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Research article (Araştırma makalesi)

Effects of the semi-rigidity coefficients on numerical analysis results in chair side frame joints

Ali Kasal[a], Mustafa Batuhan Ulun[a], Tolga Kuşkun[a,*]

Abstract: In this study, it is aimed to determine the semi-rigidity coefficients related to joints of chair side frame and to use them numerical analyses with finite element method (FEM). Turkish beech (*Fagus orientalis* L.) and Scotch pine (*Pinus sylvestris* L.) were used for preparing the specimens; and glued dowel joint was preferred as jointing technique. T-type and L-type specimens were utilized for representing the side frame joints. Different diameters and lengths of dowels were used in the specimens, and effects of dowel these factors on semi-rigidity coefficients of joints were determined. Specimens were tested under static bending and semi-rigidity coefficients were determined by considering the elastic region of moment-rotation graphs. Then, numerical analyses were performed using these semi-rigidity coefficients and effect of defining the joints as rigid or semi-rigid on moment distribution and deflections at the joints was determined. As a result of study, it was understood that the chairs consisting of joints with high semi-rigidity coefficients, deflections decreased and joints deformed less, and these results were consistent with the deformation characteristics results obtained from real tests. The highest semi-rigidity coefficients were obtained from the Turkish beech T-type joints connected with 10 × 35 or 40 mm (4905 *Nm/rad*) dowels while the lowest values were obtained from the Scotch pine L-type joints connected with 8 × 40 mm (1892 *Nm/rad*) dowels.
Keywords: Chair frame, Numerical analysis, Semi-rigidity coefficients

Sandalye yan çerçeve birleştirmelerinde yarı rijitlik katsayılarının nümerik analiz sonuçlarına etkileri

Öz: Bu çalışmada, sandalye yan çerçeve birleştirmelerine ait yarı rijitlik katsayılarının belirlenmesi ve sonlu elemanlar yöntemiyle (FEM) gerçekleştirilen nümerik analizlerde kullanılması amaçlanmıştır. Deney örneklerinin hazırlanmasında Doğu kayını (*Fagus orientalis* L.) ve sarıçam (*Pinus sylvestris* L.); birleştirme tekniği olarak da kavelalı-tutkallı birleştirme tercih edilmiştir. Yan çerçeve birleştirmelerini temsilen, T-tipi ve L-tipi örnekler farklı çap ve boyda kavelalar kullanılarak hazırlanmış ve yarı rijitlik katsayıları üzerinde bu faktörlerin etkileri belirlenmiştir. Örneklere statik eğilme testi uygulanmış ve moment-rotasyon grafiklerinin elastik bölgesine göre yarı rijitlik katsayıları belirlenmiştir. Daha sonra yarı rijitlik katsayıları kullanılarak nümerik analizler gerçekleştirilmiş ve birleştirmelerin rijit ya da yarı rijit tanımlanmasının, sistemin moment dağılımı ve yer değiştirmeler üzerindeki etkisi belirlenmiştir. Çalışma sonucunda, yarı rijitlik katsayıları yüksek olan birleştirmelerde, yer değiştirme değerlerinin düştüğü ve daha az deformasyon olduğu anlaşılmış olup bu sonuçlar birleştirme deneylerinden elde edilen deformasyon karakteristikleri ile tutarlıdır. En yüksek yarı rijitlik katsayıları, 10 × 35 veya 40 mm (4905 *Nm/rad*) kavelalarla birleştirilen Doğu kayını birleştirmelerde elde edilirken, en düşük değerler ise 8 × 40 mm (1892 *Nm/rad*) kavelalarla birleştirilen Sarıçam birleştirmelerde elde edilmiştir.
Anahtar kelimeler: Sandalye çerçevesi, Nümerik analiz, Yarı rijitlik katsayısı

1. Introduction

It is worth noting that the development of technology has contributed to the increased use of computer-aided numerical analysis in the engineering design of furniture, as well as in many other fields. These analyses have the potential to identify potential strengths and weaknesses in furniture before mass production, allowing for the collection of valuable feedback to enhance the design. It is also worth noting that the literature contains examples of the application of computer-aided numerical analysis to furniture (Haviarova et al. 2001a; 2001b; Gustafsson, 1996). The objective of these applications is to enhance the strength of furniture through the use of numerical analysis techniques in a virtual environment prior to production. Furniture joints are semi-rigid connections, and it may be beneficial to determine the semi-rigidity coefficient values for each joint type through experimental methods.

In the context of civil engineering, particularly in the field of steel structures, existing structure analyses typically do not consider the behavior of joints. Therefore, at the joints, two kinds of connection assumptions are usually used: fully rigid and flexible. While it is expected that there is freedom of rotation but no moment is conveyed in flexible connections, it is supposed that all moment is transferred without rotation in rigid connections. In actuality, though, a third kind of connection (the semi-rigid connection) occurs. This third type of connection allows for some rotation and the transfer of moment. Despite the concept of semi-rigid nodes, numerous numercial analyses of structural systems are based

[a] Muğla Sıtkı Koçman University, Faculty of Technology, Department of Woodworking Industrial Engineering, Muğla, Türkiye
[*] **Corresponding author** (İletişim yazarı): tolgakuskun@mu.edu.tr
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on the assumption that the joints are fully rigid or flexible. While these assumptions offer a high degree of convenience in structural analysis, they do not accurately reflect the mechanical behavior of the joints. Joints facilitate the transfer of forces from one member to another, and the moment is the most significant force they transfer in a structural system. Angular deformations (rotations) are expressed as a function of moment at the joints. The moment-rotation curves, derived from experimental studies calculating the moment capacity of the joints, further explain the mechanical behavior characteristics of these joints. The moment-rotation curves demonstrate the interaction between the moment and the degree of angular deformation resulting from the moment. One method of obtaining the actual moment-rotation characteristics of joints is through experiments in real dimensions. Since the 1930s, methods for modeling moment-rotation curves of joints have been developed with experimental studies. The experimental data obtained from experiments have demonstrated that joints considered to be flexible have a certain rotational stiffness and that joints considered to be rigid have a certain relative angular deformation between the constituent members (Faella et al., 2000). In order to incorporate the nonlinear behavior of semi-rigid connections into the structural analysis, moment-rotation curves should be accurately analyzed. Many experimental and analytical semi-rigid models have been proposed by researchers, and their incorporation into the analysis is still a subject of research. Davison et al. (1987) collected moment-rotation curves obtained from experimental studies and both created a data base and digitized the data in order to model the behavior. Based on experimental results, some researchers have also proposed various mathematical models for modeling semi-rigid joints by constructing moment-rotation curves (Frye and Morris, 1975). In the study of Sekulovic and Salatic (2001), the effect of the flexibility resulting from the semi-rigid connection on the behavior of structures under static loads was investigated. In a subsequent study, Sekulovic et al. (2002) investigated the effect of connection flexibility on the nonlinear behavior of structures. The model under consideration was developed through the implementation of a parallel connection between a rotation spring and a shock absorber.

In the structural analysis of very large contructions such as buildings, the joints constitute a negligible place within the structure. Conversely, in smaller structural systems such as chairs, sofa frames, tables, etc., the joints constitute a more considerable place. In furniture frames, the material of the members that create the system and the joints represent the strength of the entire system. The precision of numerical analysis in the furniture engineering depends on the accurate definition of materials utilized in the construction of structural elements, the precise dimensions and geometries of member cross-sections, and the specific joints employed in the structural analysis. Consequently, in the structural analysis of furniture, the mechanical behavior of the joints assumes greater significance and is predicted to exert an influence on the analysis results, thus the joints (nodes) should be defined as semi-rigid. There are many studies related to the furniture engineering in literature. In a study investigating acceptable design values for dowel joints using the lower tolerance limit method, it was reported that deformations that could occur under the loads specified in the standards could be prevented if the design values of the joints were known (Uysal and Haviarova, 2021). In a study comparing the mechanical performance of stapled furniture joints made from heat-treated and untreated wood materials under static and cyclic bending loads, the ratio of static loading to cyclic loading was found to be 2.85 (Demirel and Er, 2022). Uysal (2023) conducted structural analyses using the stiffness method in front-to-back cyclic loading tests on wooden chairs and ultimately proposed acceptability coefficients for the joints. However, a review of the literature suggests that there is a limited number of studies conducted to determine the data on the semi-rigidity coefficients of the joints forming the furniture system. It is stated that the stiffness of the corner joints affects the strength of the furniture. In this study, the stiffness of the corner joints was changed by increasing the number of dowels; first, the stiffness of the corner pieces was measured by experiments, and then the deflection values of the body furniture were calculated by finite element method (FEM). The results showed that increasing the number of dowels can reduce the furniture deflection by 5-15% (Cai and Wang, 1993). Both a numerical model of cabinet furniture constructing using semi-rigid confirmat screw joints and a mathematical model was created. As a result, it was demonstrated that well work of a rigid connection in the vicinity of substantially deformable wood-derived materials is described by models of a semi-rigid constructional node of the confirmat type (Smardzewski and Ozarska, 2005). Roche et al. (2015) investigated the semi rigid properties of dovetail joints used in laminated veneer lumber (LVL) panels. They employed numerical methods to estimate joint rigidity and examined how tab length and contact face angle influence semi-rigidity, offering insights into optimizing joint design for structural applications. The stiffness of corner type detachable joints used in furniture elements made of beech veneer plywood was investigated. Within the scope of the study, stiffness coefficients were determined by bending tests under compression (Simeonova et al., 2015). Hu and Guan (2019) developed a finite element model (FEM) to analyze the semi-rigid behavior of mortise and tenon joints, incorporating factors such as glue line thickness and friction coefficients. The model exhibited an accuracy of over 85% in predicting withdrawal and bending capacities, thus providing a valuable tool for evaluating joint performance in wooden frameworks (Hu and Guan, 2019). The study investigated the horizontal lateral shear resistance of staples commonly used in furniture frames in solid wood. In the case of joints constructed of beech, alder, and Scotch pine, it was observed that strength increased as the number of staples increased, with the highest strength achieved in beech. Furthermore, two equations developed to predict connection strength (Demirel and Kalaycı, 2020). In a representative chair side frame with semi-rigid joints, the relationships between semi-rigidity coefficients and deflections were analyzed by the slope-deflection method and this method was proposed to be used in the analysis of wooden furniture frames (Güray et al., 2022). Accordingly, in this study, the moments and deflections occurring at the joints of a chair side frame under front to back loading were obtained numerically using computer-aided three-dimensional numerical analyses with FEM. The innovative and unique aspect of the study is that it utilizes experiments to determine the "semi-rigidity coefficients" for chair side frame joints, which are very limited in the literature, and uses these values in numerical analyses. In this context, the hypothesis of the study was "in computer-aided numerical analysis, the definition of the joints in chair side frame as rigid or semi-rigid has an effect on the moment distribution and deflections in the system". The underlying goals of the study were determination of the effects of wood species, dowel diameter and length on semi-rigidity coefficients of T-type and L-type dowel joints.

2. Materials and methods

2.1. Determination of the physical and mechanical properties of the materials

In the preparation of specimens, Turkish beech (*Fagus orientalis* L.) and Scotch pine (*Pinus sylvestris* L.), which are widely used in the furniture industry were utilized. The wood materials were procured from various timber companies operating within the market. The initial phase of the furniture engineering design process entails the determination of physical and mechanical properties of the materials to be utilized in production. In this direction, the fundamental physical and mechanical properties of the materials utilized in the fabrication of the specimens were determined. In the scope of the study, tests were conducted to determine the density (TS ISO 13061-1, 2021) and moisture content of the materials (TS ISO 13061-2, 2021), as well as its bending strength (TS ISO 13061-3, 2021) and modulus of elasticity (TS ISO 13061-4, 2021).

2.2. Preparation of the T-type and L-type joint specimens

As part of the testing process, test specimens were prepared to represent the joints of a chair side frame. These specimens included T-type joints (back leg to side rail and back/front leg to stretcher) and L-type joints (front leg to side rail) as shown in Figure 1.

Both T-type and L-type specimens consist of 2 members, horizontal (side rail/stretcher) and vertical (back/front leg). In the joints, horizontal member was prepared in the dimensions of 350 × 50 × 21 mm and vertical member was prepared in the dimensions of 250 × 50 × 21 mm, taking into account the dimensions commonly used for a real chair members. In the joints, 4 different sizes of dowels prepared from Turkish beech with grooved surface, 8 and 10 mm in diameter, and 35 and 40 mm in length, randomly obtained from the market were used. In each joint, 2 dowels were used and the distance between the dowel axes was taken as 32 mm considering the suitability for mass production. The dowel holes were adjusted to be 20 mm depth in the horizontal member where the dowel was driven and 15 mm depth (penetration) in the opposite vertical member for 35 mm dowels; and 20 mm depth (penetration) for 40 mm dowels.

Polyvinyl acetate (PVAc) glue (50% solid content) was used in the joints because it is widely used in the production of frame furniture due to its features such as being used cold, easy to apply, hardening quickly, odorless and fireproof. The glue was applied to the joints, dowels and dowel holes with an average of 150±10 g/m². During the assembly process, pressure was applied to the joints in the pressing process and the specimens were kept pressed for 8 hours. Before the tests, the prepared specimens were conditioned in a chamber at 20 ± 2 °C and 65 ± 3% relative humidity (r =12%) until equilibrium was reached and the moisture differences between the specimens were eliminated. A collective view of the T-type and L-type specimens is presented in Figure 2.

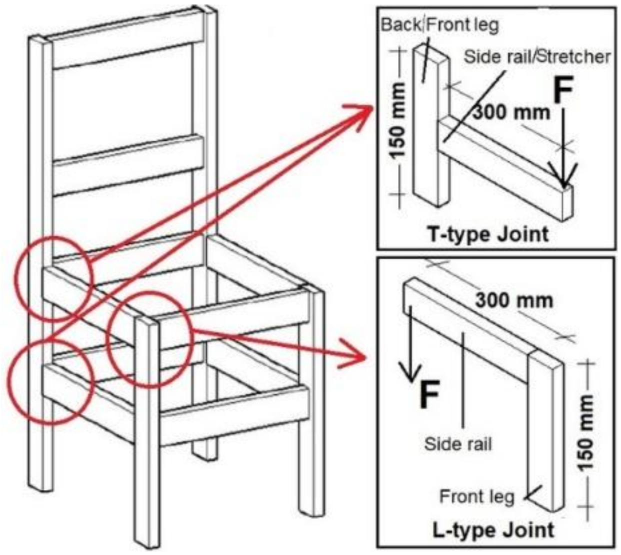


Figure 1. T-type and L-type joints representing the chair side frame joints

Figure 2. View of the prepared T-type and L-type joint specimens

Accordingly, a total of 40 T-type and 40 L-type joint specimens were prepared, including 2 wood species, 2 dowel diameters, 2 dowel length (penetration) and 5 replications of each specimen. In total, 80 specimens were prepared and tested.

2.3. Testing of the joint specimens and determination of the semi-rigidity coefficients

The prepared T-type and L-type joint specimens were tested under static bending loads in accordance with the loading form which the chairs were subjected in front to back horizontal loading tests (ALA, 1982; Eckelman, 1995;1999), and the semi-rigidity coefficients were determined for each joint by taking into account the elastic region of the moment-rotation characteristics obtained from the tests. Figure 3 shows the front to back loading of a chair frame (Figure 3a) and loading form of each joint in the side frame of a chair (Figure 3b).

In the tests, the moment-rotation relationships of T-type and L-type joints were examined, and the elasticity (semi-rigidity coefficients) values of each type of dowel joint were determined and these values were used in defining the chair joints to the numerical analysis software. In another words, the obtained elasticity values were used as the semi-rigidity coefficients of the joints. Here, the aim was to define the chair joints as semi-rigid in the numerical analyses. In particular, the semi-rigidity coefficients of each joint are important in terms of the realistic moment distribution and deflections to be obtained from the numerical analyses.

Tests were carried out in the 50 kN capacity computer-controlled universal testing machine with static loadings provided at a speed of 6 mm/min in the loading column. The test load was applied from the distance of 300 mm from the joint. In order to measure the flexibility of joints, the vertical deflections were measured and force-deflection relations were obtained accordingly. Then, these obtained force-displacement relations were converted into a moment-rotation diagram and the semi-rigidity coefficients of the joint was determined.

In defining the moment-rotation relations, linear elastic region was obtained in the section of approximately 10% and 40% of the maximum moments. In the tests, the points where the lines determining the moment-rotation relationships intersect the ordinate (y) axis are taken as the origin (0,0). Therefore; the equation of the lines obtained from the relationship is expressed as “y = ax”. Here; y: moment (*Nm*), x: rotation angle (*rad*), a: regression coefficient (slope of the line). The (a) value in the equation is the “regression coefficient”. This coefficient determines the slope of the line defining the relationship (Figure 4).

Consequently, the semi-rigidity coefficients (*K*) (*Nm/rad*) of the T-type and L-type joints were obtained from Eq. 1 through the utilization of moment (*M*) (*Nm*) and rotations (ϕ) (*rad*).

$$K = \frac{M}{\emptyset} \qquad (Nm/rad) \qquad (1)$$

2.4. Numerical analyses of the representative chair frames

For the numerical analysis, a representative simple chair model design, which is widely used in the industry was selected. In the selected chair model, the cross section dimensions of all members are equivalent in size, measuring 21 (b: Base) × 50 (h: Height) mm. In determining the dimensions of the chair, the cross-sections and dimensions commonly used in the furniture industry were taken into consideration. The dimensions of the chair that was modeled and analyzed in the scope of the study and three dimensional view of the representative chair model are shown in Figure 5 with the loading direction and value, and supports.

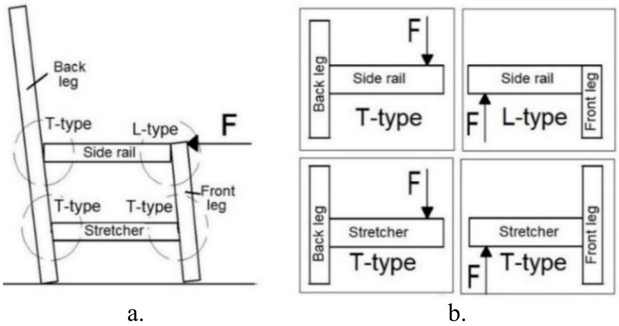


Figure 3. Typical deformation of a chair side frame in front to back loading (a) and the loading forms which the side frame joints are subjected (b)

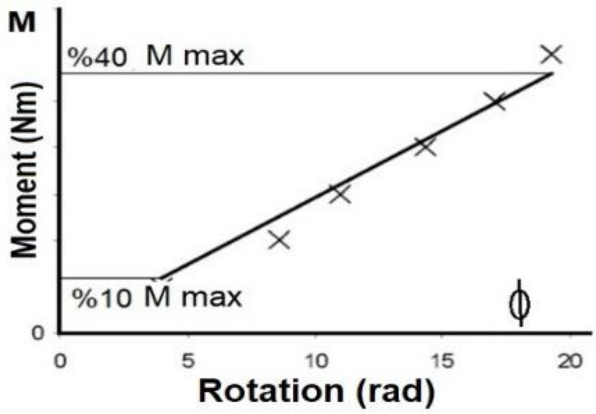


Figure 4. Moment–rotation relations in the elastic region in L-type and T-type specimens

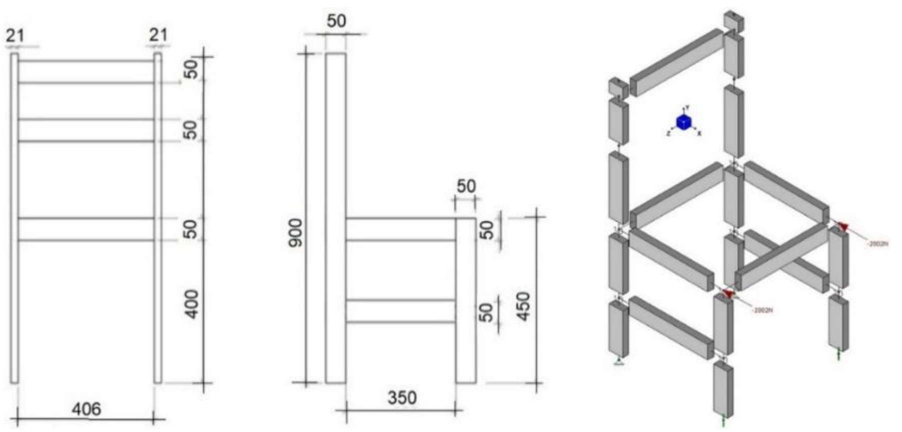


Figure 5. The representative chair model used in the numerical analyses

Computer-aided three-dimensional numerical analyses were carried out with RISA 3D, a finite element software (RISA, 2000). The representative chairs were modeled as three-dimensional frame systems in accordance with their real-life behavior in numerical analyses. The structural members of the chair are modeled as linear elastic beams. In summary, these members are defined to carry axial forces, shear forces, and moments. The grain directions of the wood material were considered during the definition of each member. In the modeling of the chair elements, care was taken to ensure that the width direction in the section was radial and the height direction was tangential. This approach was used to accurately simulate the behavior of the members under loads. At the initiation of the modeling process, the unit system was established as the fundamental framework for measurement. In this study, the metric system and the International System of Units (SI) were taken as the basis. Subsequently, the properties of the material utilized in the manufacturing of the chairs were entered into the program. In order to obtain precise results in numerical analysis, it is imperative to define certain technological properties of the Turkish beech and Scotch pine utilized in the frames of the chairs. Some of these properties were obtained from tests, while the remainder were taken from the literature (Güntekin et al., 2016a; 2016b; USDA, 2021; Güntekin, 2023). The moisture content (MC) of the Turkish beech and Scotch pine was measured to be 11.2%, and 10.8%, respectively. The properties entered into the program to define the materials are enumerated in Table 1.

Subsequently, cross-sectional properties of the member constituting the chair were introduced. In the context of the model, cross-sectional dimensions of all members are measured at 21 × 50 (radial x tangentional) millimeters. Consequently, when delineating the cross-sectional dimensions, it was stipulated that all members of chair would possess dimensions of 21 × 50 mm (Table 2). Moment of inertia (I) values in (y) and (z) directions were calculated by Eq. 2;

$$I = \frac{b \times h^3}{12} \qquad (mm^4) \tag{2}$$

while torsional constant (J) was calculated by the Eq. 3:

$$J = \left(\frac{h}{2} \times \left(\frac{b}{2}\right)^3\right) \times \left(\left(\frac{16}{3}\right) - 3.36 \times \left(\frac{\frac{b}{2}}{\frac{h}{2}}\right) \times \left(1 - \left(\frac{\left(\frac{b}{2}\right)^4}{12 \times \left(\frac{h}{2}\right)^4}\right)\right)\right) (mm^4) \tag{3}$$

In the next step, a three-dimensional chair model was created by modeling all the members of the chairs in real dimensions and cross-sectional properties. In order to analyze the chair model, the members should be merged at the intersection points. Although the chair members are in end to end contact before the merging process, there is no complete joining. In order to perform numerical analysis, each member should be fully merged to each other at the intersection points. After this process, the intersecting/contacting points in the model are merged to each other as joined. At this stage, the chair model was created and the system assigned code numbers to each node (joint) (N1, N2, ... Nn) and each member (M1, M2, ... Mn) forming the chair model. The nodal points, members and the starting (i: Red) and ending (j: Blue) points of the members of the generated models are shown in Figure 6.

According to Eckelman (Eckelman, 1968), the joints that construct the furniture systems are semi-rigid. If these joints are defined as rigid in the numerical analysis, the whole system rotates without any opening at the joints and this situation does not reflect the reality. At the same time, distribution of the total moment affecting the system to the joints and the deflections are also affected. In reality, in a furniture system under loading, rotations occur at the joints as well as rotations of the whole system. These rotations is related to elasticity (semi-rigidity coefficients) of joints. Each joint has its own semi-rigidity coefficient value. In numerical analysis, it is important to define the joints as semi-rigid in order to obtain reasonable results from the calculations (Eckelman, 1968). In the numerical analyses within the scope of the study; two different approaches were taken to define the joints. In the numerical analyses, as a first approach, all joints were defined as rigid and moment distribution, bending stresses, and deflections were obtained from the analyses. Then, as a second approach, the semi-rigidity coefficients obtained from the bending tests of the T-type and L-type joints in this study were used to define each joint (Table 6). Each joint in the chairs was defined as a spring in the software and the the semi-rigidity coefficient values obtained for each joint were entered into these joints as spring constant values. Considering the front to back loading in the analyses, the spring constant values were defined as rotations around the (Z) axis. In the numerical analysis, first of all, the modeled chair legs (nodes in contact with the ground) were supported. In the front to back loading test in the American Library Association technology report specification (ALA, 1982; Eckelman 1995; 1999), roller supports are used in the end of front legs and pinned supports are used in the end of back leg.

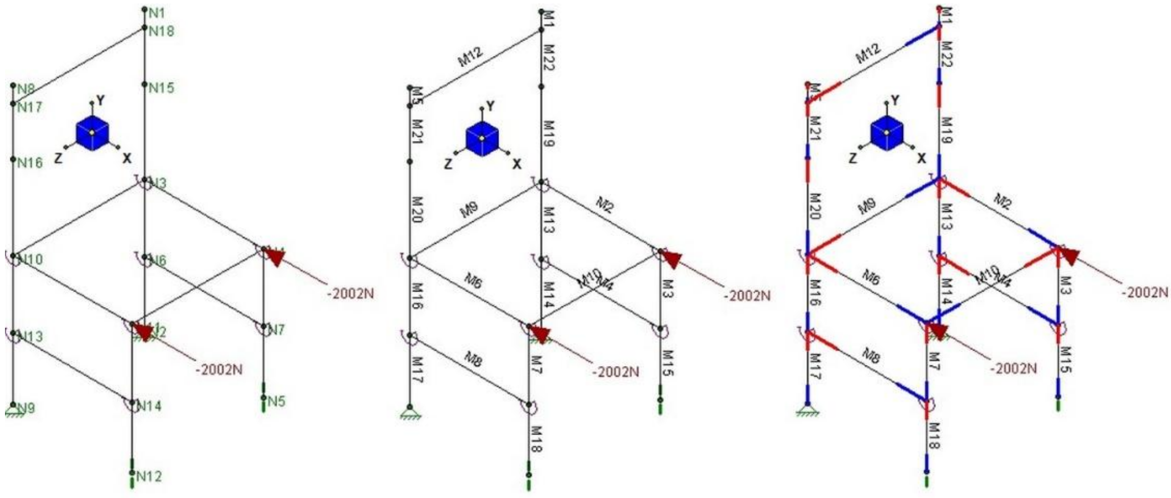
Table 1. Some physical and mechanical properties of Turkish beech and Scotch pine

Wood species	Modulus of elasticity (E_L) (N/mm^2)	Shear modulus (G_{LR})(N/mm^2)	Poisson ratio (μ)	Thermal conductiv. ($W/m.K$)	Density (kg/m^3)	Bending strength (σ_e) (N/mm^2)
Turkish beech	11800	1230*	0.63**	0.18****	630	125
Scotch pine	10289	1334***	0.72**	0.13****	450	99

* Taken from Güntekin et al. (2016a), ** Taken from Güntekin et al. (2016b), *** Taken from Güntekin (2023), **** Taken from USDA (2021)

Table 2. Cross sectional properties of the chair members

Section size ($b \times h$)(mm)	Area ($A=bxh$) (mm^2)	Moment of inertia (I_z) (mm^4)	Moment of inertia (I_y) (mm^4)	Torsional constant (J) (mm^4)
21 × 50	1050	218750	38588	113615



a. b. c.

Figure 6. Nodes (a), members (b) and starting (red) and ending (blue) points (c)

Accordingly, while defining the supports in numerical analysis, for the pinned support setting; translations in the *X*, *Y*, *Z* directions for the nodal point of the back leg are reacted and rotations are left free. For the roller support setting in the front leg; only translations in the *Y* direction are reacted at the nodal point and all other translations and rotations are left free. At the load application phase, a constant load value (2002 *N*) was applied to chair model and the moments, bending stresses and deflections at the member ends of the chair models were examined under the same load. For this load value, the acceptable heavy use loads in the technology report specification (ALA, 1982; Eckelman, 1995; 1999) were taken as reference.

After the supporting, the front to back loadings were applied by considering the load application axis and direction so that the points where the load would be applied were the same as the application points in the real tests. Although the acceptable design loads specified in the specification (ALA, 1982; Eckelman, 1995; 1999) are according to the cyclic stepped increasing loading method, the chair model was solved according to static loading in numerical analysis. Therefore, the relationship between the static and cyclic loads was taken into account when applying the loads in the numerical analysis. In the literature, it is stated that the strength of a frame structure under cyclic loads should not exceed 50% of the strength under static loads (Eckelman and Erdil, 1999; Likos et al. 2012; Kuşkun et al. 2018). In this case, the strength of a frame system under cyclic loads is considered to be half of its strength under static loads. Therefore, in numerical analyses, accordingly, twice the load values to be applied are taken into account. For this reason, while entering the load value, the test load value was entered as two times in total to be applied to each side frame separately.

3. Results and discussion

3.1. Experimental results of the T-type and L-type joints

The bending tests were completed in approximately 90-120 seconds. The specimens showed an expected deformation characteristic. Generally, the joints were opened by an angular deformation (rotation). In the openings, the dowels came back out of the holes; in other words, the deformation was caused by excessive shear stresses in the glue line. In the specimens joined with 8 × 40 mm dowels, which can be characterized as thin and long, fractures in the dowels were observed. The typical deformation characteristics of the T-type and L-type joints in the chair side frame after the bending tests are shown in Figure 7.

These findings demonstrated that the deformation behavior is influenced by the shear strength of adhesive and the geometry of the dowels. The dowel withdrawal indicates that the glue line may not have provided sufficient resistance to shear forces, possibly due to limited bonding area or insufficient dowel penetration. Similar rotational deformation were reported in the previous studies (Kasal et al., 2016; Chen et al., 2018), supporting the observed failure modes. The fractures observed in the 8 × 40 mm dowels indicate that their slender dimensions may not withstand bending stresses efficiently. Therefore, utilizing shorter or thicker dowels, or improving adhesive application methods, could enhance the performance of such joints in future applications.

a. b. c. d.

Figure 7. Deformation characteristics of T-type (a: Turkish beech, b: Scotch pine) and L-type (c: Turkish beech, d: Scotch pine) specimens representing chair side frame joints

In the statistical evalation of the test results, elasticity (semi-rigidity coefficient) data were obtained from each test and this value was considered as the dependent variable. Then, the effects of the main factors of wood species (WS), dowel diameter (DD) and dowel length (DL) (independent variables) and their interactions on the semi-rigidity coefficients of T-type and L-type joints were determined by multiple variance analysis (MANOVA). If the differences were found to be statistically significant at p<0.05 as a result of the variance analysis, the least significant difference (LSD) comparison test was used for the significance of these differences between the groups. Minitab Statistical Software program was used for statistical analyses. The MANOVA results for both T-type and L-type joints are given in Table 3.

According to the results of MANOVA, effects of the main factors of WS and DD on the semi-rigidity coefficients of T-type and L-type joints were found to be significant, while effects of the main factor of DL were found to be statistically insignificant. Among the two-way interactions; effects of WS × DD and DD × DL on the semi-rigidity coefficient values of both T-type and L-type joints were found significant, while effect of WS × DL interaction was found insignificant. The results of the three-way interaction were statistically significant for both joint groups. According to these results, LSD comparison tests were performed for main factors, two-way and three-way interactions found significant in the MANOVA. When the F-values in the MANOVA are analyzed, effect of WS on semi-rigidity coefficients of L-type joints is much more significant than the DD. On the other hand, both DD and WS have a significant effect on semi-rigidity coefficient values of T-type joints. The comparison of the means of effects of the main factors of wood species and dowel diameter, which were found statistically significant in the MANOVA, on the semi-rigidity coefficient values of the T-type and L-type joint test specimens are given in Table 4.

According to these results, the specimens prepared from Turkish beech were 16% more rigid in T-type joints; and 39% more rigid in L-type joints than the specimens prepared from Scotch pine. This indicates that Turkish beech provides significantly higher joint stiffness, likely due to its higher density and mechanical strength compared to Scotch pine. This finding supports the preference for hardwoods such as beech in applications where joint rigidity is critical (Örs and Efe, 1998; Ceylan et al., 2021). As a result of the comparisons made for dowel diameter; it is understood that the increase in the dowel diameter causes an increase in the stiffness of both T-type and L-type joints. In both joint type, increasing the dowel diameter from 8 mm to 10 mm increased the stiffness of the joints by 15% on average. This result confirms that larger dowel diameters contribute positively to joint stiffness, likely due to the increased contact area and load distribution. The observed increase in joint stiffness with larger dowel diameters supports with findings from previous studies conducted by Chen et al., 2018; Yüksel et al., 2022). The study conducted by Chen et al. (2018) demonstrated that increasing dowel diameter significantly enhances the bending strength of both T-shaped and L-shaped double wood joints. The study also established linear regression equations correlating dowel diameter with bending strength, indicating a positive relationship between dowel size and joint stiffness (Chen et al., 2018). The mean comparison for the effects of DD × DL two-way interaction on the semi-rigidity coefficient values of T-type and L-type joint specimens is given in Table 5.

Table 3. Results of variance analyses for both T-type and L-type joints

Joint	Sources	Degrees of freedom	Sum of squares	Mean square	F-value	Probability (p<0.05)
T-type joint	WS	1	4101721	4101721	27.19	0.000*
	DD	1	4434083	4434083	29.39	0.000*
	DL	1	14288	14288	0.09	0.760
	WS x DL	1	1926651	1926651	12.77	0.001*
	WS x DL	1	44290	44290	0.29	0.592
	DD x DL	1	895613	895613	5.94	0.021*
	WSxDDxDL	1	77045	77045	0.51	0.480*
	Error	32	4828080	150878	-	-
	Total	39	16321771	-	-	-
L-type joint	WS	1	7319906	7319906	49.31	0.000*
	DD	1	1255915	1255915	8.46	0.007*
	DL	1	42939	42939	0.29	0.594
	WS x DL	1	70491	70491	0.47	0.496*
	WS x DL	1	42787	42787	0.29	0.595
	DD x DL	1	735470	735470	4.95	0.033*
	WSxDDxDL	1	51264	51264	0.35	0.491*
	Error	32	4750244	148445	-	-
	Total	39	14269016	-	-	-

WS: Wood species, DD: Dowel diameter, DL: Dowel length, * Statistically significant

Table 4. Mean comparison for wood species and dowel diameter on semi-rigidity coefficients

Variables	Semi-rigidity coefficient (*Nm/rad*)			
	T-type Joint		L-type Joint	
	X	HG	X	HG
Wood species				
Turkish beech	4737.91	A	3048.08	A
Scotch pine	4097.47	B	2192.71	B
Dowel diameter				
8 mm	4084.74	B	2443.30	B
10 mm	4750.63	A	2797.69	A

X: Mean Value, HG: Homogenity Group

According to the DD ×DL two-way interaction, the dowels providing the most stiff joints in T-type or L-type joints were obtained as those with a diameter of 10 mm and a length of 40 or 35 mm. Accordingly, it is understood that when a 10 mm diameter dowel is used, whether the length of the dowel is 35 mm or 40 mm does not affect the stiffness of the joints. The dowel that provided the most flexible joint was the dowels with a diameter of 8 mm and a length of 40 mm, which can be described as relatively thin and long. When the deformation characteristics were examined, it was observed that these 8 × 40 mm dowels, which provided a flexible joint, broke in the experiments. Three-way interaction results of semi-rigidity coefficient values obtained as a result of the tests of L-type and T-type joint specimens under static bending loading are given in Table 6 together with the coefficients of variation.

Accordingly, considering all the factors tested within the scope of the study, the highest semi-rigidity coefficient values were obtained for both T-type and L-type joints constructed of Turkish beech and connected with the dowels of 10 mm diameter and 35 or 40 mm length (15 or 20 mm penetration). However, in the T-type joints, the differences between the dowels of all sizes were found to be statistically insignificant, as the effect of WS was very obvious. Again, in T-type joints, the joints prepared from Scotch pine and connected with 10 mm diameter and 35 or 40 mm length dowels were in the same HG with all groups prepared from Turkish beech. The lowest semi-rigidity coefficients were obtained in the specimens prepared from Scotch pine with 8 mm diameter and 40 mm length dowels which could be characterized as elongated compared to other dowels.

3.2. Numerical analyses results of the representative chair model

The general deformation characteristics of chair model are shown in Figure 8a in side view and Figure 8b in three dimensional. In the numerical analyses, the moments, bending stresses and deflections occurring in the members as a result of front to back loading were obtained from the numerical analysis results. The diagram showing the distribution of the moments occurring in the chair members is shown in Figure 8c.

Table 5. Mean comparison for DD × DL two-way interaction on semi-rigidity coefficients

Dowel diameter	Dowel length	Semi-rigidity coefficient (*Nm/rad*)			
		T-type Joint		L-type Joint	
		X	HG	X	HG
8 mm	35 mm	4253.28	B	2611.66	AB
	40 mm	3916.21	B	2274.94	B
10 mm	35 mm	4619.90	A	2694.86	A
	40 mm	4253.28	B	2611.66	AB

X: Mean Value, HG: Homogenity Group

Table 6. Mean comparison for effects of three-way interactions on semi-rigidity coefficients

Wood species	Dowel diameter	Dowel length	Semi-rigidity coefficiens (*Nm/rad*)					
			T-type joint			L-type Joint		
			X	COV(%)	HG	X	COV(%)	HG
Turkish beech	8 mm	35 mm	4782.36	10.62	A	3000.56	9.20	AB
		40 mm	4466.51	5.77	A	2657.65	14.86	BC
	10 mm	35 mm	4797.82	7.83	A	3096.11	13.64	AB
		40 mm	4904.96	4.55	A	3438.79	16.92	A
Scotch pine	8 mm	35 mm	3724.20	11.31	B	2222.77	15.62	CD
		40 mm	3365.91	9.66	B	1892.23	17.98	D
	10 mm	35 mm	4441.98	11.29	A	2293.60	16.46	CD
		40 mm	4857.78	8.15	A	2362.26	10.34	CD

COV: Coefficients of Variation, X: Mean Value, HG: Homogenity Group

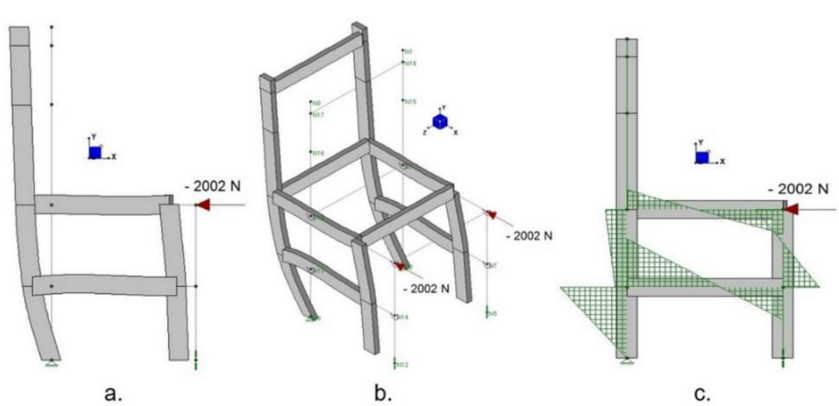


Figure 8. Typical deformation (a, b) and moment diagram (c) of the modeled chairs

For the chairs modeled with “rigid” joint definition and “semi-rigid” joint definition according to the type of dowel used in the numerical analyses, the values of the total moment generated as a result of front to back loading distributed to the side frame joints and the percentage distribution of the moments are given in Table 7.

The total moment created in the chair side frame system by the horizontal force of 2002 N applied to each side frame was theoretically obtained by multiplying this horizontal force by the height at which the test load was applied. Since the test load was applied at a height of 420 mm, the total moment carried by the side frame joints was calculated by multiplying the load value applied from front to back by 0.42 m and the total moment was obtained as 840.84 *Nm*. In the chairs modeled with rigid joints, all amount of the total moment is distributed to the joints. However, in the chair models with semi-rigid joints, a part of the moment (approximately 10%) accumulated before the rotation started in the joints, in other words, until the spring constant values were exceeded. The remaining part of the total moment (90%) was shared to the joints in the side frame. According to the moment distribution obtained from the numerical analyses, it is seen that the joint subjected to the highest moment values in chair side frame is the back leg to stretcher joint.

In structural systems with rigid joints, since the moment distribution and ratios of the moments in the joints are not material dependent variables, they do not vary according to the wood species, and they have equal values and ratios for the chairs assumed to be made of both wood species. Similarly, since the cross-sectional dimensions of members constructing the chairs modeled from both wood species are the same, bending stress values at the ends of members due to the moments do not vary according to wood species and occur at the same values for both wood species. However, in the results of numerical analyses, different values were obtained in the distribution of the total moment to the joints and the bending stress values corresponding to each joint by defining the joints as rigid or semi-rigid, and even by defining different joints with different semi-rigidity coefficients. The bending stress values occured et each side frame joint are given in Table 8. The deflections (mm) of each joint in the horizontal (X) direction was also obtained from the numerical analysis. The deflection (translation) of each joint in the side frame in the horizontal (X) direction as a result of front to back loading in the chairs modeled with “rigid” joint definition and “semi-rigid” joint definition according to the type of dowel used in the numerical analysis are also given in Table 8.

Since the deflections (translation or rotation) occurring at the joints of the structural system are related to the modulus of elasticity of the material, the amount of deflection varies according to the wood species. The numerical analysis results confirmed this phenomena. It was also observed that the deflections varied when the joints were defined as rigid or semi-rigid, and even when different joints were defined with different semi-rigidity coefficients.

Table 7. Moments (*Nm*) and moment distribution ratios (*%*) occured in side frame joints

Joint type	Moment (*Nm*) / Moment distribution ratio (%)					
	Side frame joint				Numerical total moment (*Nm*)	Theoretical total moment (*Nm*)
	Front leg to side rail	Back leg to side rail	Front leg to stretcher	Back leg to stretcher		
Turkish beech						
Rigid joints	165 / 19.62	131 / 15.57	217 / 25.83	328 / 38.96	841 / 100	841 / 100
8 × 35 mm	146 / 17.40	116 / 13.79	194 / 23.08	294 / 35.00	751 / 89.28	841 / 100
8 × 40 mm	148 / 17.57	117 / 13.92	196 / 23.25	296 / 35.24	757 / 89.99	841 / 100
10 × 35 mm	146 / 17.37	116 / 13.77	194 / 23.07	294 / 34.98	750 / 89.21	841 / 100
10 × 40 mm	145 / 17.24	115 / 13.70	194 / 23.01	293 / 34.88	747 / 88.85	841 / 100
Scotch Pine						
Rigid Joints	165 / 19.62	131 / 15.57	217 / 25.83	328 / 38.96	841 / 100	841 / 100
8 × 35 mm	148 / 17.65	118 / 13.98	196 / 23.35	298 / 35.39	760 / 90.39	841 / 100
8 ×40 mm	150 / 17.86	119 / 14.14	198 / 23.57	300 / 35.72	768 / 91.31	841 / 100
10 × 35 mm	147 / 17.43	116 / 13.77	193 / 22.94	293 / 34.81	748 / 88.96	841 / 100
10 × 40 mm	146 / 17.30	115 / 13.65	191 / 22.70	290 / 34.47	741 / 88.14	841 / 100

Table 8. Bending stresses (N/mm^2) and deflections (*mm*) in side frame joints

Wood species	Joint type	Bending stress (N/mm^2) / Deflection (*mm*)			
		Side frame joint			
		Front leg to side rail	Back leg to side rail	Front leg to stretcher	Back leg to stretcher
Turkish beech	Rigid Joints	18.85 / 6.18	14.96 / 6.17	24.83 / 4.53	37.44 / 4.48
	8 × 35 mm	16.72 / 5.81	13.25 / 5.80	22.18 / 4.30	33.63 / 4.25
	8 × 40 mm	16.88 / 5.84	13.37 / 5.83	22.34 / 4.31	33.87 / 4.26
	10 × 35 mm	16.69 / 5.81	13.24 / 5.80	22.17 / 4.30	33.62 / 4.25
	10 × 40 mm	16.57 / 5.80	13.17 / 5.79	22.11 / 4.29	33.52 / 4.24
Scotch pine	Rigid Joints	18.85 / 7.09	14.96 / 7.08	24.83 / 5.20	37.44 / 5.13
	8 × 35 mm	16.69 / 6.71	13.44 / 6.70	22.44 / 4.96	34.01 / 4.90
	8 × 40 mm	17.17 / 6.74	13.59 / 6.73	22.65 / 4.98	34.32 / 4.92
	10 × 35 mm	16.75 / 6.65	13.23 / 6.64	22.04 / 4.92	33.45 / 4.86
	10 × 40 mm	16.63 / 6.62	13.11 / 6.60	21.82 / 4.90	33.13 / 4.84

4. Conclusions

Based on current study, the followings were obtained:

- Effects of wood species and dowel diameter on semi-rigidity coefficients of joints were found to be significant, while effects of dowel length were found to be insignificant.
- Turkish beech specimens were more rigid than the Scotch pine specimens.
- The increase of dowel diameter causes an increase in the stiffness of joints.
- The lowest semi-rigidity coefficients were obtained in the specimens prepared from Scotch pine with 8 mm diameter and 40 mm length dowels.
- The highest semi-rigidity coefficient values were obtained with the Turkish beech spevcimens connected with 10 mm diameter and 35 or 40 mm length dowels.
- It was found that the moment and bending stress values are reduced and the joints become safer in structural systems consisting of joints with high semi-rigidity coefficients.
- The numerical analysis results are consistent with the deformation characteristics obtained from the actual tests of T-type and L-type joints.
- Lower moment and bending stress values were obtained in the joints of chairs modeled with the dowels with high semi-rigidity coefficients.
- The hypothesis of the study is accepted; the results obtained from the numerical analysis vary as a result of defining different semi-rigidity coefficients for the joints.

The semi-rigidity coefficients obtained from this study bridge the gap between the idealized and realistic behavior of dowel-type furniture joints. The use of these coefficients leads to more efficient, accurate, and sustainable designs while laying the groundwork for industry-wide standardization and engineering applications. The dissemination of the study's findings, particularly concerning their real-world industrial applications, is crucial for enhancing comprehension of practical solutions and industrial applications. Future research on the semi-rigidity of furniture joints could concentrate on developing advanced modeling techniques, such as finite element analysis and nonlinear joint models, to better predict joint behavior under various loads. Additionally, investigating the effects of different materials, jointing techniques, and cyclic loading conditions could improve understanding of joint strength. In order to create reliable design guidelines, experimental studies should be conducted examining various wood species, fastener arrangements, and loading conditions.

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