Combined stress analysis of mitered spline furniture joints under diagonal loading

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Abstract: Experiments were conducted to determine the effects of frame wood species, spline material type (beech wood and plywood), and spline depth of penetration (10-, 15-, and 20-mm) on diagonal tension load-bearing capability and corresponding combined stresses of mitered spline furniture joints. Joint frames (horizontal and vertical members) were made out of beech (*Fagus orientalis* L.), hornbeam (*Carpinus betulus*), white oak (*Quercus alba*), and poplar (*Populus deltoides*). It was found that joints made with beech frames were significantly stiffer than joints constructed of other wood species. Joints fabricated with plywood splines were approximately 166% stronger than joints made with beech wood spline. For the specimens constructed with plywood spline, penetration depth of 20-mm gave better results than penetration depths of 10- and 15-mm, while in case of joints made with beech wood spline the best results were obtained for 15-mm penetration depth. Based on the numerical analysis, average values of compression stress at the outer edge of the joints was greater than average tension stress values at the inner edge. During the tests, tension perpendicular to the grain failure occurred in beech wood spline, whereas for joints with plywood spline most failures occurred in the glue line between the plies of the plywood.
Keywords: bending strength, combined stress, furniture, load-bearing capacity, mitered spline joints, plywood spline.

1 Introduction

Among the various types of corner joints used in furniture industry, mitered corner joint is one of the most popular ones; specifically, because it is very easy and quick to produce. However, a mitered corner joint itself is not strong enough to be used and needs to be reinforced with connectors such as splines, dovetail keys, dowels, etc. Studies have been performed on strength performance of mitered corner joints so far that most of them are in conjunction with the load performance of mitered corner joints constructed with dovetail keys (Kılıc et al. 2009; Alton et al. 2010; Maleki et al. 2012a; Dalvand et al. 2013). As an example, a new method have recently been introduced by Maleki et al. (2012) for combined stress analysis of mitered corner joints with dovetail keys under diagonal tension loads. These researchers demonstrated that using the combined stress analysis very useful information is available on how a specific furniture corner joints behaves under external loads. Over the different types of mitered joints used in furniture structures, mitered corner joint constructed with spline –or mitered spline corner joint– is one of the strongest ones. The splines used for this kind of connections are commonly constructed of wood or plywood if desire. In the scientific literature, there is published information on strength performance of mitered spline joints with frames made of particleboard and medium-density fiber board (MDF) (Maleki et al. 2012b); however, information on strength behavior of this most widely used joint with solid wood frames is completely restricted. Therefore, to identifying factors affecting the strength performance of mitered spline joint, a series of laboratory tests have been conducted in this study to determine the effects of spline material type, spline depth of penetration, and frame wood species on load-carrying capability of mitered spline joints under diagonal tension loads. It was also the objective of this study to estimate the combined stresses that occur at the joints using a numerical method and the grass values of loads applied on test joints.

2 Materials and Methods

2.1 Specimens Description

Four different wood species including oriental beech (*Fagus orientalis* L.) hornbeam (*Carpinus betulus*) poplar (*Populus deltoides*) and white oak (*Quercus alba*) were selected to producing the horizontal and vertical (frame) members of L-type mitered spline joints used in the study (Fig.1). The splines used were also made out of beech wood and three-ply plywood.

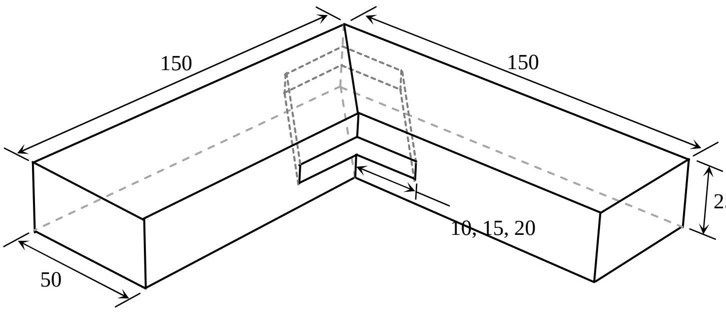

Figure 1. Geometry of joint specimens used in the study (measurements in mm).

The depths of embedment of the spline in the vertical and horizontal elements were 10-, 15-, and 20-mm. The thickness of the spline was equal 3-mm for all joint specimens. With four replications for each treatment in the study, totally, 96 joint specimens were fabricated with PVAc adhesive (60% solid contents). The glued specimens were clamped for a night and then stored at a climatic chamber (60% RH and 20°c Temp) for three weeks prior to the test process (Maleki et al. 2012b; Derikvand et al. 2013; Derikvand and Ebrahimi 2013).

2.2 Test Procedure

Utilizing standard equipment, load-bearing capacities of test specimens were examined with a loading rate of 5 mm/min (Fig.2). Maximum applied load (P) and modulus of failure were recorded for each specimen.

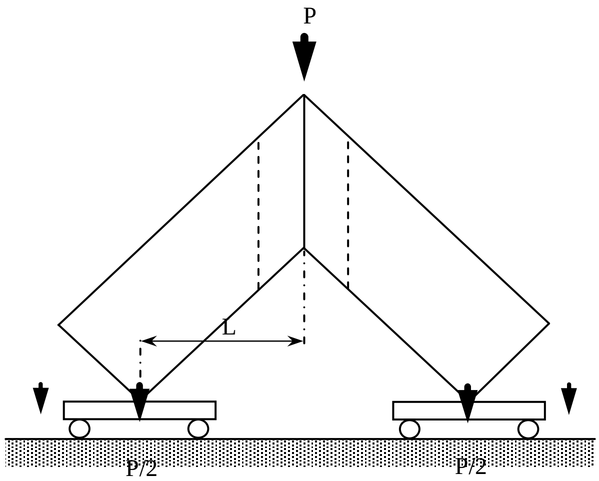

Figure 2. Method of loading of joint specimens.

2.3 Data Evaluation

Bending strength of test joints was estimated by equation:

$$M_t = \frac{P}{2} \times L \qquad (1)$$

Where P is the ultimate load [N], and L (70.7 mm) is the moment arm.

According to Maleki et al (2012), the combined stresses that occurred at the joints were calculated by following equations:

Compression stress at outer edge of joints $= -(\sigma_b + \sigma_a) = -\left[\frac{3PL}{tb^2} + \frac{P\cos 45}{2bt}\right]$ (2)

Tension stress at inner edge of joints $= \sigma_b - \sigma_a = \frac{3PL}{tb^2} - \frac{P\cos 45}{2bt}$ (3)

Where σ_b is the bending stress (MPa), and σ_a is the axial stress, P is the ultimate load (N), L is the moment arm (mm), t and b are also the thickness and width of the joint members, respectively.

3 Results and Discussion

3.1 Failure modes of joints

During the tests, four types of joint failures were occurred:

1. Tension perpendicular to the grain failure in beech wood spline (Fig.3.a-b).
2. Failure in the glue line between the spline surfaces and inside walls of the slots made in joint elements.
3. Failure in the glue line between the plies of the plywood spline (Fig.3.c-d).
4. Combined fractures.

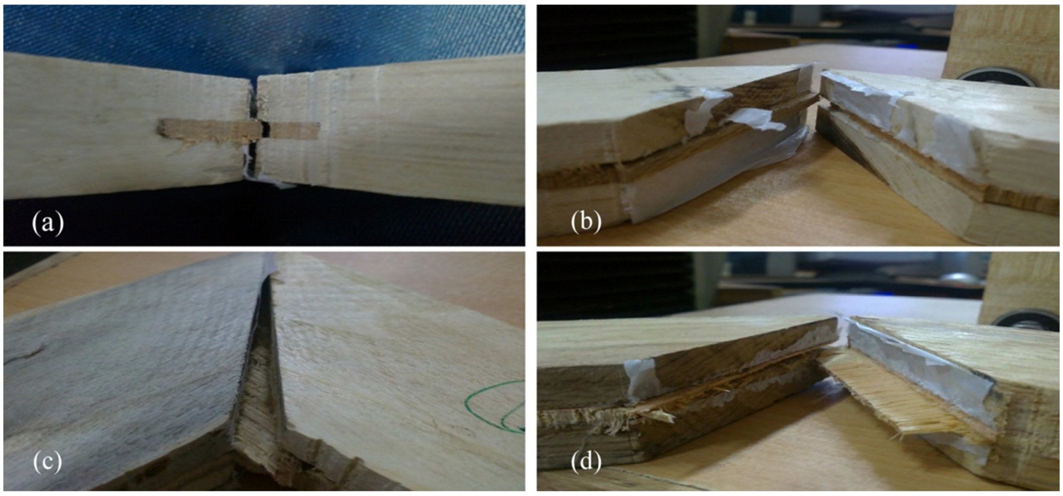

Figure 3. Examples of failure modes of tested specimens.

In the case of joints with beech wood splines, most fractures occurred along the fiber direction (Fig.3.a-b), whereas for joints constructed with beech plywood most failure occurred at the glue line between the plies of the plywood (Fig.3.c-d). In all cases, the first sign of the joint failures were observed in the inner side of the joints.

3.2 Bending strength and stress performance of test joints

The average values of the load-bearing capacities of the joint specimens are given in Table 1.

Statistical analysis of variance (ANOVA) results for determination of the bending strength of the joint specimens showed highly significant difference between the groups in term of the spline material type (p = 0.000). As can be seen in Figure 4, bending strength of joints fabricated with plywood spline was significantly higher than those of joints with beech wood splines–with a difference of approximately 166%. The phenomenon was probably due to inappropriate direction of the fiber in beech wood spline. The longitudinal axis of the splines made of beech wood was mostly parallel to the direction of the fibers; therefore, as wood is primarily weak in tension perpendicular to the grain, the joints made with beech splines were destroyed under tension load before they reach their final load capacities. The results also showed an irregularity for the effect of spline depth of penetration in joints made with beech wood splines (Fig.5).

As can be seen in Table 1, in some cases, load-carrying capacity of beech wood spline increased with increase in the spline depth of penetration from 10- to 15-mm and from 15- to 20-mm, while in other cases the load capacity increased firstly with increase in the spline depth of penetration from 10- to 15-mm and then this trait decreased along with increase in the depth of penetration from 15- to 20-mm. ANOVA results revealed that the difference between the groups was not significant in term of the spline depth of penetration (p = 0.052) for the bending strength of test joints fabricated with beech wood spline. However, average bending moment resistance of joints with 15-mm depth of penetration beech wood splines was higher than depths of 10- and 20-mm. In addition, for the joints with splines made of plywood, joint's bending strength increased significantly (p = 0.000) with the penetration depth of the spline from 10- to 20-mm (Fig.5).

Table 1. Average bending strength and combined stress of test joints.

Wood species	Spline's material type	Penetration depth [mm]	Bending strength [Nm]		Combined stresses [MPa]			
					Inner edge		Outer edge	
			$\overline{x}$	COV [%]	$\overline{x}$	COV [%]	$\overline{x}$	COV [%]
Beech	Wood	10	35.71	23.02	3.15	22.86	3.72	23.12
		15	42.06	35.66	3.70	35.68	4.37	35.93
		20	37.93	19.98	3.34	20.06	3.95	20
	Plywood	10	70.90	37.67	6.24	37.66	7.37	37.72
		15	117.02	15.65	10.30	15.63	12.17	15.61
		20	138.10	14.97	12.15	14.98	14.36	14.97
Hornbeam	Wood	10	43.07	8.57	3.79	8.44	4.48	8.48
		15	39.86	37.25	3.51	37.32	4.15	37.11
		20	30.47	11.46	2.68	11.57	3.17	11.36
	Plywood	10	52.46	25.30	4.62	25.32	5.46	25.27
		15	106.98	20.62	9.41	20.62	11.13	20.58
		20	138.00	12.92	12.14	13.18	14.35	12.89
Poplar	Wood	10	39.37	14.02	3.46	14.16	4.09	13.94
		15	44.70	18.25	3.93	18.32	4.65	18.28
		20	29.68	7.95	2.61	8.05	3.09	8.09
	Plywood	10	89.85	16.07	7.91	16.06	9.34	16.06
		15	84.06	21.95	7.40	21.89	8.74	21.97
		20	104.29	2.82	9.18	2.83	10.84	2.86
Quercus	Wood	10	23.49	6.98	2.07	6.76	2.44	6.97
		15	33.38	7.46	2.94	7.48	3.47	7.49
		20	34.17	17.73	3.01	17.61	3.55	17.75
	Plywood	10	76.09	14.47	6.70	14.48	7.91	14.41
		15	100.13	16.92	8.81	16.91	10.41	16.91
		20	83.65	17.18	7.36	17.12	8.70	17.13

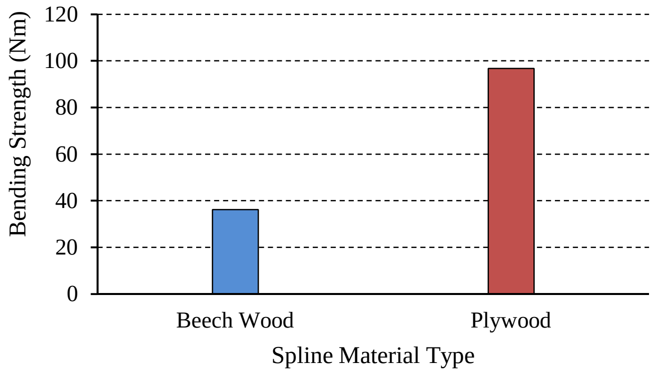

Figure 4. Bending strength of joints as a function of spline material type. p = 0.000.

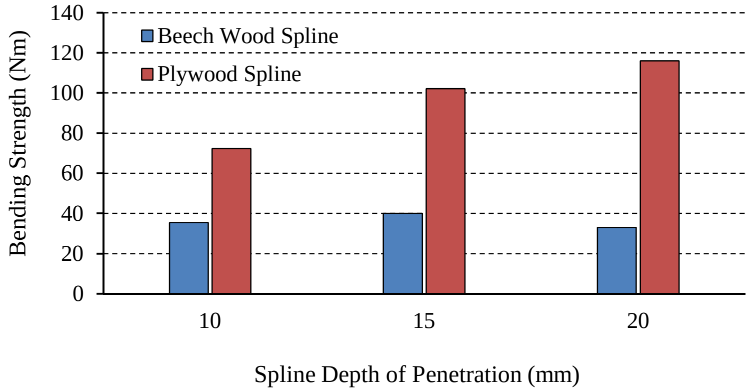

Figure 5. Bending strength of joints as a function of spline type and spline depth of penetration. Plywood spline: p = 0.000; Beech wood spline: p = 0.052.

Figure 6 illustrates the average values of the bending strength of mitered spline joints with the frame elements made of different wood species. For the joints with beech wood splines, there were no significant differences between bending strengths of joints with the elements made of beech, hornbeam, and poplar wood species. On average, joints with beech wood elements behaved stronger than other wood species. Likewise, white oak showed the worst mean bending strength among wood species used.

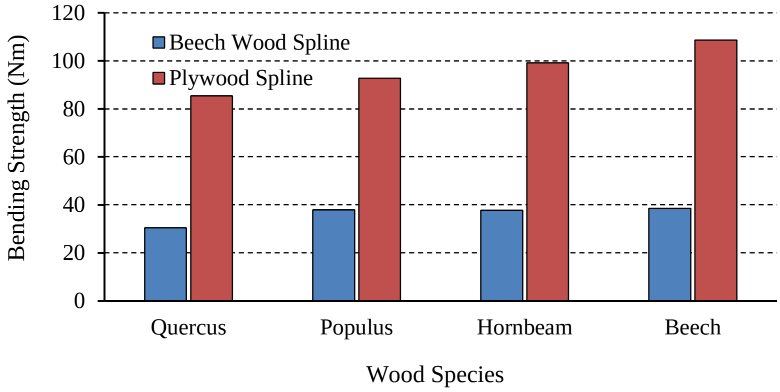

Figure 6. Bending strength of test joints as a function of wood species and spline material type. Plywood spline: p = 0.029; Beech wood spline: p = 0.046

The results of the numerical analysis for the combined stresses of joints revealed that the average compression stress values at the outer edge of the joints were significantly higher than those of tension stress at the inner edge of the joints (Fig.7). However, as descripted in the subsection 3.1, failures occurred at the inner edges of the joints where was under tension stress. The high values of the compression stresses at the outer edge of the joints caused a destructive non-elastic deformation in the vertical and horizontal elements of the joints so that these elements were pressed together at the outer corner of the joints. However, as these two parts of joints almost always support each other under heavily load; they were subjected for only some compressions deformations. The average values of combined stresses for the joints with beech members were higher than those of joints with members made of other wood species. Furthermore, as descripted, the bending strength of the joints with the plywood spline was greater than that of the joints with beech wood spline, as a result, the combined stresses that occurred at the joints with plywood spline were also greater than those of joints with beech wood splines (Fig.7).

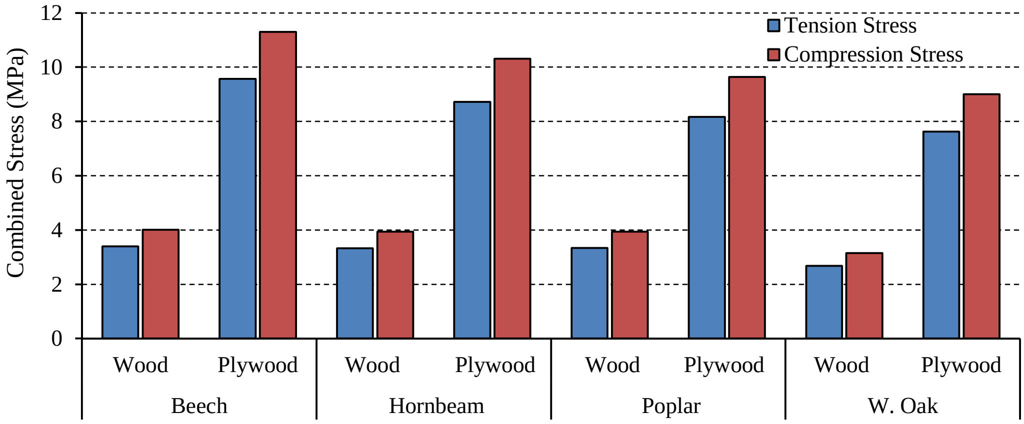

Figure 7. The average values of combined stresses of joints related to wood species and spline type.

The effect of the spline depth of penetration on combined stresses of joints was also the same with the spline depth of penetration effect on the bending strength of joints.

The results obtained from the numerical analysis in this study are in very good agreement with those reported by Maleki et al. (2012) for the combined stresses of mitered dovetails L-type joints under diagonal tension loads.

4 Conclusions

Impacts of some constructing parameters–including wood species, spline material type, and spline depth of embedment–on the load-bearing capacity and combined stress of mitered spline joints were studied. Test results showed highly significant correlations between the constructing parameters and the load capacity of the joints. Joints with frames made of beech wood had the highest load-carrying capacity among joints with members of other wood species. Plywood spline showed more appropriate stiffness for making a strong mitered joint in compare to beech wood spline. For mitered joints made with plywood spline, the load-carrying capacity and corresponding combined stress of the joints increased with the spline depth of penetration from 10- to 20-mm, while the best values for beech wood spline were obtained at a penetration depth of 15-mm. Although the results of the combined stress analysis indicated that the average values of compression stress at the outer corner of the joints were greater than the average tension stress at the inner corner, joints failures were started from the inner corner of the joints. It was also demonstrated that the numerical analysis of the combined stresses that occurred at the joints has more reasonable explanations on modulus of fractures and behavior of mitered spline corner joints under diagonal tension loads in compare to analysis of bending moment resistance of joints.

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