Reliability Measurements of the Furniture Frames with Selected Joint Types

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The reliability was evaluated for frame construction with mortise and tenon (MT), dowel, and non-glued and glued staple joints made of beech wood. The moment capacities of the T-shaped joints were determined under static vertical loads. The MT joint had an average moment capacity of 204 Nm, followed by dowel joints (154 Nm). In staple joints, joint strength increased after gluing. A three-seat sofa frame was defined and theoretically subjected to loads on arm rails, side rails, and back posts. Moment levels on the joint of the frame were obtained by using the stiffness method. To measure the reliability, these moment levels were assumed to be normally distributed with a coefficient of variation of 10%; accordingly, the normal distribution of the data sets was transformed into a normal standard distribution, and then, the reliability of each joint on the frame was obtained by using probabilistic approaches. MT joints were found to have the highest moment capacity and, correspondingly, the highest reliability (99.99%). Gluing the staple joints increased the strength, so their reliabilities were increased. In designing frame construction, the critical joints should be determined, and then, the joinery system with the higher reliability should be used.

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INTRODUCTION

Reliability is a is a measure of a product’s ability to serve its function appropriately during its expected life cycle. Therefore, furniture manufacturers should provide reliable furniture products to customers. However, Kłos and Fabisiak (2013) stated that 53% of companies in Poland were unaware of information about the warranty time of their product and did not comprehend the significance of the product reliability. The recognition of reliability would be a key success factor in the 2020s and 2030s in the global competitive furniture industry (Kłos *et al*. 2017). In order to produce more reliable furniture, the joinery system should be designed appropriately, as joints are the weakest part of the furniture construction (Smardzewski 2009). Besides, most of the failures in furniture construction occur due to loose or failed joints rather than furniture members (Eckelman 2003). This is because bending stress mainly increases on the end of the furniture members, and joints on the ends have narrower cross-sections compared to these members; correspondingly, wood, adhesive, *etc*. failure frequently occurs at the joint. Therefore, the reliability of the furniture relies on the reliability of the furniture joints located on critical connections (Uysal 2019). The critical joints in frame construction are the rail-to-the-back post joints. In this respect, reliability measurements of furniture frames come into prominence for various types of joinery systems; namely, glued and stapled joints are preferred in frame-type constructions due to durability and ease of operation, respectively.

The types of material, the position of the furniture elements, and the joinery system used in the construction are essential in the strength of furniture frame construction. Kasal (2006) examined five wooden materials used to construct furniture frames with dowel joints and determined failure load under imposing vertical loads on rails and horizontal loads on back posts; correspondingly, it was concluded that furniture construction made of beech wood provided higher failure load compared to those of plywood, medium density fiberboard (MDF), and oriented strandboard (OSB). In addition, adding slats on the side frames increased failure load from 54.2% to 107.6%. Besides, a furniture frame construction meets specifications rather than specifying load level to validate its reliability. Eckelman (1988, 1999) defined universal structural performance test methods. Eckelman and Erdil (2000) described upholstered furniture test methods according to the General Service Administration (GSA). Dai and Zhang (2007) provided a simplified analysis method to design critical furniture beam-like elements by using GSA performance test procedures.

In the strength of individual furniture joints, wood species, joint types, tenon geometry, adhesive types, manufacture processing, *etc*., are critical. Determining the strength of the furniture joint is a dynamic topic and needs to be conducted owing to changing joint design and adaption to cutting-edge technologies in the industry and environmental issues (Wu *et al*. 2021). Recently, a study about furniture joint studies was released dealing with bibliometric evaluation (Demirel and Eyüboğlu 2024). Hajdarevic *et al*. (2023) compared the strength of the MT joint constructed with angles of 102° and 112° between posts and rails and concluded that an increase in the angle between elements reduced the joint strength. Pinned or non-pinned loose tenons had been studied considering penetration length and shoulder effect (Derikvand *et al*. 2014; Derikvand and Ebrahimi 2014; Imirzi *et al*. 2015; Uysal *et al*. 2015; Zaborsky *et al*. 2018; Bas *et al*. 2023; Bas *et al*. 2024). Primarily, benchmarking of the strength of the MT and dowel joints was studied due to their favorable durability and ease of operation in the field of furniture strength design, respectively (Vassiliou *et al*. 2016; Uysal and Tasdemir 2022).

In the design of dowel joints, the number of dowels, wood species used dowel, dowel diameter, the distance between centerlines of dowels, the distance between dowel and rail edges, and the moisture content of wood come into prominence (Chen *et al*. 2018; Georgescu *et al*. 2019; Hao *et al*. 2020; Hu *et al*. 2023a). Wang and Lee (2014) discussed modeling of dowel joints in the finite element analysis (FEA) under the withdrawal test. They concluded that board type and ring angle were significant factors in the strength of the dowel joint in numerical analysis. Similarly, Záborský *et al*. (2018) stated that dowel joint strength was higher with an annual ring of 90°. Kasal *et al*. (2013) studied the shear force capacity of the dowel joints and concluded that narrower dowel spacing increased the joint strength, and wood species used in rail and rail thickness significantly affected the shear force.

In staple joints, the strength relies on the staple direct withdrawal load capacity in the main member (Hu and Zhang 2021). Besides, the stapled direction on a joint member is significant because Dai (2007) highlighted that the strength of the end-to-face single staple joint (800 N) made of plywood had higher strength compared to those of the face-to-face (778 N) in the direct withdrawal test. The holding strength of staple joints is affected by panel thickness and density (Wang *et al*. 2009; Hristodorova *et al*. 2023). Conversely, thin materials are preferable in the furniture industry due to the decreasing mass of products. Petrova *et al*. (2023) showed that miter joints could be a solution by increasing the surface area of assembled sides. The tensile load capacity of stapled joints was increased by increasing the number of staples from 1 to 2 and the amount of adhesive (Matwiej *et al*. 2018). Skorupińska *et al*. (2021) studied the tensile strength of the glued staple joint made by humans and in robotic production. They stated that the strength of the joint was higher in robotic output owing to the described and repeatable glue amount, a close gluing system that secures and keeps glue parameters on the required level. Another application of using staples in furniture frames is stapled gusset plates. Demirel and Er (2022) benchmarked the strength of gusset plate joints made of heat-treated and non-treated wood with 6 and 8 staples; namely, an increase in the number of staples expectedly increased joint strength, and joints made of non-treated ash wood had higher strength than those of heat-treated. Still, there was no statistical difference between those of scotch pine wood. Demirel and Kalayci (2020) examined the strength of gusset plates with a various number of staples and concluded that lateral shear resistance of the gusset plates increased by 16.11% and 1.38% in the case of the increasing number of staples from 2 to 4 and from 4 to 6, respectively, but joint strength decreased by 5.33% those of 6 to 8. Hu and Zhang (2021) and Demirel *et al*. (2016, 2018, 2024) evaluated the strength of the stapled one-sided gusset plate joints made of OSB having different densities. An increase in density, rail thickness, and number of staples improved the moment capacity of the joints.

Furthermore, FEA was performed to analyze the strength of the furniture joints, and its numerical results were compared to empirical results. Gustafasson (1995) and Smardzewski (1996) studied FEA for furniture construction in the 1990s, and numerical studies regarding furniture construction and furniture joints have been studied so far. Kasal *et al*. (2016) evaluated the effects of various tenon sizes on joint strength and rigidity experimental and numerically; namely, FEA results provided reasonable estimates and validation methods compared to empirical results. Hajdarevic *et al*. (2020) stated that numerical and empirical results for the strength of MT and double-MT joints provided an approximate prediction for the properties of wood construction and joints and the behavior of the adhesive profile of the joints. Hu *et al*. (2020) successfully modeled MT joints and compared results for the tensile load capacity of joints experimentally and numerically. Hu and Liu (2020) compared finite element models defining whole rigid, tie rigid, and semi-rigid MT joints to predict their strength and stated that semi-rigid joints performed better with the results of empirical data than others. Hu and Chen (2021) indicated that tenon width has a more significant effect compared to tenon length in FEA, as Hill and Eckelman (1973) highlighted experimentally. Besides, it was stated that quadratic models in FEA provided an effective method to predict and optimize the strength of the MT joint. Fu and Guan (2022) provided a comprehensive study on the contact force of the MT joints considering moisture content and grain direction of the wood material. Chen *et al*. (2022) studied dowel joints reinforced with metal connectors and compared the numerical and empirical results. Xu *et al*. (2023) studied optimizing three-dimensional MT joints by determining beneficial MT joints, so its geometry was designed appropriately to resist subjected load compared to joints assembled to post another axis. Hu *et al*. (2023b) compared numerical and experimental results of dowel-reinforced dovetail joint strength by increasing crack initiation load and critical fracture load capacity. Hu *et al*. (2024) evaluated traditional Chinese wood furniture joints considering digital manufacturing feasibility and model with FEA to compare numerical and empirical results.

Studies discussed above mainly have focused on single aspects – mean and standard deviation – to present joint strength experimentally and numerically. However, some used prediction analysis to estimate a single value in the future population. These are deterministic approaches, but probabilistic approaches provide more tangible outcomes in the reliability analysis. Reliability indicators are probabilistic reliability analysis, (ii) phenomenological theory of reliability, (iii) interference theory of reliability (ITER), (iv) synthesis of fracture mechanics and reliability, and (v) corrected theory of reliability (Veselovský *et al*. 1993; Kłos and Langová 2023). The intermediate procedure to measure the reliability of the furniture frames is to use the probabilistic approach. This approach has been investigated for case-type furniture construction but not for frame-type calculation owing to a number of elements. Simplified frame construction could provide a systematic method of measuring the implementation of theoretical reliability.

Reliability refers to the capability of furniture to fulfill its intended purposes within a set timeframe while meeting its technical specifications. This concept encompasses aspects such as failure-free service life and repairability. Furniture construction is viewed as a complex system regarding reliability, where each component contributes to the overall performance. The reliability of the whole furniture construction can be determined by assessing the reliability of individual components, considering them as systems in their own right, and subsequently applying probability principles (Kłos and Langová 2023). In this system, joints play a critical role in providing higher reliability. The use of low-reliable furniture joints in furniture construction negatively affects the overall reliability of the furniture itself (Smardzewski 2005, 2009; Kłos and Fabisiak 2013). In the case of using 6 mm wood dowel in corner joints, the reliability of the joints was 92.7%, while the reliability of the furniture construction with concerning joints was 54.6%. Otherwise, those of 8 mm wood dowels increased the reliability of joints and furniture construction to 99.9% and 99.3%, respectively (Smardzewski 2009). Therefore, the reliability measurement for furniture construction has been considered furniture joints instead of furniture members. Klos and Fabisiak (2013) and Kłos and Langová (2023) measured the reliability of the case furniture by using a probabilistic approach and concluded that the reliability of corner joints increased with the number of joints in the parallel systems because more than one joinery system in each corner reinforced another joinery system; for example, plastic dowels are used to reinforce minifix (eccentric joints) in corner joints. On the other hand, a construction with several joint members has a serial system; that is, an increase in the number of joints in construction decreases the overall reliability of the furniture. Therefore, it was vital to construct a piece of furniture with as few assembly systems as possible. Chevalier *et al*. (2022) proposed a multi-model approach by using the first- and second-order statistics of critical loads for bolted joints; namely, it was suggested to use critical value rather than safety factor for furniture, 1.2, and predict failure of joints by giving the probability of failure; *i.e.*, in the case where the local tensile strength on wood was 1.5 and 2 MPa, the probability of failure was approximately 20% and 90%, respectively. Thus, if the material strength of wood is known, the failure criteria and probability of failure could be forecast by using finite element simulation. Similarly, Uysal *et al*. (2024) studied the use of lower tolerance limits to obtain design values for mortise and tenon joints and concluded that results for empirical and numerical failure stress were close to each other when using these design values in constructing chair frames.

The advancement of analysis and design techniques focused on reliability has opened doors for improving load testing in structural engineering. Two particularly encouraging avenues for improvement exist: conducting multi-mode proof tests on structural systems and assessing test outcomes through a probabilistic evaluation (Hall and Tsai 1989). Theoretical calculations for the reliability of the constructions provide various reliability-based measures such as the design, pre-investigation, proof-loading, and quality control. The theoretical calculations would give a better presentation to understand the reliability of the system. Of course, numerical solutions should be promised for complex reliability problems (Rackwitz and Schrupp 1985).

This study aimed to measure the reliability of the furniture frame construction with selected furniture joints. In doing so, the objectives of the study were to (i) determine the moment capacity of the T-shaped MT, dowel, and glued and non-glued staple joints, (ii) theoretical structural analysis of the three-seat sofa frame under imposed loads by using the stiffness method, (iii) standardize normally distributed data set and determine the reliability of each joint on sofa frame, and (iv) measure reliability of the sofa frame by using multiple failure modes. The proposed method would provide what joinery system, or a combination of joints, can produce reliable furniture frame constructions.

EXPERIMENTAL

Materials and Specimen Constructions

In this study, beech (*Fagus orientalis* Lipsky) wood, which is widely utilized for wood furniture frames and obtained from a local sawmill in Bursa, Turkiye, was used in specimen constructions.

According to BS ISO 13061-1 and 2, specimens (20x20x30 mm) were prepared to determine the moisture content (MC) and density of the wood materials, respectively. According to BS ISO 13061-3 and 4, specimens (20x20x360 mm) were prepared for a bending test to determine the modulus of rupture (MOR) and modulus of elasticity (MOE), respectively.

All boards were machined to a thickness of 20 mm from quarter-sawn lumber. Blanks, 60 mm wide by 300 mm long and 60 mm wide and 270 mm long, were machined from these boards and numbered sequentially. The defect-free blanks were randomly selected from the material pool to construct T-shaped joints with (i) mortise and tenon (MT), (ii) dowel, and (iii) non-glued (S) and glued stable (SG) joints.

For *MT joints*, the tenons were cut with a thickness of 10 mm, a length of 30 mm, and a width of 40 mm (Fig. 1a). Matching mortises were cut with the router. The face of the tenons and the walls of the mortises were coated with polyvinyl acetate (PVA-D3) adhesive, and 2/3 of the full length of the tenons was inserted into the mortises without force, but the rest of it was inserted by clamping. All specimens were clamped for at least 24 hours. For *dowel joints*, holes were drilled at the end of the rails and the edge of the posts to a diameter of 10 mm and a depth of 25 mm (Fig. 1b). The grooved dowels made of red oak were used for the joints. The hole walls and half of the dowel length were coated with PVA adhesive, and the adhesive-coated sides of the dowel were inserted into the dowel hole in the post with a penetration of 25 mm. Then, the coated ends of each dowel were inserted into accompanying rail holes with a depth of 25 mm. All specimens were clamped for at least 24 hours. For the *staple joint*, the ends of the rail and edges of the post came together with six combinations of non-glues or non-glued and 2.5 mm-, 5mm- and 10 mm-gaps between staples (Figs. 1c to 1h). Both faces of the joints were stapled with 8 mm teeth by 20 mm long staples. All samples were kept in a conditioning room at a temperature of 20±2 °C and 65±5% humidity for at least one week.

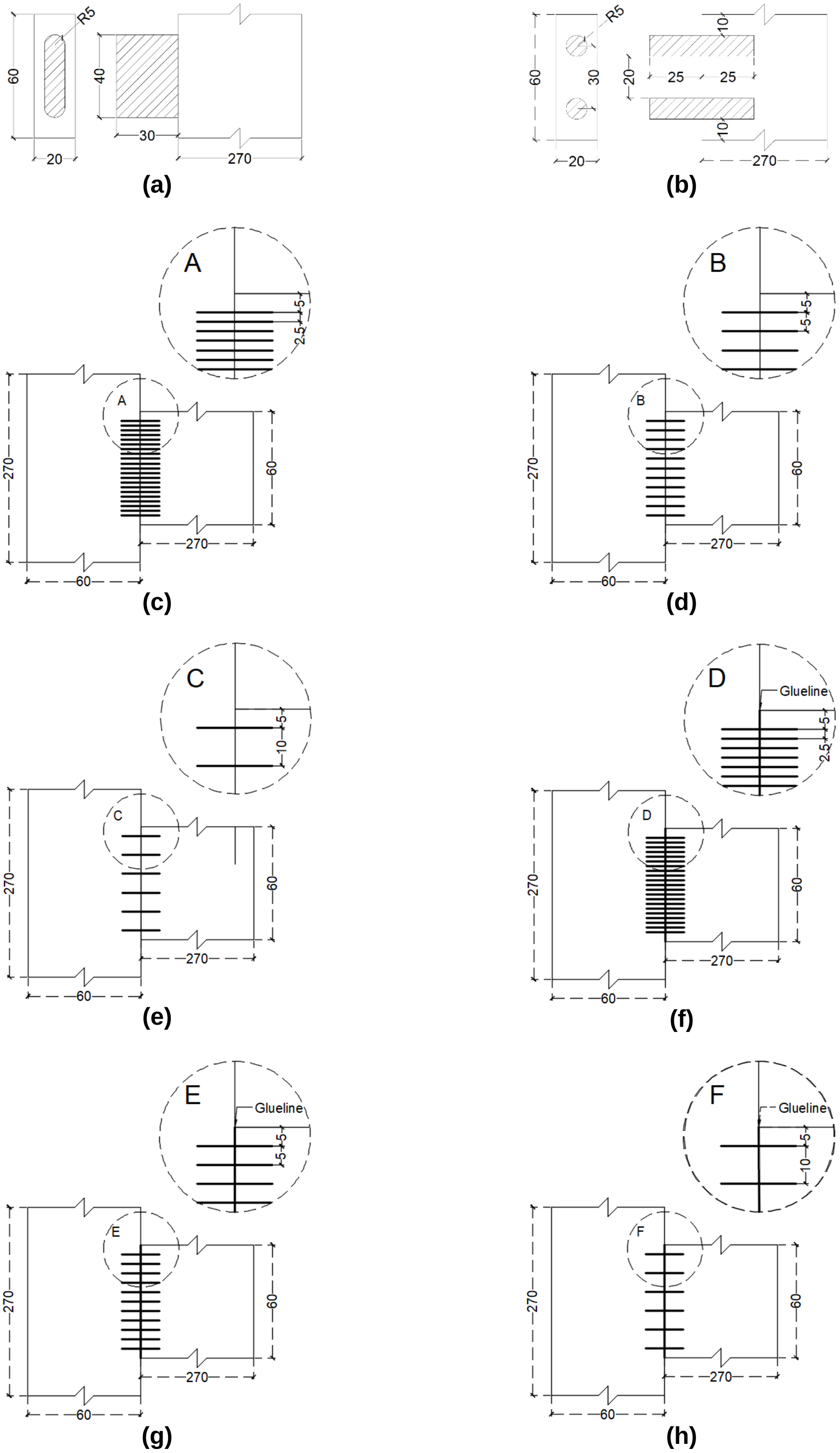


Fig. 1. Joint configuration a. MT, b. Dowel c. Non-glued staple joint with 2.5-mm gaps, d. Non-glued staple joint with 5-mm gaps, e. Non-glued staple joint with 10-mm gaps, f. Glued staple joint with 2.5-mm gaps, g. Glued staple joint with 5-mm gaps and h. Glued staple joint with 10-mm gaps (in mm).

Determination of the Moisture Content and the Density of the Wood Material

According to BS ISO 13061 – 1 and 2, five test specimens were acclimatized at 20±2 °C and 65±5% relative humidity and weighted with a 0.01 g precision scale. The dimensions were measured with a 0.01 precision caliper. Afterwards, all specimens were dried in the oven at a temperature of 103±2 °C for at least 72 h and reweighted and re-measured. The MC (%) and the density were calculated by using Eqs. 1 and 2, respectively.

$$MC = \frac{m_1 - m_2}{2} \times 100 \tag{1}$$

where m_1 is the initial mass of the specimen before drying (*g*), and m_2 is the oven-dry mass of the specimen (*g*).

$$\rho_W = \frac{m_W}{V_W} \tag{2}$$

In Eq. 2, ρ_W is the density of the specimen at MC *W* (*g/cm³*), m_W is the mass of the specimens at MC *W* (*g*), and V_W is the volume of the specimen at MC *W* (cm^3).

Determination of the Bending Properties of the Wood Material

According to BS ISO 13061-3 and 4, the MOR ($\sigma_{b,W}$, *MPa*) and the MOE (E_W, GPa) of the specimens at a MC W were tested on the SHIMADZU universal test machine (Shimadzu Corporation, Kyoto, Japan), as shown in Fig. 2. Tests were conducted with a rate of 10 mm/min. The MOR and the MOE were calculated by using Eqs. 3 and 4;

$$\sigma_{b,W} = \frac{3 \times P_{max} \times l}{2 \times b \times h^2} \tag{3}$$

where P_{max} is the ultimate load (*N*), *l* is the distance between the centers of the supports (*mm*), *b* is the breadth of the specimen (*mm*) and *h* is the height of the specimen (*mm*).

$$E_W = \frac{P \times l^3}{4 \times b \times h^3 \times f} \tag{4}$$

In Eq. 4, *P* is the load equal to the difference between the upper and the lower limits of loadings (*N*), and *f* is the deflection equal to the difference between the arithmetic means of the results obtained in measuring the deflection at the upper and lower limits of loading (*mm*).

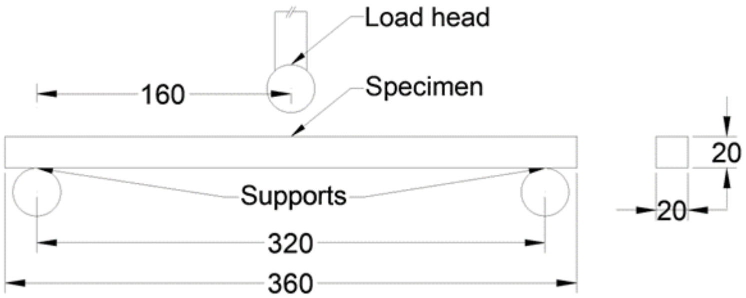


Fig. 2. Static bending test configuration (in mm)

Determination of the Moment Capacity of the Joints

All tests were conducted on the SHIMADZU universal test machine. The static vertical load was applied on the rail 250 mm from the edge of the post at a rate of 12.7 mm/min, as shown in Fig. 3 until non-recoverable failure occurred (Erdil *et al*. 2005). The moment capacities of the joints (*M*, Nm) were calculated by Eq. 5,

$$M = F_{ult} \times l \tag{5}$$

where F_{ult} is the ultimate failure load (N) and l is the moment arm (m).

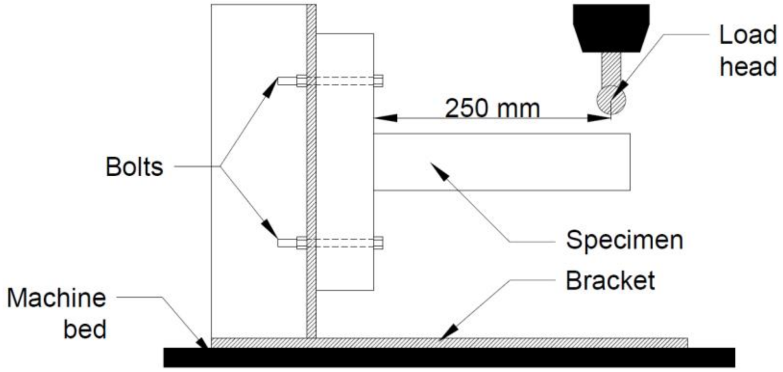


Fig. 3. Test configuration

Statistical Analysis

Data collected for all sample groups were checked for the presence of statistical significance through ANOVA analysis and Tukey pair-wise comparisons carried out in SPSS Statistical Analyses Software (IBM SPSS Statistics, New York, USA).

Structural Analysis of the Furniture Frames

A three-seat bare sofa frame (650 x 920 x 1820 mm) was defined, as shown in Fig. 4. In structural analysis, vertical and horizontal loads were assumed to be subjected to rails and posts, so side trust loads were not included in the reliability of furniture frame analysis.

Vertical loads (*P1*: 450 N) were defined on top of the back posts, while horizontal loads were defined on rails (*P2*: 1350 N) and top arm rails (*P3*: 1000 N), as shown in Fig. 5. Defined loads were selected from light-service acceptable levels in Dai and Zhang (2007).

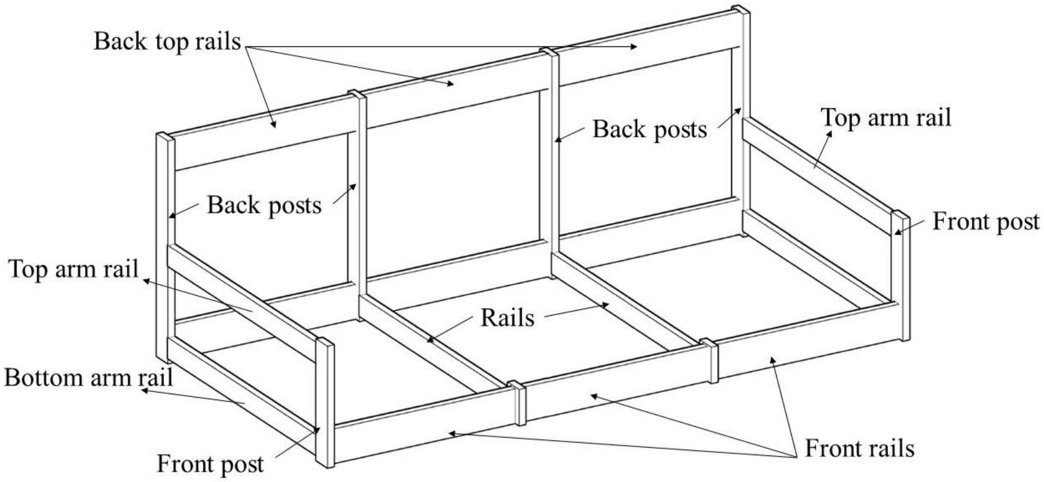
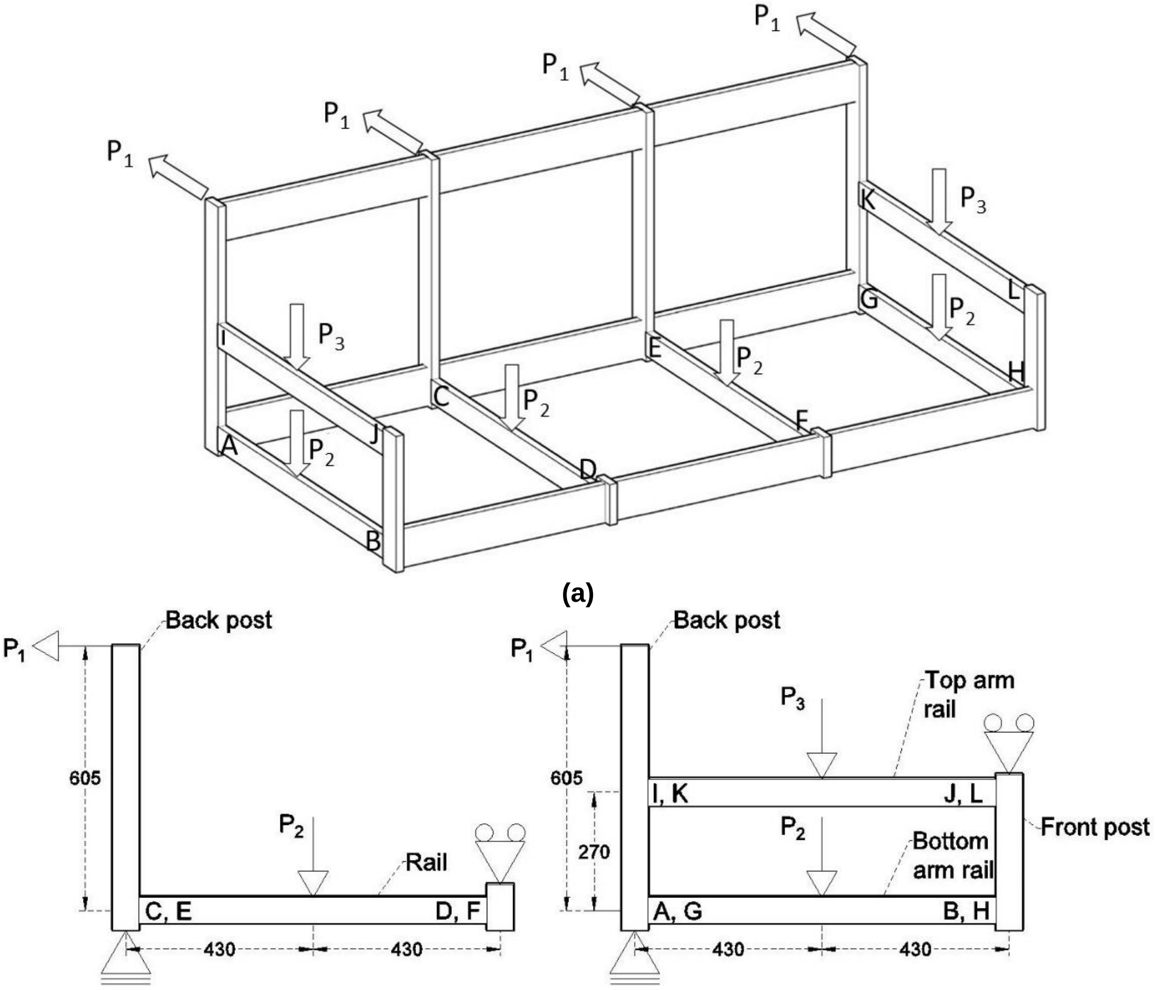


Fig. 4. Simplified three-seat sofa frame



(a)

(b)

(c)

Fig. 5. Imposed loads on (a) three-seat sofa, (b) rail to back post frame, and (c) arm rails to back post frame

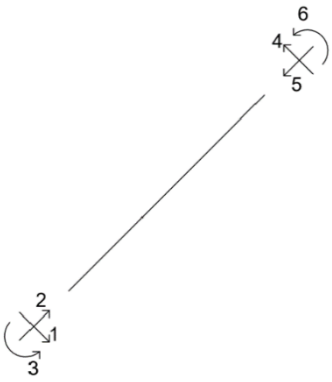


Fig. 6. Degrees of freedom for element stiffness

In the statically indeterminate frame analysis in Fig. 5b and Fig. 5c, internal forces were calculated using the stiffness method. A structure contains elements and nodes. A node has 3 degrees of freedom, and an element has 6 degrees of freedom (Fig. 6). Element stiffness was calculated by using Eqs. 6 and 7. A stiffness matrix is constructed by adding an element stiffness matrix to each other. In Fig. 5b, there are three elements and nine degrees of freedom, while those of Fig. 5c have five and fifteen, respectively (Hibbeler 2012).

$$\{f\} = [K] \times \{\mu\} \tag{6}$$

$$\begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{Bmatrix} = \begin{bmatrix} AE/L & 0 & 0 & -AE/L & 0 & 0 \\ 0 & 12EI/L^3 & 6EI/L^2 & 0 & -12EI/L^3 & 6EI/L^2 \\ 0 & 6EI/L^2 & 4EI/L & 0 & -6EI/L^2 & 2EI/L \\ -AE/L & 0 & 0 & AE/L & 0 & 0 \\ 0 & -12EI/L^3 & -6EI/L^2 & 0 & 12EI/L^3 & -6EI/L^2 \\ 0 & 6EI/L^2 & 2EI/L & 0 & -6EI/L^2 & 4EI/L \end{bmatrix} \times \begin{Bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \mu_5 \\ \mu_5 \end{Bmatrix} \tag{7}$$

Normalization of the Standardized Data Set and Probability of Failure

In this study, data were assumed to be normally distributed. Hence, M and S_M are random variables for the bending moment of the specified joint on the furniture frame and the moment capacity of the joint specimens, respectively. Correspondingly, μ_M and μ_{SM} are the average moment of the specified joint on the furniture frame and the average moment capacity of the joint specimens, respectively. In this case, $f_M(M)$ and $f_{SM}(S_M)$ are probability density functions (PDF) of the moment of a joint on a furniture frame and the average bending moment capacity of the joints (Fig. 7) (Chang 2015). The overlapped area indicates failure.

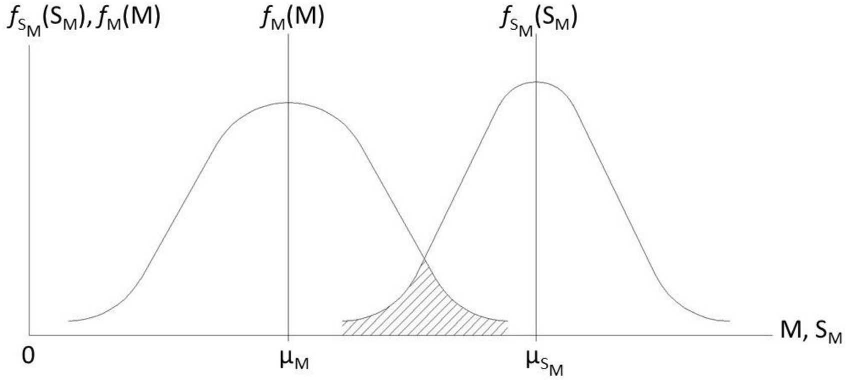


Fig. 7. PDF of the moment of the joint on the frame and the moment capacity of the joint

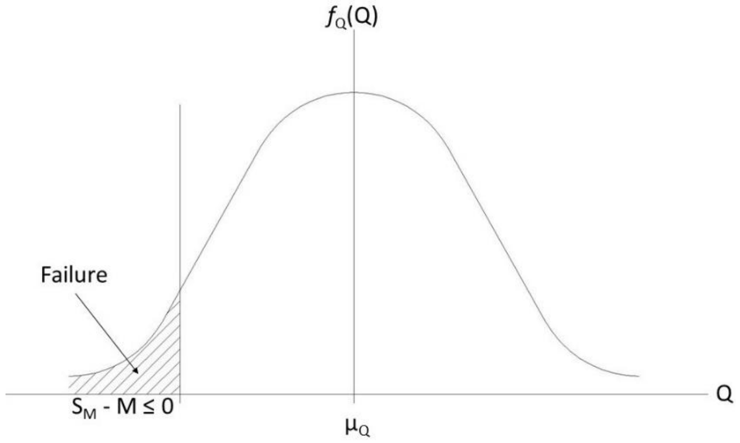


Fig. 8. PDF of failure mode

According to the PDF in Fig. 7, failure occurs when the moment of the joint on the furniture frame (*M*) exceeds the moment capacity of the joint (S_M). Hence, failure occurs when a random variable (Q) is equal to or lower than zero ($S_M - M \leq 0$), and failure mode is defined as Eq. 8. In addition, a PDF of the random variable Q ($f_{(Q)}(Q)$) is given in Fig. 8. The shaded area is defined as the probability of failure (P_f) (Chang 2015).

$$Q = S_M - M \tag{8}$$

$$P_f = \int_{-\infty}^{0} f_Q(Q)dQ \tag{9}$$

$$f_Q(Q) = \frac{1}{\sigma_Q\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{Q-\mu_Q}{\sigma_Q}\right)^2} \tag{10}$$

where μ_Q and σ_Q are mean and standard deviation, respectively, of the random variable Q.

The probability of failure (*Pf*) is calculated by transforming the PDF of a normal distribution ($f_Q(Q)$) to a standard normal distribution ($\phi(z)$), which has mean value μ_z=0 and standard deviation σ_z=1. Then, transformation can be simplified as (Chang 2015):

$$z = \frac{Q-\mu_Q}{\sigma_Q} \tag{11}$$

and the standard normal distribution function is;

$$\phi(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} \tag{12}$$

The probability of failure is calculated as follows,

$$P_f = \int_{-\infty}^{0} f_Q(Q)dQ = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}t^2} dt = \Phi(z) \tag{13}$$

where $\Phi(z)$ is the cumulative density function (CDF) of the $\phi(z)$ and is also calculated by using the MATLAB function of *normcdf(z)* or a function syntax in the Microsoft Office Excel of *norm.s.dist(z, cumulative)*.

Multiple Failure Modes in Reliability

A furniture frame consists of several elements. Two or more elements join together in a joinery system. A joint strength does not reflect the strength of the furniture frame because each joint on the furniture frame is subjected to various loads during service. Therefore, multiple failure modes can be an intermediate procedure to estimate the reliability of the furniture frames by considering the reliability of a single joint of furniture joint (*R = (1-Pf)*). The failure mode of joints on furniture frames is connected to a series system, which is a failure element at a specific joint in the frame (Fig. 9) (Chang 2015).

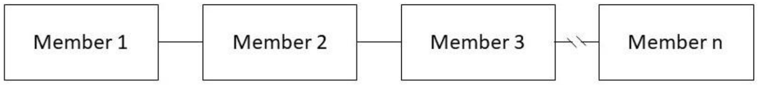


Fig. 9. Series system in multiple failure mode

The reliability of the furniture frame in the series system (R_{SS}) is calculated as follows,

$$R_{SS} = \prod_{i=0}^{n} R_i \tag{14}$$

where n is the number of joints in the system, and R_i (i = 1, 2, 3 … n) is the reliability of each joint.

RESULTS AND DISCUSSION

Moisture Content, Density, and Bending Properties of the Wood Material

The results of the MC, density, MOR, and MOE of wood are given in Table 1. According to the results, specimens had an MC of 9.71% during testing. The density of the wood specimens was 0.66 g/cm^3 with a standard deviation of 0.01 g/cm^3. Besides, the average MOR of the beech was 126.23 MPa with a standard deviation of 5.75 MPa while those of the MOE were 14.35 GPa and 0.74 GPa, respectively.

Table 1. The MC, the Density and the Bending Properties of Beech Used in the Study

	MC (%)	Density (g/cm^3)	MOR (MPa)	MOE (GPa)
Average	9.71	0.66	126.23	14.35
SD*	0.20	0.01	5.75	0.74
CoV*	2.10%	1.09%	4.55%	5.16%

*SD: Standard deviation and CoV: Coefficient of variability

Load-Deformation Curve of the Joints

Results for the typical load-deformation curves of joints are given in Fig. 10. The MT joint failure occurred at higher loads and deformations compared to other joint types. This was expected because MT joints had higher rigidity and strength (Eckelman 2003). MT joints failed around 600 to 900 N load level and reached their ultimate load capacity at the deflections above 10 mm but not the fifth specimen. Here, it can be observed there was a sudden failure after reaching ultimate load owing to wood failure. On the contrary, other MT joints resisted to subjected load until a certain point due to sliding tenons in the mortises. In dowel joints, load-deformation curves showed the same pattern with an ultimate load of no more than 700 N. Furthermore, gluing application for staple joints increased failure loads, but increases in the number of staples or gaps between staples did not increase proportionally failure loads. Miao *et al*. (2022) observed that the withdrawal strength of staple joints increased with an increase in the number of staples, but these increases were 32.38% for joints with one staple to two staples, 16.86% for joints with two staples to three staples, and 1.49% for joints with three staples to four staples. An increase in the number of staples somewhat increased the failure load. Similarly, Demirel and Kalaycı (2020) observed a decrease in the strength of the staple gusset plate in the case of increasing the number of staples from 6 to 8. After a certain number of staples were stapled on joints, the number of cracks increased with the shock impacts. Therefore, joints with narrower gaps between staples failed earlier. The failure modes for staple joints with gaps of 2.5 and 5 mm were mainly large cracks on the face of the posts, whereas those of 10 mm had small cracks and almost no cracks but separation for glued staple joints with 10 mm gaps. Moreover, it was observed that large cracks on the face of the posts caused earlier failure of joints for SG2.5.

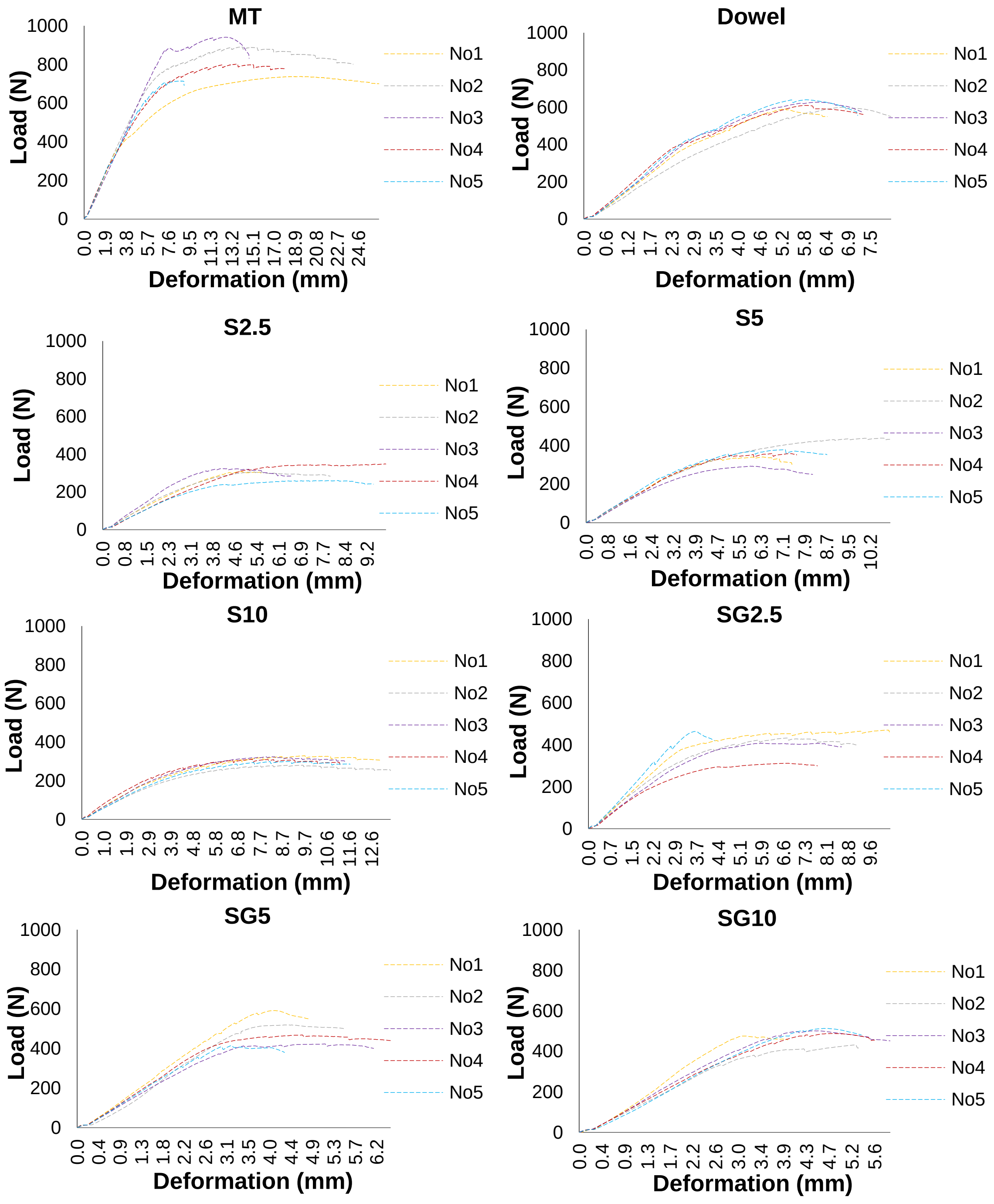


Fig. 10. Load deformation curves of T-shaped joints

Moment Capacity of the Joints

Table 2 shows the moment capacity of the joints. The MT joints had the highest average moment capacity (204.29 Nm) with a standard deviation of 24.34 Nm. Dowel joints had 153.53 Nm moment capacity following the MT joints with a standard deviation of 4.98 Nm. For non-glued staple joints, joints stapled with a 5-mm gap had a moment capacity of 90.41 Nm, which was 16.71% and 17.06% higher than those of 2.5-mm and 10-mm, respectively. Besides, gluing increased the moment capacity of the joints; namely, increases were 34.82%, 33.65%, and 56.03% for joints stapled with the 2.5-, 5-, and 10-mm gaps, respectively. The increase was similar for joints stapled with 2.5 mm and 5 mm gaps, but those with 10 mm had a greater increase compared to the others.

Table 2. Results of Moment Capacity of the Joints (Nm)

No	Joint Type							
	MT	Dowel	S2.5	S5	S10	SG2.5	SG5	SG10
1	184.52	147.89	77.23	85.14	82.39	117.64	147.87	118.80
2	222.67	150.15	76.52	109.51	70.12	108.23	129.73	108.37
3	235.29	156.90	80.93	73.16	80.99	101.96	105.75	125.23
4	200.47	152.58	87.20	89.58	77.64	78.10	117.15	128.15
5	178.52	160.14	65.15	94.64	75.02	115.95	103.70	121.95
Avg.	204.29	153.53	77.41	90.41	77.23	104.37	120.84	120.50
SD*	24.34	4.98	8.05	13.31	4.91	15.98	18.33	7.63
CoV*	11.91%	3.24%	10.40%	14.72%	6.35%	15.31%	15.17%	6.34%

*SD: Standard deviation and CoV: Coefficient of variability

One-way ANOVA was performed to examine the significance of the effect of joint types on the moment capacities of T-shaped furniture joints (α = 0.05). Besides, Tukey pair-wise mean comparison analysis was also conducted to observe whether there is a statistically significant difference among sample groups at a 95% confidence level. According to the results, the joint type (p-value ≈ 0.001) factor significantly impacted the moment capacity of joints, as shown in Table 3. Moreover, the average moment capacity of MT and dowel joints was significantly different. In contrast, there was no evidence to prove the statistically significant difference between the average moment capacities of glued staple joints with 2.5-, 5-, and 10-mm gaps (Table 4). The same phenomena were observed for those of non-glued staple joints. In addition, the bending moment capacities of glued staple joints with 5- and 10-mm gaps were significantly different from the other staple joints, but there is no evidence to prove it for those of 2.5-mm gap. Thus, it can be clearly stated that gluing staple joints may not be effective for narrower stapled joinery systems.

Table 3. One-way ANOVA for Moment Capacity of Joints

	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	64887.16	7	9269.59	48.38	0.000
Within Groups	6131.03	32	191.59		
Total	71018.19	39			

Table 4. Tukey Pair-wise Mean Comparison for Moment Capacity of Joints

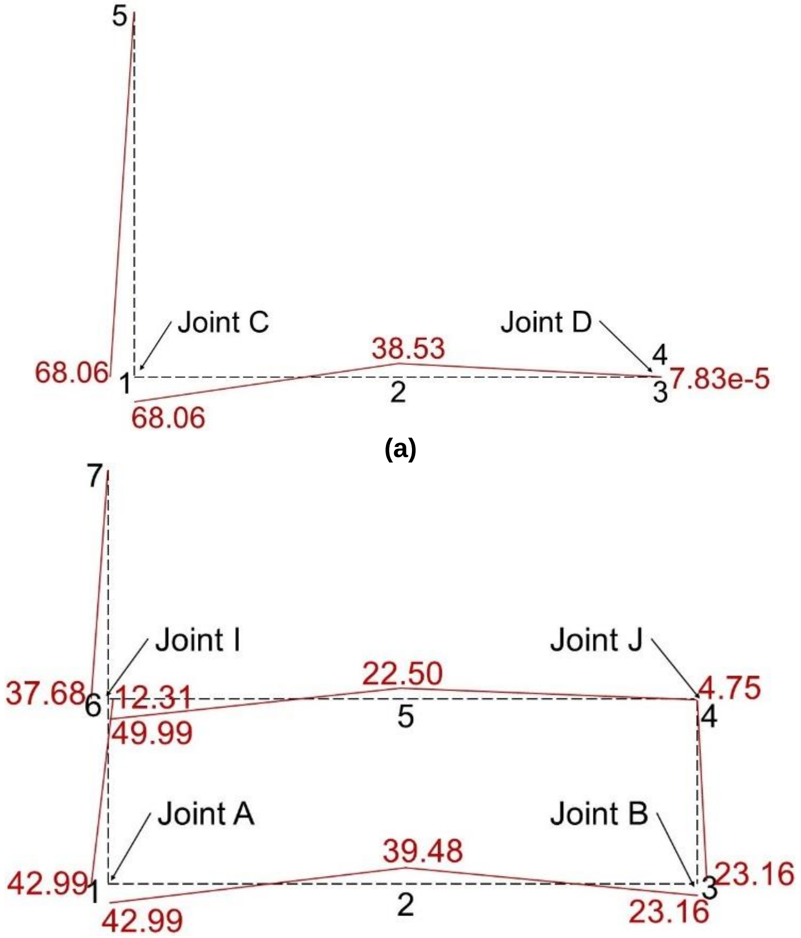
Joint type	N	Grouping			
S10	5	A			
S2.5	5	A			
S5	5	A			
SG2.5	5	A	B		
SG10	5		B		
SG5	5		B		
Dowel	5			C	
MT	5				D

*There is no significant difference between groups having the same letter

Structural Analysis of Frames

The moments after imposing P_1, P_2, and P_3 loads on the frame defined in Fig. 5 are given in Fig. 11 and Table 5. The *A-B-I-J* and *G-H-K-L* joints belong to the arm rails-to-back joints of the side frames, while *C-D* and *E-F* joints belong to rail-to-back-post joints on the middle of the sofa frame shown in Fig. 5. Besides, nodes on each element were defined in the structural frame analysis. Nodes 1 and 3 are on the joint *C* and *D*, and nodes 2 and 4 are where P_2 and P_1 are imposed on the rail-to-back post as shown in Fig. 5b. Nodes 1, 3, 4, and 6 are on the joint *A*, *B*, *I*, and *J*, and nodes 2, 5, and 7 are at where P_2, P_3 and P_1 are imposed on the arm rails-to-back post shown in Fig. 5c.

Under the imposed loads of P_1, P_2, and P_3, the highest moments were obtained for joints on the rails-to-back posts, which were critical joints in frame-type constructions. In the case of imposing loads of P_1 (450 N), P_2 (1350 N), and P_3 (1000 N), the moment of joint *A* (node 1) was 42.99 Nm, while those of joint *B*, *I*, and *J* (node 3, 6 and 4) were 23.16 Nm, 49.99 Nm, and 4.75 Nm, respectively. Due to symmetry, *G-H-K-L* joints on the arm rails-to-back joints of the side frames had equal moments. Moreover, joint *C* (node 1) had a moment of 68.06 Nm under the imposed loads of P_1 (450 N) and P_2 (1350 N), while those of joint *D* (node 3) were almost 0. Here, E-F joints on the rail-to-back-post joints in the middle of the sofa frame were similar, too.



(a)

(b)

Fig. 11. Moments on (a) rail to back post joint and (b) arm rail to back post joints (in Nm)

Table 5. Moments of Joints on Each Node of the Sofa Frame (in Nm)

Frame Type	Nodes						
	1	2	3	4	5	6	7
Rail-to-back post-frame	68.06	38.53	0	0	-	-	-
Arm rails-to-back post-frame	42.99	39.48	23.16	4.75	22.50	49.99	0

Reliability of Frames

Assume that the moments of the joints on rail-to-back posts and arm rails-to-back post frames are normally distributed with an average of μ and a standard deviation of 0.1μ; namely, a moment of joints on a three-seat sofa frame was obtained theoretically while the moment of the T-shaped joints was empirical data. Using Eqs. 8 to 14, the reliabilities of each joint and sofa frame were obtained and shown in Table 6. In the case of using MT and dowel joints, the reliabilities of the sofa frames were over 99.99%. On the other hand, the reliabilities were 65.74 %, 86.51%, and 74.42% in non-glued staple joints with 2.5, 5, and 10-mm gaps, respectively. Glued staple joints used in sofa frames increased their reliabilities by 46.39%, 12.86%, and 34.37% for 2.5-, 5-, and 10-mm gaps, respectively. Although MT and dowel joints had 69.53% and 27.41% higher bending moment capacities than glued staple joints with a 10 mm gap, they all had the highest reliability (99.99%…) comparable to the others. Here, the variation of the datasets is as significant as their average in the calculation of the reliability; namely, MT had a coefficient of variation of 11.91%, while those of dowel and glued staple joints with a 10 mm gap were 3.24% and 6.34%, respectively. Similarly, even though glued staple joints with 5-mm (120.84 Nm) and 10-mm (120.50 Nm) gaps had roughly identical moment capacities and statistical analysis showed that there was no significant difference between their average moment capacities, the reliability of glued staple joints with 5 mm gap was 0.72% lower than those of 10-mm due to fact that its coefficient of variation 15.17% which was 139.47% higher than those of 10-mm. Similarly, it was observed in the critical joints I and K (Fig. 11 and Table 6) that S5 had a higher strength than S2.5 and S10, and the CoV of their moment capacities were 14.72%, 10.40%, and 6.35%, respectively. Hence, the higher CoV, correspondingly standard error, increases the chance of overlapping areas in the PDF of the capacities of joint strength and subjected loads. Increasing sample sizes in sample groups would reduce standard error, correspondingly, standard deviation, and coefficient of variation in datasets. Besides, moments in the joints of the sofa frame were not only theoretically obtained in the structural analysis, but a normality assumption was also made with a coefficient of variation of 10% for them. In the case of various coefficients of variation, the reliability of each joint in the frame may change so that overall reliability would be deviated positively or negatively. Given this information, an appropriate joint can be selected by measuring its reliability in constructing furniture frames.

In sum, this study showed how to measure the reliability of construction. This systematic method could be applied to any furniture construction, including the case-type construction mentioned above. A future study will examine the reliability measurement of furniture construction *via* FEA.

Table 6. Reliabilities of the Joints and Furniture Frame (%)

Joint Type	**Reliability of each joint on the sofa frame**												**Reliability of the sofa frame (R_{SS})**
	R_A	R_B	R_C	R_D	R_E	R_F	R_G	R_H	R_I	R_J	R_K	R_L	
MT	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*
Dowel	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*
S2.5	99.992	99.99*	81.245	99.99*	81.245	99.99*	99.992	99.99*	99.810	99.99*	99.810	99.99*	65.746
S5	99.965	99.99*	93.255	99.99*	93.255	99.99*	99.965	99.99*	99.776	99.99*	99.776	99.99*	86.516
S10	99.99*	99.99*	86.273	99.99*	86.273	99.99*	99.99*	99.99*	99.995	99.99*	99.995	99.99*	74.423
SG2.5	99.990	99.99*	98.171	99.99*	98.171	99.99*	99.990	99.99*	99.942	99.99*	99.942	99.99*	96.244
SG5	99.998	99.99*	99.653	99.99*	99.653	99.99*	99.998	99.99*	99.990	99.99*	99.990	99.99*	99.284
SG10	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*	99.99*

* Values are 99.999999…

CONCLUSIONS

1. This study investigated the reliability of the mortise and tenon (MT), dowel, and non-glued and glued staple joints in the frame construction made of beech wood. In this respect, T-shaped joints were examined to obtain moment capacities under statical load test. The probabilistic approach was used to determine the reliability of the frames. Consequently, this study revealed the following outcomes.
2. Reliability is a concern for product quality and long service life. Therefore, manufacturers should consider the reliability of furniture frames, especially critical joints in the frames, to satisfy their customers.
3. Single aspects for joint strength cannot alone explain the reliability of the construction. Therefore, probabilistic approaches provide a systematic method to establish an intermediate procedure.
4. The moment capacities of the MT joints (204 Nm) were expected to be higher than those of other types of joints and provided higher reliability for frame-type construction. Dowel joints (154 Nm) followed the MT joints.
5. In staple joints, gluing increased the joint strength. Increasing the number of staples in the joints also increased the joint strength, but narrower gaps between staples may reduce it. The highest moment capacity was obtained for both glued (121 Nm) and non-glued (90.4 Nm) staple joints with 5-mm gaps.
6. The standard error was critical to measuring the reliability of the frame construction due to the fact that the overlapping areas representing the failure of probability were getting larger. This was observed for the staple joints; namely, joints with 5-mm gaps had higher strength than those of 2.5- and 10-mm gaps, while their reliabilities on the joint were 99.81%, 99.77%, and 99.99%, respectively. Those of 5-mm had the lowest reliability owing to higher standard error even though they had higher strength compared to 2.5 and 10 mm.
7. In the frame-type construction, the load level should be determined after tributary loadings under imposed loads on the frame. Then, the critical joints should be determined, and their reliability should be ensured with the joint type having higher reliability. In doing so, the staple joints at low strength, for example, could be used for other joints; accordingly, the overall reliability of the frame construction could be established by reducing assembly time and cost because the machinery process is needed to prepare MT and dowel joints.

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