplar was 141.78 N.m according to equation 10. In the case that initial moment capacities were higher than failure load and acceptable load levels, slopes presented a decreasing trend. On the contrary, they were in increasing trends ıf initial moment capacity were lower than failure load and acceptable load levels. Initial moment capacities for critical joints on chairs with one stretcher were lower than those of with acceptable load levels subjecting to chairs (Figure 7.a and 7.b). In Figure 7.c, d and e, initial moment capacities for critical joints on chairs with two stretchers made of both wood species and three stretchers made of soft maple wood were lower than the moments when acceptable heavy-duty service load was imposed on chairs. The slopes trending an increase from initial moment capacity to any moment capacity on nodes when acceptable load levels were applied stated that joints, and hence chairs, failed.

On the other hand, joints survived under imposed loads and passed the specified acceptable load capacity levels. Only chairs with three stretchers passed all the acceptance levels under horizontally front-to-back cyclic load. However, the chair made of soft maple wood failed to meet the acceptable heavy-duty service load level criteria. The purpose of the study is to determine the coefficient of the acceptability (CoA) of chairs in order to state how much chairs depending on critical joints performed better serviceability in the use of their life. Table 6 shows the coefficient of the acceptability for critical joints based on slopes between lifeline and acceptable service load. CoA was a positive value when that chair passed the performance test; otherwise, it is a negative value. Here, the coefficient of acceptability refers to how well serviceability is presented when the value is away from zero. For instance, the chair made of yellow poplar and soft maple wood with two stretchers passed the test with the moment capacity of 62.60 N.m and 58.60 N.m, respectively; namely, chairs made of yellow poplar had 6.83% greater strength than those of soft maple. On the other hand, the coefficient of the acceptability was differentiated 28.57% between chairs made of yellow poplar and the ones of soft maple wood; that is, not only the criteria about whether the product passed or failed the performance test and how much bending moment capacity on joints was obtained is significant but the coefficient of accessibility would also give a vital insight into serviceability and durability in their utilization in service.

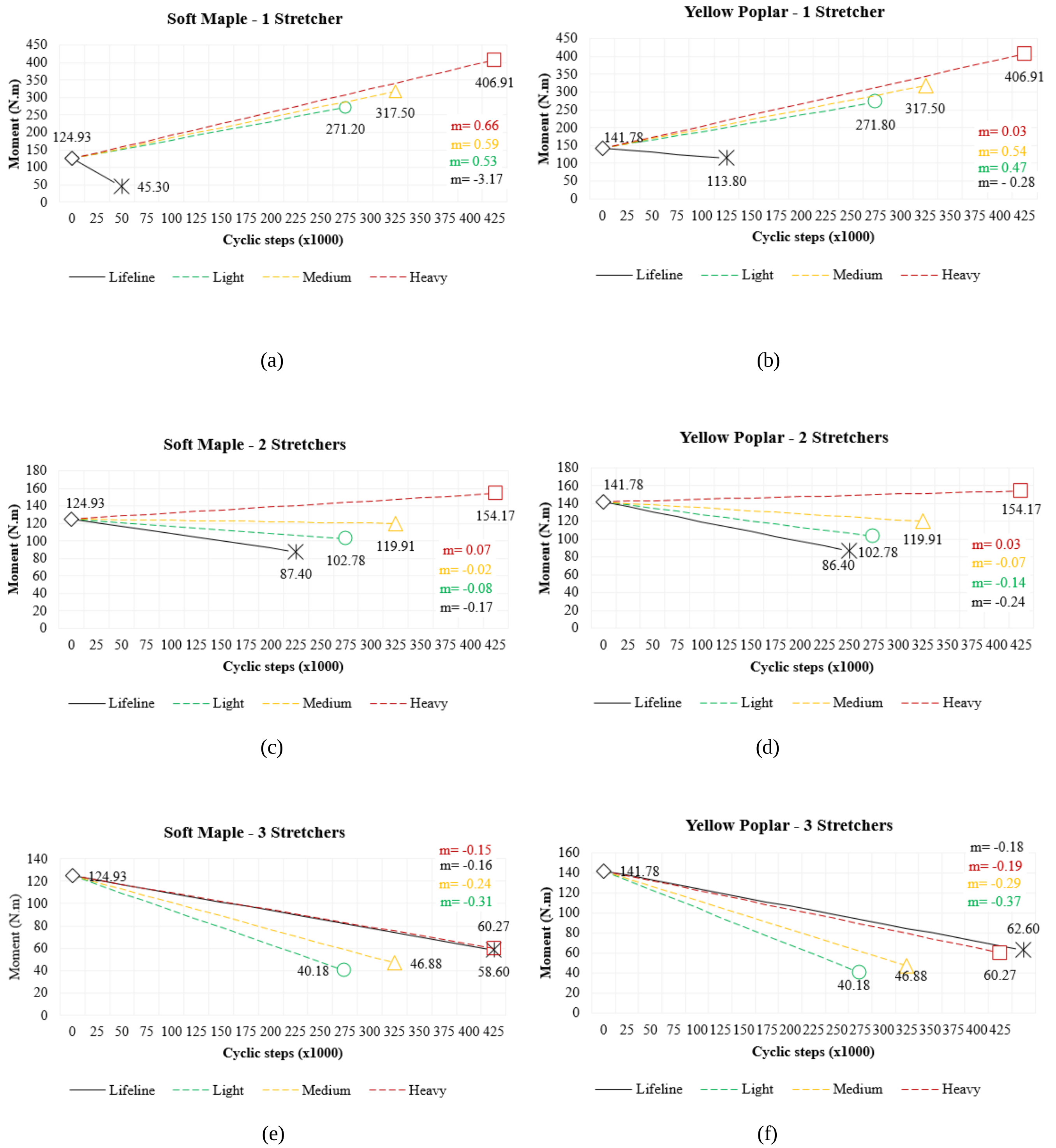


Figure 7. The slopes between moments on critical joints at failure, acceptable light-duty service, acceptable medium-duty service, and acceptable heavy-duty service load a. soft maple with one stretcher, b. yellow poplar with one stretcher, c. soft maple with two stretchers, d. yellow poplar with two stretchers, e. soft maple with three stretchers, and f. yellow poplar with three stretchers

Table 6. The coefficient of acceptability of critical joints and pass/fail criteria according to ALA specification

Wood Species	# of stretchers	Moment capacity at critical joints	Moment capacity at critical joint at acceptable light-duty cyclic load	Results	CoA	Moment capacity at critical joint at acceptable medium-duty cyclic load	Results	CoA	Moment capacity at critical joint at acceptable heavy-duty cyclic load	Results	CoA
Soft maple	1	45.30	271.20	Fail	-1.17	317.50	Fail	-1.19	406.91	Fail	-1.21
	2	87.40	87.42	Fail	-0.52	102.78	Fail	-0.91	119.91	Fail	-1.41
	3	58.60	40.18	Pass	0.91	46.88	Pass	0.49	60.27	Fail	-0.06
Yellow poplar	1	113.80	271.20	Fail	-2.70	317.50	Fail	-2.95	406.91	Fail	-1.11
	2	86.40	87.42	Fail	-0.42	102.78	Fail	-0.72	119.91	Fail	-1.12
	3	62.60	40.18	Pass	1.07	46.88	Pass	0.63	60.27	Pass	0.07

4. Conclusion

In this study, the coefficient of acceptability (CoA) for critical joints of chair frames was determined to provide insight into their serviceability and durability in service life. In doing so, three chair configurations made of soft maple and yellow poplar wood were used.

Critical joints on chair frames with one stretcher were node 2, whereas those of two and three stretchers were node 4. Based on moment capacities on these nodes obtained by imposing failure load and acceptable load level, joints, and hence chair frames, made of yellow poplar wood have greater strength than those of soft maple in in three-chair-configuration. Increasing the number of stretchers enhances chair durability because of the double-moment effect members; namely, the moment arm on the furniture member becomes narrower or the load is distributed to two and more members joined to one node when stretchers are added to the chair. Thus, the moment effect decreases on members or is fluctuated in both negative and positive zone on the moment diagram.

Knowing the initial strength of a joint is beneficial to design a durable and strong joint. Even theoretical structural analysis could determine whether a joint passes or fails according to an acceptable load level. According to the test results, the initial strength of joints for chairs with one and two stretchers did not meet any acceptable level, so they could fail in the early stage of their life. Besides, their CoA was negative, and their non-acceptability levels were high. On the other hand, when the number of stretchers increases, CoA turns to a positive value, e.g., chairs with three stretchers. In the light service load level, the CoA gives a better value of about 1; when severe load levels are applied, it is close to 0.

The CoA gives an insight into joint durability and serviceability in performance tests rather than only pass/fail tests. Therefore, if critical joints in chair frames are considered rather than full-frame strength in structural analysis, a better understanding of the lifetime or service of chair frames can be presented.

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