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Bending Moment Capacity of Metal Plate Connected Wood-Splice Joints Constructed with Red Pine (*Pinus brutia* Ten.) Lumber

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Abstract: The ultimate bending moment carrying capacity of metal-plate-connected (MPC) wood-truss-splice joints constructed with red pine (*Pinus brutia* Ten.) lumber was investigated. Lumber 38 mm by 90 mm and 3 different sizes of metal plate connectors were utilized in constructing the joints. A 4-point loading method was used to determine the joints' bending moment capacity. Tensile splice joints were tested in both flat- and edgewise positions. The effects of tooth orientation and metal plate size on the bending moment capacity of the joints were investigated. The results indicated that both tooth orientation and plate size significantly influenced the joints' bending moment capacity. Plate size seemed to increase the bending moment capacity of the joints when plate size was increased to 76 mm by 100 mm from 76 mm by 76 mm. There was no significant difference between 76 mm by 100 mm plates and 76 mm by 152 mm plates in bending moment capacity. There was also no conclusive relationship between the bending moment capacity of the joints and the specific gravity of the lumber, and between the lumber's modulus elasticity.

Key Words: MPC splice joints, bending moment capacity, red pine

Kızılçam (*Pinus brutia* Ten.) Kerestesi ile Yapılmış Metal Plakalı Uç Birleştirmelerinin Moment Taşıma Kapasiteleri

Özet: Bu çalışmada Kızılçam (*Pinus brutia* Ten.) kerestesi kullanılarak yapılmış metal plakalı uç birleştirmelerinin moment taşıma kapasiteleri araştırılmıştır. Birleştirmelerin yapılmasında 38 mm x 90 mm enine kesitinde kereste ve üç farklı metal dişli plaka kullanılmıştır. Birleştirmelerin maksimum moment taşıma kapasitlerinin bulunmasında dört-nokta yükleme metodu tatbik edilmiştir. Metal plakalı uç birleştirmelerine yatık ve dik pozisyonlarda eğilme testleri uygulanmıştır. Diş yönünün ve metal plaka boyutunun birleştirmelerin moment taşıma kapasiteleri üzerine etkisi de çalışmada araştırılmıştır. Elde edilen bulgular hem diş yönünün hemde plaka boyutunun birleştirme kapasitesi üzerinde anlamlı etkisi olduğunu ortaya koymuştur. Plaka boyutu 76 x 76 mm'den 76 x 100 mm'ye çıktığında birleştirme moment kapasitesini yükseldiği görülürken, 76 x 100 mm ile 76 mm x 152 mm plakalar ile yapılmış birleştirmeler arasında istatistiksel olarak anlamlı bir fark görülmemiştir. Ayrıca birleştirmelerin yapımında kullanılan kerestenin özgül ağırlığı, elastikiyet modülü ile moment taşıma kapasiteleri arasında anlamlı bir ilişki bulunamamıştır.

Anahtar Sözcükler: Metal plakalı birleştirmeler, eğilmede moment taşıma kapasitesi, kızılçam

Introduction

Metal connector plates have been used for connecting wood truss members at joints, and metal-plate-connected (MPC) wood trusses are commonly used in roofs and floors in residential, industrial, and commercial construction (Gupta et al., 1996). Today a wide variety of metal plates is used by the wood truss industry.

A vast amount of literature exists on MPC wood truss joints. Most of the early studies focused on testing and modeling of tensile connections to evaluate strength, stiffness, load-slip characteristics, and failure modes as well as the effects of some variables on the joint behavior. According to Barron and Kim (2000), some of the variables that affect joint behavior include size and number of teeth, plate thickness and orientation, grain orientation and direction of loading, lumber species, specific gravity of the lumber, moisture content of the lumber, the joint pressing force used to seat the plate, and the time between fabrication and testing. Later investigations are centered on the other types of joints under different types of loading conditions and modeling.

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Moura et al. (1995) investigated the influence of wood density on MPC perpendicular wood joints under static and cyclic loading. They found that high-density wood joints were not more rigid than low-density wood joints but they could bear 30% greater load. Furthermore, apart from the initial imposed load level, wood density does not influence the mechanical behavior of joints. A study by Kent et al. (1997) states that seismic loadings do not affect the strength of heel and splice joints, but cause stiffness degradation. Cyclic loading was also found to have a significant effect on the strength of MPC wood joints. A similar study conducted by Gupta et al. (2004b) revealed that dynamic loads that simulate hurricane wind and impact loads do not have any effect on MPC heel and splice joints' strength, but cause an increase in joint stiffness because of wood densification near the teeth of the metal plates.

More recently, truss analysis and design procedures that consider system effects have been receiving more attention. According to Gupta et al. (2004a), conventional design procedures may not include all of the system effects in the design, thereby excluding both positive and negative effects of system behavior. A system analysis and design procedure can provide a more realistic description of the behavior of trusses in assembly and may lead to improved truss system design, increased safety, and potential reduction in truss fabrication (Gupta et al., 2004a). Consideration of bending moments in truss design and analysis may lead to more realistic descriptions of the behavior of trusses.

In trusses, forces in the diagonal members resist the external shear forces while chord forces resist moments. A tension joint in the bottom chord of a truss is subjected to both axial and bending loads, but truss design standards do not require moment inclusion for tension joints. There is also no standard to evaluate the bending moment capacity of tension joints. Theoretically, a truss joint may be analyzed as a pin, but, in reality, eccentric loadings can create bending conditions in connector plates. Out of plane loadings also create bending conditions in MPC joints during transportation, erection, and handling. Gupta (1994) found that increases in applied moment in MPC tension-splice joints resulted in decreases in joint axial load capacity. It was stated by Stahl et al. (1994) that the combination of bending moment and axial load carried by the joint has a critical effect on the buckling load of connectors.

Although many investigations exist about the tensile properties of MPC wood truss joints, information on their ultimate bending moment carrying capacity is scarce. The primary objective of the present study was to evaluate the bending moment carrying capacity of MPC wood splice joints. The effects of plate size, tooth orientation, and type of loading as well as failure types were also investigated.

Materials and Methods

A total of 120 splice joint specimens were prepared using red pine (*Pinus brutia* Ten.) lumber supplied from a local lumber company. The lumber specimens were 300 cm long and 38 by 90 mm in cross section. Lumber pieces were cut into 50 cm pieces. Pieces with knots, checks, etc. were excluded from the study. The lumber's specific gravity (SG) and moisture content (MC) were based on representative sections cut from each specimen near the joint. Sections were approximately 20 x 20 mm in cross section and 25 mm in length. The MC and SG values for all tests were based on oven-dry conditions. Modulus of elasticity (MOE) and modulus of rupture (MOR) of the lumber were calculated from adjacent pieces used in the joint construction, assuming these values were similar.

Three different sizes of metal plates (76 by 76 mm (S), 76 by 100 mm (M), and 76 by 152 mm (L)) used in the study were supplied by a commercial plate manufacturer. Some properties of the plates are summarized in Table 1. Only one plate was pressed each

Table 1. Metal plate properties.

Plate type	Wave plate, M20
Thickness	1 mm
Teeth configuration	wave
Width	76 mm
Length	76-100-152 mm
Plate area	57-76-115 cm^2
Slot width	3 mm
Slot length	12 mm
Tooth depth	8 mm
Yield strength	275. 790 MPa
Tensile strength	379. 211 MPa
Allowable tensile stress	165. 474 PMa
Allowable shear stress	110.316 MPa

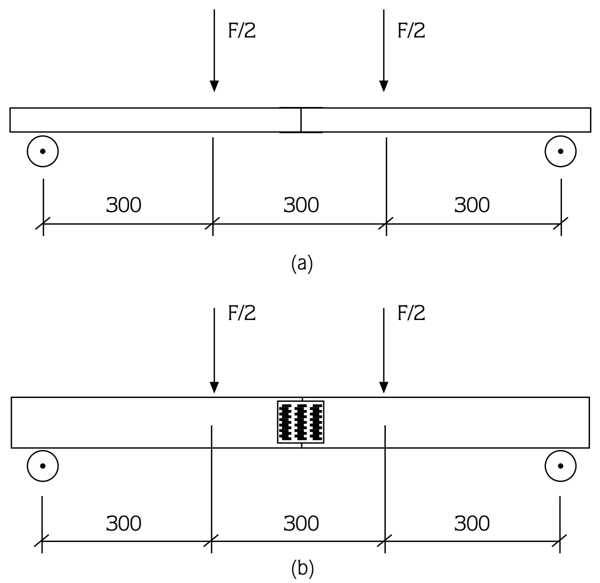

Figure 1. General configuration of loading: a) edgewise, b) flat (dimensions in mm).

time, using a hydraulic press. All joints were tested 7 to 14 days after fabrication. A screw-driven testing machine with a capacity of 50 kN was used in the evaluation of the ultimate bending moment capacity of the joints. A constant testing speed of 2 mm min^{-1} was applied to reach maximum load in 3 to 6 min. General configuration of the loading is shown in Figure 1. This type of loading, which was also used by Gupta (1994) and Kevarinmaki (2000), ensures that no shear is applied to the plates while pure moment occupies the joint. The moment on the joints has a magnitude of *PL/6,* where *P* is the force applied and *L* is the span.

Results and Discussion

Some physical and mechanical properties of the lumber material used in the study are summarized in Table 2. MC ranged from 10% to 11%, while SG ranged from 0.42 to 0.64. Average moment carrying capacity of the joints tested in the study is presented in Table 3. A 2-way analysis of variance (ANOVA) general linear model procedure was run for moment data with SAS software to interpret principal and interaction effects on the moment carrying capacity of the joints. ANOVA results (Table 4) indicate that test type, plate size, and tooth orientation have significant effects ($P < 0.0001$) on moment carrying capacity at the 5% significance level. The coefficient of variation was 5.6% within the reasonable limits that make results of the experiment rather reliable. ANOVA results also indicate (Table 4) that there was a plate size and tooth orientation interaction at the 5% significance level in the analysis of moment carrying capacity, which makes the effect of principal variables less meaningful. This means that either plate size or tooth orientation has an effect on the other.

Duncan's multiple range test at the 5% significance level was performed within the SAS program to determine the mean differences for each significant test result. In general, the joints tested in the edgewise position were almost 70% stronger than those tested in the flatwise position (Table 5). In the edgewise position, 2 parallel plates were resisting bending moment that was trying to tear the 2 plates simultaneously. In the flatwise position one plate was in tension while another was in compression. It is shown in Table 6 that M plates and L plates were not significantly different in bending moment carrying capacity, but they had approximately 30% higher

Table 2. Some physical and mechanical properties of the lumber used in the study.

Property	Mean	Minimum	Maximum	Standard Deviation	Coefficient of variation (%)
SG	0.52	0.42	0.64	0.046	8.8
MC (%)	10.05	9.47	11.32	0.31	3.08
MOE (MPa)	8498.21	4171.06	11,677.93	1618.39	19.04
MOR (MPa)	102.44	63.07	137.69	16.55	16.15

Table 3. Bending moment capacity (Nm) of the splice joints tested in the study (PS- plate size, TO- tooth orientation, TF- test face of lumber, SS- sample size, Min- minimum, Max- maximum, cov- coefficient of variation).

PS (mm)	TO	TF	SS	Mean	Std Dev	Min	Max	cov (%)
76 x 76	AA*	Edge	10	1899.36	69.13	1777.48	2035.95	3.6
76 x 76	AE**	Edge	10	1780.29	88.22	1641.50	1935.50	4.9
76 x 76	AA	Flat	10	941.65	96.48	790.12	1104.95	10.2
76 x 76	AE	Flat	10	899.51	76.02	774.20	1002.05	8.4
76 x 100	AA	Edge	10	2389.85	105.78	2169.48	2513.70	4.4
76 x 100	AE	Edge	10	1890.91	91.00	1755.43	2002.88	4.8
76 x 100	AA	Flat	10	1569.96	45.96	1496.95	1651.30	2.9
76 x 100	AE	Flat	10	1063.79	14.76	1048.6	1087.8	1.3
76 x 152	AA	Edge	10	2421.34	170.54	2205.00	2616.60	7.0
76 x 152	AE	Edge	10	1907.04	57.28	1837.50	1978.38	3.0
76 x 152	AA	Flat	10	1622.27	94.49	1470.00	1727.25	5.8
76 x 152	AE	Flat	10	1045.42	23.33	1026.55	1085.35	2.2

*AA orientation means plate slots run parallel to wood grain

** AE orientation means plate slots run perpendicular to wood grain.

Table 4. ANOVA table for moment (Nm) values.

Source	DF	Sum of squares	Mean squares	F value	Pr > F
Model	11	2,7102,327.73	2,463,847.98	285.27	<0.0001*
Test type	1	1,8505,590.79	1,8505,590.79	2142.61	<0.0001*
Plate size	2	4,784,472.98	2,392,236.49	276.98	<0.0001*
Test type*plate size	2	57,797.27	28,898.64	3.35	0.0398
Orientation	1	2,603,140.34	2,603,140.34	301.40	<0.0001*
Test type* orientation	1	990.61	990.61	0.11	0.7357
Plate size*orientation	2	1,129,921.33	564,960.67	65.41	<0.0001*
Test type*plate size*orientation	2	20,414.42	10,207.21	1.18	0.3115
Error	88	760,050.72	8636.94		
Corrected Total	99	27,862,378.46			
	R-Square	Coeff Var	Root MSE	Moment Mean	
	0.972721	5.640013	92.93514	1647.782	

* highly significant

Table 5. Results of Duncan's multiple range test for test type.

Duncan grouping	Mean (Nm)	N	Test type
A	2077.96	60	Edge loaded
B	1217.60	60	Flat loaded

Table 6. Results of Duncan's multiple range test for plate size.

Duncan grouping	Mean	N	Plate size
A	1839.94	40	large
A	1812.39	40	medium
B	1380.21	40	small

Table 7. Results of Duncan's multiple range test for tooth orientation.

Duncan grouping	Mean	N	Tooth orientation
A	1807.41	60	parallel
B	1408.35	60	perpendicular

bending moment capacity than S plates. Plates with AA orientation had 28% more bending moment carrying capacity than plates with AE orientation (Table 7). Literature on the moment carrying capacity of metal plates is scarce. When compared to a study conducted by Gupta (1994), they are higher than values found for joints that were constructed with southern yellow pine and in-line tooth oriented plates. Lumber MOE and joint ultimate moment carrying capacity evidently are unrelated (Figure 2). Specific gravity and joint ultimate moment carrying capacity are also seemingly not related (Figure 3). Although lumber material had high coefficients of variation for MOE (19%) and MOR (16%), the joints' moment carrying capacity did not reflect this variability.

Failure types in the joints were also analyzed. While metal plate failure was common in the joints that were edgewise tested (Figure 4), tooth withdrawal (Figure 5) and metal plate failure were widely observed for the joints that were flat tested. When S plates were used, tooth withdrawal was generally found, and M and L plates tended to suffer metal plate net failure. Wood failure was also observed in 3 of the 120 joints tested. It seems that M plates are adequate to resist moments that splice joints may encounter in service. Since most of the failures occurred in the metal net sections, it is somewhat expected that there is no logical relationship between wood properties and joints' ultimate moment carrying capacity. To evaluate the relationship between wood

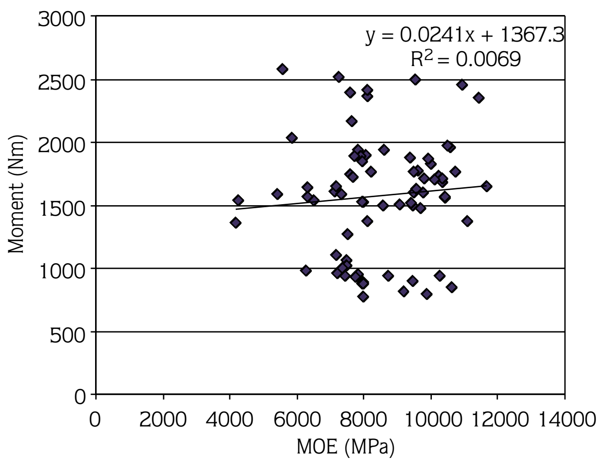

Figure 2. Relationship between lumber MOE and joints' moment carrying capacity.

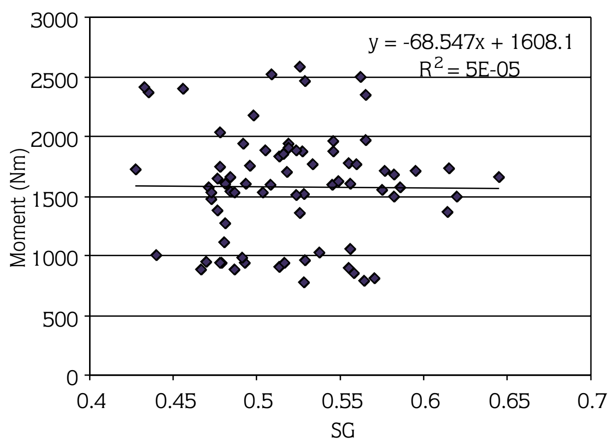

Figure 3. Relationship between lumber specific gravity and joints' moment carrying capacity.

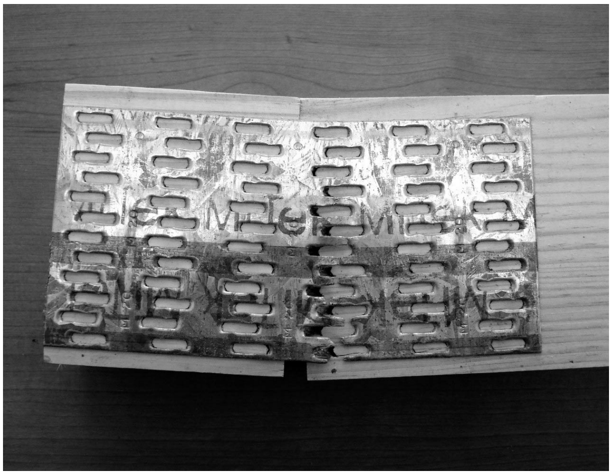

Figure 4. Metal plate failure mostly occurred in the joints that were tested in the edgewise position (plate shown is in AA orientation).

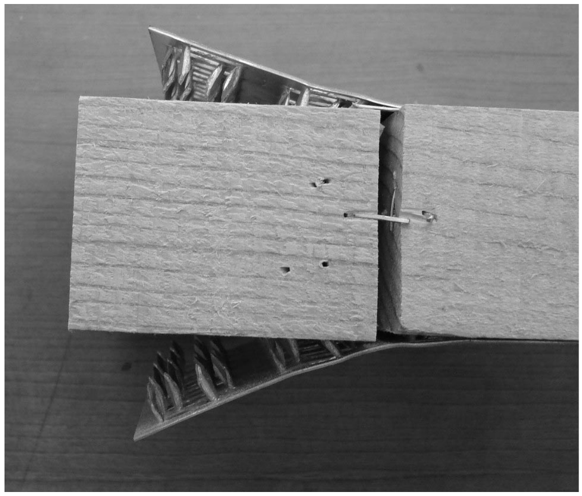

Figure 5. Tooth withdrawal failure was associated with S plates that were tested in the flat position.

properties and moment carrying, another investigation should be carried out using S plates.

Conclusions

A total of 120 MPC wood splice joints were tested to determine their bending moment capacity. Both plate size and plate tooth orientation were found to have effects on the bending moment capacity besides the type of loading. M plates were not significantly different from L plates. Both plate sizes had higher bending moment capacity than S plates. The joints that were tested in the edgewise position had significantly higher bending moment capacity. The relationship between the joints' bending moment capacity and the lumber's MOE was not significantly significant.

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