Effects of Wood Species, Number of Teeth, and Adhesive Type on Moment Capacities of Box-Joints

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Effects of the wood species, number of teeth, and adhesive type were studied relative to the moment capacities of box joints under tension and compression loadings, which is commonly used in case type solid wood furniture. For this purpose, L-type specimens were prepared from Scotch pine (*Pinus sylvestris* L.), poplar (*Populus sp*.), and fir (*Abies sp*.). Polyvinyl acetate (PVAc) and polyurethane (PU) adhesives were used in the preparation of joints. Tension and compression tests with 360 samples were performed under static loading. According to the results, the highest moment capacities were obtained for Scotch pine under tension, and poplar specimens under compression. With respect to the number of teeth, the highest moment capacities were obtained with 12-tooth joints under both tension and compression loadings. For adhesive types, the specimens glued with PVAc gave better results in both tension and compression. In manufacturing of solid wood based case-type furniture, the higher number of teeth resulted in a slightly better performance; however, the results with the 4-tooth structure was not too far from 8-tooth. Furthermore, it was concluded that Scotch pine as a substance and PVAc as adhesive could be recommended.

Keywords: Case construction; Wood; Box-joint; Tension; Compression; Moment capacity

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INTRODUCTION

In the construction industry there are four types of furniture categories, namely frame, case, crust, and combination types. Case-type furniture construction is widely utilized with both solid wood and wood-based panels. The assembly of case-type furniture could be made with adhesive or with a variety of connectors such as knock-down fasteners, minifix, screws, *etc*. A box-joint is commonly used, especially when the construction involves use of an adhesive. Box-joinery creates a wider surface area and a chance of interlocking the wood members in order to create a robust joint *via* the substance's own strength. There are variety of traditional and contemporary box-joints, such as butt-joint, dowelled, biscuit, splined, lock, finger, and dovetail, *etc*. Due to the fact that the box-joints typically are very robust, they have been widely used in wooden furniture in the past and present. In particular, box-joints are preferred for the drawers of the furniture, as such elements are in frequent motion.

Box joints are actually multiple interlocking finger joints with many different configurations. Chan (2002) indicated that even though they are commonly associated with drawers, larger boxes such as pedestals and cabinets could be manufactured with box-joints. The most prominent advantage of box-joints is that they could be sawn by hand or conventional table saw, they can also be cut in precision with state of the art CNC technology. Murphey and Rishel (1972) claimed long ago that finger joints could be a replacement for mortise and tenon or dowel joints in furniture production.

Polyvinyl acetate (PVAc) and polyurethane (PU) adhesives are widely used in furniture joinery because their formulas allow them to cure under ambient temperatures. While PVAc has had a more extensive history of use as an adhesive, research has shown that one-part PU (Lange *et al.* 2001) and two-part PU (Chen and Walworth 2001) both could be employed in structural finger joints.

According to Nicholls and Crisan (2002), box-type of furniture is subjected to both static and dynamic loads. Thus, the joints of such furniture pieces have to be strong and stiff enough to endure these loads. Ors *et al.* (2003) studied dovetail corner joints. They found the highest bending strength with okoume plywood, and the lowest bending strength values with solid Scotch pine and poplar, respectively. However, considering the technical and economic factors, the use of wood-based composite materials is recommended in the production of case furniture. Kamboj *et al.* (2019) studied the effect the geometry on the elastic stiffness of finger corner joints. They analyzed the factors of wood species, adhesive type, and number of teeth. The study revealed that the highest stiffness values were obtained with 5-tooth beech with PVAc under tensile loads, while the lowest values were obtained with 2-tooth spruce bonded with PVAc under compression. Efe and Imirzi (2008) found higher moment values on plywood and medium density fiberboard (MDF) corner joints assembled with glue and screw. The experimental samples prepared with 18 mm thickness gave better results than 16 mm panel thickness. However, the 16 mm thick materials showed applicability from technical and economic aspects. Ustundag (2008) studied the diagonal compression and tension performance of dovetail corner joints with PU-based and PVAc-based adhesives. He found the highest compression performance on Oriental beech with PU based adhesive; while the lowest was of MDF with PVAc adhesive. Atar *et al.* (2010) studied the effect of adhesives on corner joints under diagonal tension and compression. They found the highest diagonal tension values in European oak with PVAc glue, while the lowest value was obtained in MDF with PU based adhesive. They concluded that PVAc as glue could be suggested to obtain some advantages on the dovetail joint process for box-type furniture made from both solid wood and MDF.

Freedman (1997) has noted that the strength of box joints comes from interlocking fingers, which create large glue surface area. Some researchers (Ayarkwa *et al.* 2000; Bustos *et al.* 2011; Franke *et al.* 2014) argued that the strength of box joints are associated with surface area. However, there has been no robust demonstration that the surface area, *i.e.* the number of teeth, is directly related to high strength of joint. Furthermore, as can be seen from the literature, the effect of adhesive is inconclusive when it comes to decide between PVAc and PU in box-joints. Therefore, in this study, it was aimed to compare the effects of the number of teeth, wood species, and adhesive type on moment capacity of box-joints under diagonal compression and tension.

EXPERIMENTAL

Materials and Methods

In this study, specimens were prepared with Scotch pine (*Pinus sylvestris* L.), poplar (*Populus* sp.), and fir (*Abies* sp.). The adhesive type used were polyvinyl acetate

(PVAc), and polyurethane (PU). Corner joints were prepared as box-type joints with three different numbers of teeth, namely 4, 8, or 12 teeth.

Wood materials were kept at 20 °C ± 2 °C and at 65% ± 3% relative humidity until their weight became stable in an environmentally controlled conditional chamber. Moisture contents (MC) and densities of the wooden materials were measured according to TS 2471 and TS 2472 standards, respectively. MC, density, MOR, and MOE values of woods used in testing are given in Table 1. In this study, three different tooth configurations were utilized. Box-joints were prepared under laboratory conditions using a table saw and a box joint jig with a stacked dado set. The clearance of notch and finger was near kept near 0+/-0.01 mm in order to ensure a snug fit. Assembly was done with an application of thin but thorough layer of adhesive. Corner joints were then clamped together and kept clamped and kept in laboratory for 24 hours until the adhesives were totally cured. The 3D configurations and dimensions of the specimens are given in Figs. 1 and 2.

The total number of specimens was 360: 3 wood species (Scotch pine, poplar, and fir), 2 adhesive types (PVAc and PU), 3 different tooth numbers (4, 8, and 12 tooth) × 2 loading type (tension and compression strength) × 10 replications (3x2x3x2x10=360).

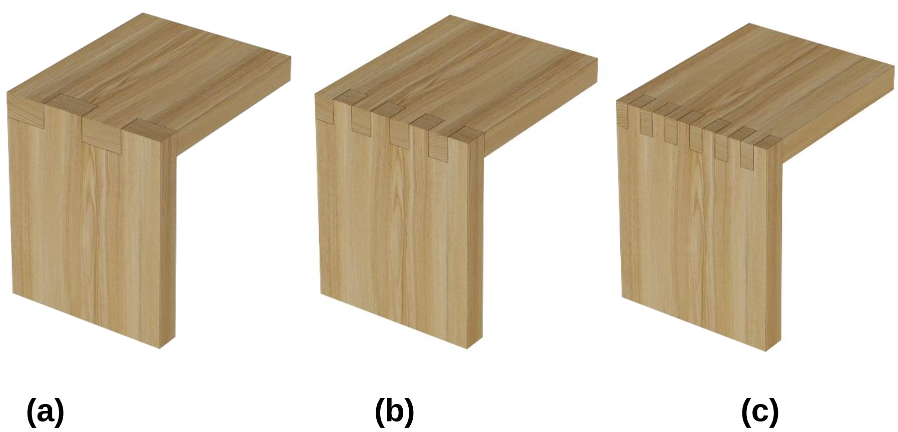

Fig. 1. 3D Specimen configurations: 4-tooth (a), 8-tooth (b), and 12-tooth (c)

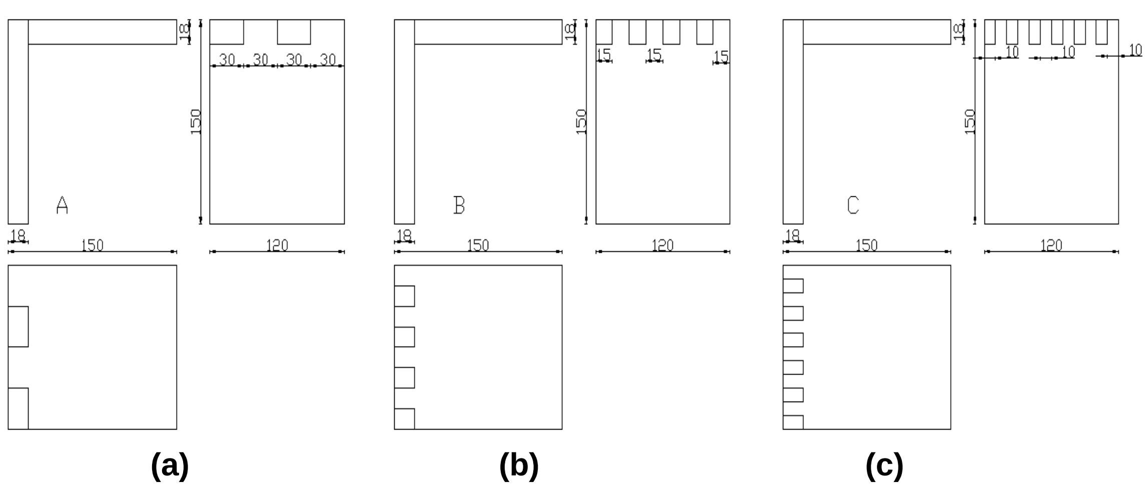

Fig. 2. Specimen dimensions (in mm): 4-tooth (a), 8-tooth (b), and 12-tooth (c)

Tests were carried out in a Universal testing machine with specimens prepared according to the procedures outlined in ASTM-D 143-83 (1983). The rate of the static loading was 2 mm/min. Test set-up is shown in the Fig. 3. Maximum loads read from the test machine were recorded in units of Newton.

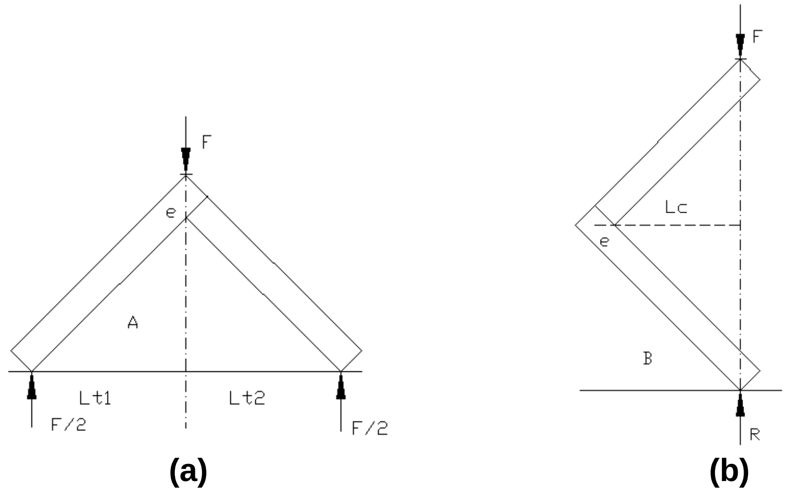

Fig. 3. Method of loading: tension (a) and compression (b)

Because the supports are outside in the diagonal tension tests and the joint is out of force direction in diagonal compression tests, the moment force (M) occurs at the corner joints. Moment is calculated from Eqs. 1 and 2 for diagonal tension and diagonal compression tests, respectively,

$$M_t = 0.5F_{max} \ x \ L_{t1} \ (or \ L_{t2}) \tag{1}$$

$$M_c = F_{max} \ x \ L_c \tag{2}$$

where, M_t is the moment in diagonal tension and M_c is the moment in diagonal compression (Nm), F_{max} is the ultimate force at time of failure (N), L_{t1}, L_{t2} is perpendicular distance from the point force applied to supports (m), and L_c is horizontal distance from force applied to the rotation point (m). The moment arm (L_{t1}, L_{t2}, L_c) was calculated as 0.0933 m for both compression and tension loads.

Table 1. MC, Oven-dry and Air-dry Density, MOR, and MOE of the Specimens

Wood Species	MC (%)	Oven-dry Density (g/cm^3)	Air-dry Density (g/cm^3)	MOR (MPa)	MOE (MPa)
Scotch pine	11.2	0.49	0.52	75.8	12135
Poplar	10.8	0.46	0.50	74.4	9859
Fir	11.3	0.40	0.44	69.6	10894

RESULTS AND DISCUSSION

In general, specimens both under compression and tension showed a similar mode of failure in which the joints did not show any sign of failure until an abrupt loss of strength occurred. The observation showed glue line failure in virtually all specimens. In other words, no failure was observed on the notches or fingers. The minimum, maximum, average ultimate forces under diagonal tension of tested joints with their coefficients of variation are summarized in Table 2. Table 3 summarizes the forces recorded under diagonal compression with their coefficients of variation.

Table 2. Ultimate Force Results Under Diagonal Tension for Box-type Joints

Wood Species	Adhesive Type	Number of Teeth	Number of Replications	Minimum Value (N)	Maximum Value (N)	Mean Value (N)	Coefficients of Variation (%)
Scotch Pine	PVAc	4	10	2700	3300	2990	5.8
		8	10	2300	3400	2800	10.9
		12	10	3900	4800	4350	8.1
	PU	4	10	1700	2200	1910	8.4
		8	10	2300	3400	2610	11.7
		12	10	2700	3900	3240	14.7
Poplar	PVAc	4	10	1700	2400	2190	11.8
		8	10	2100	2800	2510	7.9
		12	10	2800	4000	3300	13.9
	PU	4	10	1300	2000	1620	14.5
		8	10	2100	3100	2480	13.0
		12	10	2600	3600	3170	13.4
Fir	PVAc	4	10	1500	2300	1920	13.4
		8	10	1900	2700	2180	10.6
		12	10	2800	4100	3420	13.3
	PU	4	10	1100	1500	1330	11.2
		8	10	1100	1600	1340	11.8
		12	10	2400	3700	2940	16.2

Table 3. Ultimate Force Results Under Diagonal Compression for Box-type Joints

Wood Species	Adhesive Type	Number of Teeth	Number of Tests	Minimum Value (N)	Maximum Value (N)	Mean Value (N)	Coefficients of Variation (%)
Scotch Pine	PVAc	4	10	500	700	560	15.1
		8	10	400	700	570	16.6
		12	10	900	1200	1120	11.6
	PU	4	10	300	400	350	15.06
		8	10	600	800	660	12.8
		12	10	1000	1400	1180	11.2
Poplar	PVAc	4	10	500	700	610	12.1
		8	10	600	700	640	8.1
		12	10	900	1300	1100	12.1
	PU	4	10	400	600	500	13.3
		8	10	700	1000	850	11.4
		12	10	1100	1600	1320	13.6
Fir	PVAc	4	10	400	600	530	12.7
		8	10	400	600	460	15.2
		12	10	900	1200	1020	10.1
	PU	4	10	300	400	350	15.1
		8	10	400	600	480	13.2
		12	10	300	500	410	13.9

Analyses for the Moment Capacities under Diagonal Tension

Multiple variance analysis was performed on the calculated moment capacity data obtained from a total of 180 specimens for determining the effect of wood species, adhesive type, number of teeth. M-STAT-C software was used for statistical analyses. The results of the analysis of variance are shown in Table 4.

Table 4. Summary of the ANOVA Results for Moment Capacities under Tension

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F- value	Prob. (sig. 5%)
Wood species (A)	41407.9	2	20704.0	33.46	.000
Adhesive type (B)	30467.6	1	30467.6	49.24	.000
Number of teeth (C)	142256.3	2	71128.1	114.95	.000
A × B	5242.0	2	2621.0	4.24	.016
A × C	5428.0	4	1356.9	2.19	.072*
B × C	2537.0	2	1268.5	2.05	.132*
A × B × C	5945.9	4	1486.5	2.40	.052*
Error	100245.5	162	618.8		
Total	2925278.3	179			

*: Not significant

The effects of the main factors including wood species (*A*), adhesive type (*B*), and number of teeth (*C*) were found to be statistically significant at the level of 0.05. All two-way and three-way interactions except for wood species × adhesive type (*A* × *B*) were not statistically significant ($p \leq 0.05$). The least significant difference mean comparisons procedure at 5% significance level were performed to determine the mean differences of moment capacities under diagonal tension with respect to the main effects and a significant interaction.

When the comparison results of wood species were examined, it was seen that the highest moment capacity was obtained for Scotch pine. The moment capacities of poplar and fir specimens were much lower. The density of Scotch pine wood was higher than the density of the other woods used in the experiments. Mean comparison results according to wood species are given in Table 5.

Table 5. Mean Comparison Results of Moment Capacities under Tension for Wood Species

Wood species	Moment under tension (Nm)	
	X	HG
Scotch pine	139.2	*A*
Poplar	118.7	*B*
Fir	102.2	*C*

When the effect of adhesive was examined, PVAc specimens were more successful than PVAc specimens. The PU adhesive expands its volume after being applied to the wood material. Mean comparisons of moment capacities with respect to adhesives are given in Table 6.

Table 6. Mean Comparison Results of Moment Capacities under Tension for Adhesive Type

Adhesive type	Moment under tension (Nm)	
	X	HG
PVAc	133.0	*A*
PU	106.7	*B*

When the effect of number of teeth was examined, 12-tooth joints yielded better results. As the number of teeth increased in the corner joints, the resistance of the joint increased. This situation may be due to the increase in surface area involved in the adhesion in 12-tooth joints. However, results did not demonstrate any directly linear relationship of moment capacities *vs*. number of teeth; *i.e*., performance of box-joints did not drastically increase with an increase from 4-tooth to 8 or 12-tooth. Moment capacities according to the number of teeth are given in Table 7.

Table 7. Mean Comparison Results of Moment Capacities under Tension for Number of Teeth

Number of teeth	Moment under tension (Nm)	
	X	HG
4	93.0	*C*
8	108.2	*B*
12	158.8	*A*

Mean comparisons for two-way and three-way interactions were not provided due to the fact that all interactions were insignificant except for wood species x adhesive interaction. However, a multiple comparison with a lower bound confidence interval is provided in Table 8 to draw a complete picture for results. Overall, the best result was obtained in 12-tooth joints with PVAc adhesive in Scotch pine. The lowest result was obtained in 4-tooth joints with PU adhesive in fir.

Table 8. Multiple Comparison Results under Tension for Wood Species × Adhesive Type × Number of Teeth Interaction

Wood species	Adhesive	Number of teeth	Mean	Std. Error	95% Confidence Interval Lower Bound
Fir	PU	12	137.15	7.86	121.62
		4	62.04		46.51
		8	62.51		46.98
	PVAc	12	159.54		144.01
		4	89.57		74.03
		8	101.70		86.16
Poplar	PU	12	147.88		132.35
		4	75.57		60.04
		8	115.69		100.16
	PVAc	12	153.95		138.41
		4	102.16		86.63
		8	117.09		101.56
Scotch pine	PU	12	151.15		135.61
		4	89.10		73.57
		8	121.76		106.22
	PVAc	12	202.93		187.39
		4	139.48		123.95
		8	130.62		115.09

Analyses for the Moment Capacities under Diagonal Compression

Multiple variance analysis was performed on the data obtained from a total of 180 specimens for determining the effect of wood species, adhesive type, and number of teeth on moment capacities under compression. The results of the analysis of variance are shown in Table 9.

Table 9. Summary of the ANOVA Results for Moment Capacities under Compression

Source	Degrees of freedom	Sum of squares	Mean squares	F-value	Prob. (sig. 5%)
Wood species (*A*)	30189.5	2	15094.8	15.80	.000
Adhesive type (*B*)	3494.0	1	3494.0	3.66	.058*
Number of teeth (*C*)	98946.6	2	49473.3	51.81	.000
A × *B*	5165.9	2	2582.9	2.70	.070*
A × *C*	13506.1	4	3376.5	3.54	.009
B × *C*	8131.3	2	4065.7	4.26	.016
A × *B* × *C*	6333.3	4	1583.3	1.66	.162*
Error	154694.6	162	954.9		
Total	1133986.0	179			

* Not significant

According to the results of this analysis, the effects of the main factors of wood species (*A*) and number of teeth (*C*) were found to be statistically significant, while adhesive (*B*) was insignificant at the level of 0.05. Three factor interactions of wood species × adhesive type × number of teeth (*A* × *B* × *C*) were also statistically insignificant ($p \leq 0.05$).

When mean comparisons of wood species were examined, the highest moment capacity was obtained in poplar specimens. The moment capacities of Scotch pine and fir were lower. Results according to wood species are given in Table 10.

Table 10. Mean Comparison Results of Moment Capacities under Compression for Wood Species

Wood Species	Moment under Compression (Nm)	
	X	HG
Scotch pine	69.0	*B*
Poplar	82.1	*A*
Fir	50.5	*C*

When the effect of adhesive was examined, PVAc adhesive was more successful than PU adhesive. Moment capacities with respect to adhesive used in experiments are given in Table 11.

Table 11. Mean Comparison Results of Moment Capacities under Compression for Adhesive Type

Adhesive Type	Moment under Compression (Nm)	
	X	HG
PVAc	71.6	*A*
PU	62.8	*A*

When the effect of number of teeth was examined; the moment capacities of the 12-tooth joints were the highest, while the moment capacities of the 4-tooth joints were the lowest. As the number of teeth increased, the strength of the joint was also increased. This situation may be due to the increase in surface area involved in the adhesion using 12-tooth joints. However, the relationship between number of teeth and moment capacities was not linear. As a matter of fact, the means for 4-tooth and 8–teeth were close to each other, even if they were not in the same homogeneity group. By contrast, there was a clear jump from 8 to 12-tooth structures. The moment capacities according to the number of teeth are given in Table 12.

Table 12. Mean Comparison Results of Moment Capacities under Compression for Number of Teeth

Number of Teeth	Moment under Compression (Nm)	
	X	HG
4	45.1	*C*
8	56.9	*B*
12	99.7	*A*

Multiple comparisons with a lower bound confidence interval are provided so as to draw a complete picture for results. Overall, the best result was obtained in 12-tooth joints with PVAc adhesive in poplar. The worst result was obtained in 4-tooth joints with PU adhesive in fir wood. Multiple comparisons of moment capacities are given in Table 13.

Table 13. Multiple Comparison Results under Compression for Wood Species × Adhesive Type × Number of Teeth interaction

Wood species	Adhesive	Number of teeth	Mean	Std. Error	95% Confidence Interval Lower Bound
Fir	PU	12	38.25	9.77	18.96
		4	32.66		13.36
		8	44.78		25.49
	PVAc	12	95.17		75.87
		4	49.45		30.15
		8	42.92		23.62
Poplar	PU	12	119.42		100.13
		4	46.65		27.35
		8	79.31		60.01
	PVAc	12	130.62		111.32
		4	56.91		37.62
		8	59.71		40.42
Scotch pine	PU	12	110.09		90.80
		4	32.66		13.36
		8	61.58		42.28
	PVAc	12	104.50		85.20
		4	52.25		32.95
		8	53.18		33.88

CONCLUSIONS

1. *In diagonal tension:* The highest performance in wood species was obtained with Scotch pine. The lowest performance was attained in fir. This can be attributed to the density of the Scotch pine being higher than the density of the other wood species

tested in this study. In terms of number of teeth, the 12-tooth joints performed better than the 8- and 4-tooth joints. However, there was not clear linear relationship with respect to surface area. When the type of adhesive used in the experiments was examined, the PVAc was found to be more effective than PU.

2. *In diagonal compression:* The highest performance in wood species was obtained with poplar. The lowest performance was found in fir. In terms of number of teeth, the 12-tooth joints performed better than the 8- and 4-tooth joints. As with the tension results, the effect of surface area was not linearly effective in the moment capacities. Thus, it is worth thinking about not utilizing many number of teeth, while a reasonable performance could be achieved with less. When various types of adhesives were examined, PVAc was more successful than PU.
3. The use of Scotch pine wood in the box-type corner joints subjected to moments under tension and the use of poplar wood in the joints subjected to moments under compression will increase the moment capacity of the joints. Increasing the number of teeth will improve the performance of box joints. Furthermore, the use of PVAc adhesive in the joints increased the strength of the bonding.
4. The results of the tests did not give a robust conclusion regarding the effect of number of teeth, which is contrary to the literature cited (Bustos *et al.* 2011 and Franke *et al.* 2014). Therefore, a detailed analysis with respect to surface area was not included in the study. However, specific consideration should be given to further analyze the surface area effect in order to give an idea to engineers and manufacturers as well as designers to decide whether it is worthwhile to increase the number of teeth in box joints.

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