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Slip Modulus of Cold-Formed Steel Members Sheathed with Wood Structural Panels

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Abstract

Cold-formed steel framing sheathed with wood structural panels is a common method of construction for wall, roof and floor systems in cold-formed steel structures. Since wood structural panels are attached with screws at relatively close spacing, a certain amount of composite behavior will be present. The benefit of composite behavior is not currently being taken advantage of in the design of these structural systems. While composite effects are present, they are not yet being accounted for in design due to a lack of statistical data. To determine the amount of composite action taking place in these systems, the slip modulus between steel and wood is required. The slip modulus reflects the amount of shear force able to be transferred through the screw connection, to either member of the composite system. This paper presents the results of a study conducted to determine values of the slip modulus for varying thicknesses of cold-formed steel and plywood sheathing. Shear tests were conducted and the slip moduli were determined based on ISO 6891 and ASTM D1761. Compared with data from a previous preliminary study performed by others, the slip modulus values determined from these tests were deemed reasonable. The determination of the slip modulus will lead to the ability to calculate a composite factor. Determination of a composite factor will allow cold-formed steel wood structural panel construction to become more economical due to the available increase in bending strength.

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Introduction

Cold-formed steel wood structural panel construction (CFSWSPC) is typically used in a repetitive member assembly such as a floor, roof or wall application. ASTM D6555-03, Standard Guide for Evaluating System Effects in Repetitive-Member Wood Assemblies (ASTM, 2003) defines a timber-timber composite structure (TTCS) repetitive member assembly as a system in which a transverse load-distributing element connects three or more members. This definition can also be applied to CFSWSPC. In the case of CFSWSPC the transverse load-distributing element is the wood structural panel, which is one of the most commonly used load distributing elements for most low-rise buildings in North America according to Rosowsky, et al. (2004) in Partial Factor Approach to Repetitive-Member System Factors. The member used in this case is a cold-formed steel member.

According to ASTM D6555-03, “The apparent stiffness and strength of repetitive member wood assemblies is generally greater than the stiffness and strength of the members in the assembly acting alone. The enhanced performance is a result of load sharing, partial composite action and residual capacity obtained through the joining of members with sheathing or cladding, or by connections directly.” (ASTM, 2003)

ASTM D6555-03 (2003) defines “composite action” of TTCS as “interaction of two or more connected wood members that increases the effective section properties over that determined for the individual members.” To simplify, as stated previously, the addition of the sheathing as a member increases the section properties because the system is then able to be designed as a T-beam, and not a simple joist. Figure A shows an illustration of cold-formed steel members in a repetitive member system attached to wood structural panel (plywood, in this case) and the effective T-beam created by the two members. Effective T-beams with partial composite action can be modeled by numerous structural analysis formulations which include the finite difference method, the finite element method, the direct stiffness method and the exact analytical model. The direct stiffness method is used in this paper.

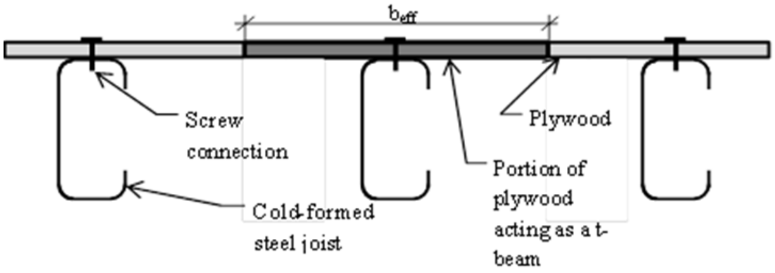

Figure A. CFSWSPC Effective T-Beam

To resist bending in the composite member, the plywood acts as the compression flange and the bottom of the cold-formed steel member acts as the tension flange. However, due to the non-rigid connection between the dissimilar elements of the CFSWSPC, full composite action may not exist, and thus should not be assumed. Partial composite action is a condition in which full composite action is not able to be developed. The connection and possibility of gaps between the joist and sheathing creates the non-rigid connection in which slip must be accounted for. This non-rigid connection can be accounted for using a slip modulus.

The slip modulus is a value reflective of the stiffness of a connection between two materials. As the stiffness and rigidity of a connection decrease, the slip modulus decreases. Composite action decreases as the rigidity of the connection between the cold formed steel and the sheathing decrease.

In order to determine the magnitude of the partial composite action taking place, the slip modulus must be determined. For CFSWSPC the additional stiffness and strength of the composite structure is not currently being accounted for in design. CFSWSPC can gain stiffness and strength in a repetitive member system by partial composite action obtained through the joining of the members with sheathing.

This paper determines a lower bound for the slip moduli for CFSWSPC in order to provide a methodology to account for the increase in stiffness and strength through partial composite action between the cold formed steel and wood structural panel sheathing.

Test Plan

The study of the slip modulus of CFSWSPC was comprised of four test series. All series were using cold-formed steel joists with plywood sheathing and two screws, spaced at 12” (30.48cm), on each side of the member. Table A shows the different combinations of materials for each CFSWSPC test series. 43 mil cold-formed steel studs were not available at the time of this study.

Table A. Test Combinations

Series	Test Combinations		
	Steel Thickness	Plywood Thickness	Screw Size
1	33 mil	1/2” (1.27cm)	#10
2	54 mil	1/2” (1.27cm)	#10
3	68 mil	1/2” (1.27cm)	#10
4	97 mil	23/32” (1.83cm)	#10

*Materials provided by Hi-Tech Interiors and KDK Engineering

The CFSWSPC was tested using variation in the cold-formed steel thickness and plywood thickness; however the connection type and spacing remained constant. The screws were #10, 1 7/16” (3.65cm), self-drilling, self-tapping TEKS 5 type, Phillips Flat Head. The connection method and spacing chosen to test is based upon “The Study of Slip Modulus for Cold Form Steel – Timber Composite Floor Structures (Chan, 2009).” 12” (30.48cm) screw spacing is the normal spacing used for roof, floor and wall sheathing for members not located at a sheathing panel joint. Thus, to imitate most typical construction methods this test is limited to the use of two connectors with 12” (30.48cm) spacing.

The plywood thickness was changed for test series four to imitate typical construction practices. Each test series was run a minimum of three times.

Apparatus

Shear tests were used to determine the slip modulus of CFSWSPC. The apparatus used for the test are shown in Table B and Figure B.

Table B. Test Apparatus

Apparatus	Description
MTS Machine	Machine can apply loads up to 55 kips (244kN). It operates at either a constant stroke or constant force and has an accuracy of +/- 1% when calibrated. Last calibrated 3-21-11. See Figure B.
Loading plate	1.25” (3.18cm) steel plate to distribute the load evenly to the cross section of the specimen from the MTS Machine.
Screws with washers	Fabricated to aid in the measurement of slip such that they

and angle plate	did not affect the material performance.
Transducer	Schaevitz DC-EC 2000 LVDT. The transducer measures the slip between the cold formed steel and plywood during the test. It has a sensitivity of 0.001” (0.00254cm).

Figure B. MTS Testing Machine and specimen

Experimental Procedure

The plywood pieces were 6” (15.24cm) by 24” (60.96cm) and the CFS members were 24” (60.96cm) in length. Specimens were assembled using two pieces of plywood and one steel section. Two self-screwing, self-tapping screws were used to attach each piece of plywood to each side of the steel member (Figure C). The transducer was attached to the steel and the plywood by a bolt and a small angle iron, which was attached using a small screw to the plywood. All screws were installed using a hand held drill.

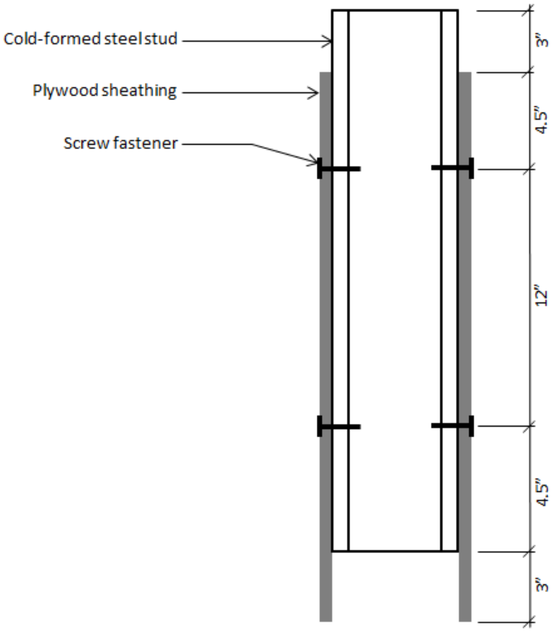

Figure C Test Specimen Set-up

The specimens were loaded using a constant displacement of 0.0394 in/min (1 mm/min). For each series one initial specimen is loaded to failure to determine the ultimate load for the test series. This test procedure was based on ISO 6891 and ASTM D1761. The procedure is as follows:

1) Conduct a preliminary test to determine the ultimate load in order to set up the proceeding tests. The ultimate load, P_u, is defined as the load corresponding to specimen failure or 0.591" (15mm) of slip.
2) Estimate the load at which failure will occur in the future specimens, P_{est}, based upon the ultimate load, P_u
3) Apply load according to ISO 6891 as follows:
    i. Apply load until it reaches $0.4*P_{est}$
    ii. Maintain load for 30 seconds
    iii. Relieve load from $0.4*P_{est}$ to $0.1*P_{est}$
    iv. Maintain load for 30 seconds
    v. Increase load to $0.7*P_{est}$
    vi. Increase load until failure

4) Compare the ultimate load, P_u, to the estimated load, P_{est}. The ultimate load is the load at which failure occurs. Failure may occur by a number of different mechanisms, however screw shear and screw tilting were the only two observed in this study. Screw tilting failure is determined to be at a tilting or slip value of 0.591in (15mm). If the difference between P_u and P_{est} is more than 20%, the test must be thrown out and a new specimen must be tested. If the difference is less than 20% continue to step 5.
5) Plot the load and displacement curve
6) Determine the slip modulus

The use of 0.591" (15mm) as a benchmark for tilting failure of the specimen was used previously by Chan, et al (2009) in the preliminary study conducted by Slab Group of Kitchener, Ontario to determine the slip modulus of CFSWSPC and governed by ISO 6891.

The load vs time curve as described in step 3 above is shown in Figure D.

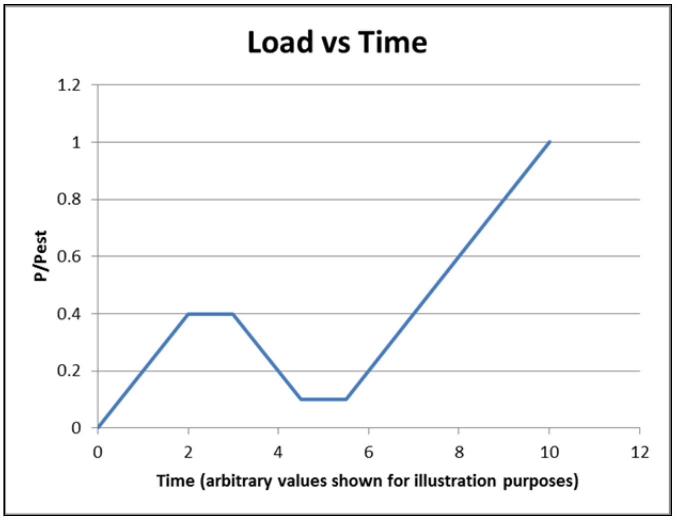

Figure D. Loading Curve

Slip Measurement

A transducer was attached to the side of each specimen in order to measure the slip between the two materials. Slip was measured through the entirety of the test, from when the initial load was applied through failure. The failure mechanism for each specimen is shown in Table C. Data was recorded every 0.001 inches (0.254mm) of slip.

Test Data

Figures E through H show the load vs. displacement curve of each specimen, by test series. The data collected has been compiled for use in Table C.

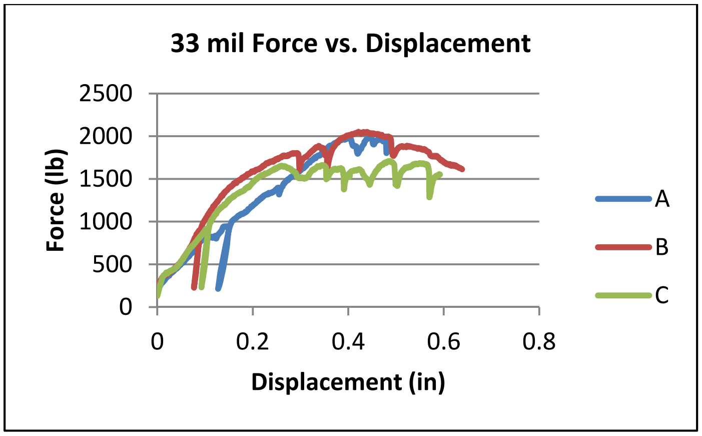

Figure E. 33 mil Force vs. Displacement Curve

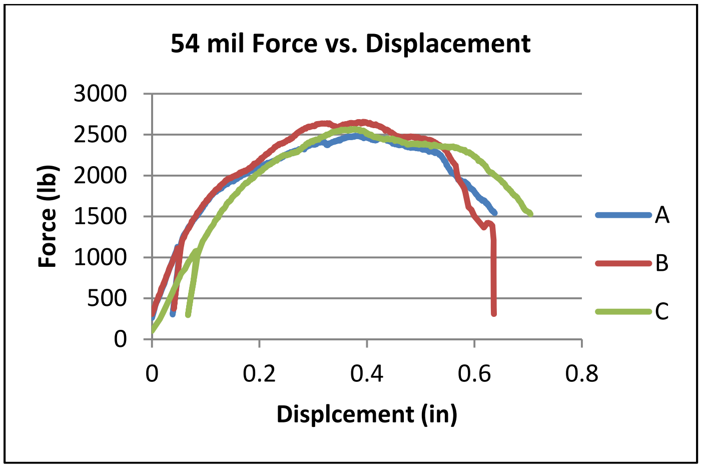

Figure F. 54 mil Force vs. Displacement Curve

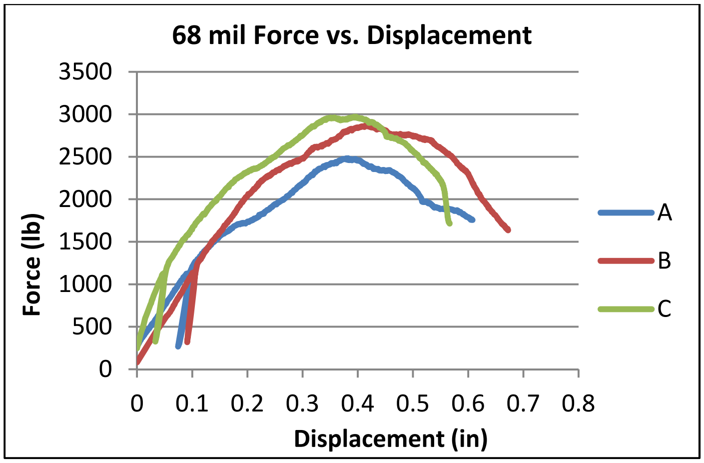

Figure G. 68 mil Force vs. Displacement Curve

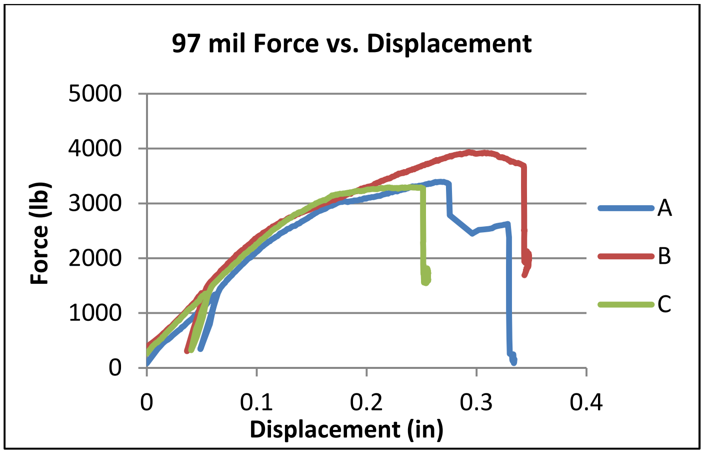

Figure H. 97 mil Force vs. Displacement Curve

Table C. Test Results

Test Series	Steel Gauge	Plywood Thickness	Specimen Code	Maximum Force	Maximum Slip	40% P_u	Slip at 40% P_u	Failure Mechanism
	ga (mil)	in		lb	in	lb	in	
1	20 (33)	1/2"	20A	1986	0.4625	845	0.1290	Screw Tilting
	20 (33)	1/2"	20B	2052	0.6006	845	0.0816	Screw Tilting
	20 (33)	1/2"	20C	1708	0.6055	845	0.1010	Screw Tilting
2	16 (54)	1/2"	16A	2488	0.6019	1084	0.0352	Screw Tilting
	16 (54)	1/2"	16B	2657	0.5099	1084	0.0383	Screw Tilting
	16 (54)	1/2"	16C	2570	0.6006	1084	0.0259	Screw Tilting
3	14 (68)	1/2"	14A	2483	0.6051	1127	0.0808	Screw Tilting
	14 (68)	1/2"	14B	2865	0.6039	1127	0.0464	Screw Tilting
	14 (68)	1/2"	14C	2971	0.6046	1127	0.0361	Screw Tilting
4	12 (97)	23/32"	12A	3393	0.2110	1354	0.0322	Screw Shear
	12 (97)	23/32"	12B	3936	0.3979	1354	0.0324	Screw Shear
	12 (97)	23/32"	12C	3294	0.8922	1354	0.0463	Screw Shear

Discussion of Results

The maximum load for each specimen generally increased as the thickness of the cold-formed steel joists increased. The maximum slip also generally increased with exceptions in the 97 mil steel tests (test series 4). This is likely due to the brittle and sudden nature of the screw shear failure that took place for test series 4. Test series 1, 2 and 3 had screw tilting failure mechanisms, and thus were slower, more predictable failures.

The sharp decline at the end of each of the force vs. displacement curves of the 97 mil specimens in Figure H was due to the failure mechanism of screw shear. The remaining tests shown in Figures E through G all had much less sudden curves, thus indicating the slow, predictable failure as mentioned previously.

The most common mode of failure was screw tilting. This occurred either when the screws were no longer effective in attaching the plywood and the steel or when the slip between the two materials was measured by the transducer as 0.591” (15mm).

Implications for Practice

In order to calculate the effective bending stiffness of the composite material, the normalized slip modulus and the shear bond coefficient was calculated.

The slip modulus was calculated for each test specimen. The slip modulus is equal to the quotient of forty percent of the ultimate load and the corresponding amount of slip at that load, as shown in Equation 1. A normalized slip modulus will reflect the composite action for one screw connection, per inch of sheathing, as shown in Equation 2. Table D shows the values for the slip modulus and normalized slip modulus obtained for each specimen.

Equation 1. Slip Modulus

$$K = \frac{0.4P_U}{v_{0.4}}$$

Equation 2. Normalized Slip Modulus

$$K_N = \frac{(\frac{0.4P_U}{v_{0.4}})}{ns}$$

Where:

K= slip modulus (lb/in)
K_N = normalized slip modulus (lb/in/in)
P_u = ultimate load (lb)
$v_{0.4}$ = measured slip at 40% of P_u (in)
n = number of screws
s = spacing of screws (in)

Table D. Slip Modulus Calculations

Test Series	Specimen Code	CFS Thickness (mil)	Slip Modulus (lb/in)	Normalized Slip Modulus (lb/in/in)
1	20A	33	6549	136.4
	20B	33	10353	215.7
	20C	33	8364	174.3
2	16A	54	30809	641.9
	16B	54	28315	589.9
	16C	54	41871	872.3
3	14A	68	13944	290.5
	14B	68	24283	505.9
	14C	68	31211	650.2
4	12A	97	42046	876.0
	12B	97	41787	870.6
	12C	97	29242	609.2

When examining the slip modulus values in Table D, Test 14A appears inconsistent with the other values within test series 3. Test 14A also appears inconsistent with trend that as the thickness of the cold-formed steel increases, the slip modulus increases. During testing the specimen seemed to perform similarly to the other two within the series; however more slip occurred earlier in the test than in tests 14B and 14C.

Recommendations

The statistics for the normalized slip modulus are shown in Table E, using a 95%, two tailed probability.

Table E. Normalized Slip Modulus Statistical Data

Test Series	Standard Deviation, σ	Mean	Median	Confidence Interval	Coefficient of Variation
1	32.38	175.4	174.3	137 – 214	0.185
2	122.7	701.4	641.9	557 – 846	0.175
3	147.8	482.2	505.9	307 – 657	0.307
4	124.5	785.3	870.6	638 – 932	0.159

From these tests with #10 screws spaced at 12” on center, the following nominal slip modulus values are recommended:

- 140 lb/in/in for 33 mil cold-formed steel with 1/2" plywood sheathing
- 560 lb/in/in for 54 mil cold-formed steel with 1/2” plywood sheathing
- 640 lb/in/in for 97 mil cold-formed steel with 23/32” plywood sheathing

These recommended values are based on the lower bound of the 95%, two tailed probability confidence intervals. The confidence interval is the range of values with which 95% of tests will fit into. The values recommended are nominal values.

In order to provide accurate recommendations for test series 3, further study is needed. Due to the small number of samples and high variation in the test data, a high standard deviation was recorded in the calculation of the slip modulus, and thus a lack of reliability of the values present.

The shear bond coefficient is used to determine the effective bending stiffness of the composite material. The effective bending stiffness will show the relative amount of stiffness increase from the composite action of the CFSWSPC compared to the stiffness of the cold-formed steel joist alone. The value of the shear bond coefficient relates the amount of shear force able to be transferred through the connection. The shear bond coefficient is dependent upon the slip modulus, as shown in Equation 3, as seen originally in Steinberg, et al (2003). Values of the shear bond coefficients are shown in Table F.

Equation 3. Shear Bond Coefficient

$$\gamma = \frac{1}{1 + \frac{\pi^2 s E_S A_S}{K L^2}}$$

Where:

γ = shear bond coefficient
s = spacing of connectors (in)
E_S = Modulus of Elasticity of sheathing (psi)
A_S = Area of sheathing (in^2)
K = slip modulus (lb/in)
L = length of member (in)

Table F. Shear Bond Coefficients

Test Series	Shear Bond Coefficient, γ
1	0.003
2	0.012
4	0.010

The effective stiffness is calculated using Equation 4 as seen originally in Steinberg, et al (2003). Table G shows the values for effective stiffness for each test series.

Equation 4. Effective Stiffness

$$(EI)_{eff} = E_S I_S + \gamma E_S A_S a_1^2 + E_J I_J + E_J A_J a_2^2$$

Where:

$(EI)_{eff}$ = effective stiffness of composite (lb*in^2)

$E_S I_S$ = bending stiffness of sheathing (lb*in^2)
γ = shear bond coefficient
$E_S A_S$ = axial stiffness of sheathing (lb)
a_1 = distance between sheathing centroid and CFSWSPC centroid (in)
$E_J I_J$ = bending stiffness of joist (lb*in^2)
$E_J A_J$ = axial stiffness of joist (lb)
a_2 = distance between joist centroid and CFSWSPC centroid (in)

Table G. Effective Stiffness

Test Series	Joist Bending Stiffness, $E_J I_J$ (lb*in^2)	Effective Bending Stiffness, $(EI)_{eff}$ (lb*in^2)
1	51.9×10^6	84.5×10^6
2	82.9×10^6	116×10^6
4	139×10^6	221×10^6

The effective bending stiffness of the composite member [$(EI)_{eff}$] is notably larger compared to the bending stiffness of the cold-formed steel member alone ($E_J I_J$), by an average factor of 1.5. Thus, it can be seen that CFSWSPC systems are much stronger and can be much more economical than CFS members alone.

Conclusion

Recommended values for the slip modulus are 140 lb/in/in for 33 mil cold-formed steel, 560 lb/in/in for 54 mil cold-formed steel and 640 lb/in/in for 97 mil cold-formed steel. The bending stiffness is increased by an average factor of 1.5 when comparing the partial composite member to the cold-formed steel member alone. This is a significant increase and warrants consideration for the design of CFSWSPC systems.

Recommendations for Further Research

Further study should be conducted to support the values that have been recommended for the slip modulus. Additionally, expanding the variables of similar experiments to determine their effects on the slip modulus is suggested. Ultimately, further study would confirm a method for determining the slip modulus of a given CFSWSPC construction type.

Further study should also include developing a method for determining the effective flange width of the T-beam that is assumed in CFSWSPC.

Appendix – References

ASTM Standard D1761, 2006, “Standard Test Methods for Mechanical Fasteners in Wood,” ASTM International, West Conshohocken, PA, www.astm.org.

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