LOAD-SLIP CHARACTERISTICS OF METAL PLATE CONNECTED WOOD JOINTS TESTED IN TENSION AND SHEAR

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ABSTRACT

Thirty-six metal plate connected wood joints were tested in tension and shear to failure to determine their strength and stiffness characteristics and failure modes. Twenty-one of the joints were tested in tension, and the rest were tested in shear. Test specimens included the four Canadian standard orientations and intermediate orientations of 30, 45, and 60°. For the joints tested in tension, failure was by plate shear for the 0°, by tooth withdrawal for the 30 and 45°, and by wood failure for the 60 and 90° orientations. For the joints tested in shear, failure was consistently by tooth withdrawal for the 0, 30, and 45°, and by plate shear for the 60 and 90° orientations.

A 2-parameter nonlinear model characterized the P-Δ curve quite well. When characterizing the P-Δ curve, the entire curve extending from zero to the ultimate load was used. The stiffness values for the intermediate angles were calculated from the stiffness values of the standard orientations using a Hankinson-type formula.

Keywords: Load-slip, metal plate, wood joint, stiffness, strength, modeling.

INTRODUCTION

Sophisticated computer programs such as SOLVER (Gebremedhin 1986), PPSA II (Suddarth and Wolfe 1984), and SAT (Varoglu 1984) have been developed for modeling wood structures. The applicability and usefulness of these programs would be expanded if truss joint models can be incorporated into these programs. To improve the design of metal plate connected trusses and make them more economical and reliable, more information about metal plate connected joint performance is needed. Data vital to this understanding include the determination of the load-displacement relationship, strength, stiffness values, and mode of failure of these joints.

Properties of lumber such as modulus of elasticity, moisture content, specific gravity, angle of grain, and properties of the metal connector plate such as size, thickness, tooth length, tooth density, configuration, and yield strength affect the performance of truss joints. Conducting experimental investigation on each and possible combinations of these properties would be costly and time-consuming. A theoretical model that would predict the load-displacement relationship and stiffness of truss joints would alleviate the necessity to conduct

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extensive testing of every type of joint. The model should be validated by experimental data.

The present study includes analysis of load-deformation of truss joints tested in shear and in tension. The configurations of the joints tested are shown in Fig. 1.

Objectives

The objectives of this study were to:

1) determine experimentally the strength and stiffness values of metal plate connected wood joints tested in tension and shear,
2) understand the behavior of the joints through their failure modes when subjected to tension or shear loads, and
3) develop models that would predict the load-deformation (P-Δ) relationships and stiffness values for the joints tested.

LITERATURE REVIEW

Several investigators have studied the mechanics of metal plate connected truss joints. Foschi (1977) developed a three-parameter nonlinear model that correctly characterized the P-Δ curves of metal plate connected truss joints. To use Foschi's model, one must fit parameter values to the P-Δ curve obtained experimentally. McCarthy and Little (1988) assessed the sensitivity of Foschi's model parameters to different parameter determination methods. They reported that alternative determination methods may produce a variance up to 70% among the same parameters. The validity of their conclusion should be confirmed by comparison with other data sets obtained from conducting similar joint tests. Currently, no standard exists for method of analysis such as determining the parameter values from test results. For example, Foschi set one of the three parameters to equal to zero (Foschi 1977); Triche and Suddarth (1988), and McCarthy and Little (1988) determined the parameters by fitting the P-Δ curve up to the critical slip (=0.015 inch); but McCarthy and Wolfe (1987) considered the data curve up to the ultimate load. Also no standard exists as to whether or not the data for replicates should be averaged to generate a mean load-slip curve. Lau (1987) and McCarthy and Little (1988) averaged the data for replicates, but McCarthy and Wolfe (1987) did not.

Because of the number of variables that affect joint performance, future research effort should probably focus on several areas. Of fundamental importance is confirmation of the appropriateness of current testing methods for metal plate connected joints. The ASTM Standard D 1761 (American Society for Testing and Materials 1985) includes only one standard joint configuration. This standard may not be sufficient for collecting data for joint stiffness for all fasteners. The Canadian Standard, CSA S347 (Canadian Standards Association 1980), includes four standard configurations of plate and wood grain to load orientations. These orientations simulate actual truss joint action under axial loading conditions. Triche and Suddarth (1988) extended the finite element model originally developed by Foschi (1977) to include determination of allowable load per tooth. The finite element model has been incorporated in PPSA II and provides a new engineering design tool that can support the expansion of wood truss and frame applications. Recently, Gupta and Gebremedhin (1990) have developed a novel computer-controlled testing apparatus and methods for testing metal plate connected truss joints. The system provides flexibility to test different joints such as tension splice joint, heel joint, and web at the bottom chord joint subjected to axial, bending, or combined axial and bending loading conditions.

Consideration must be given to the moment-carrying capacity of a truss joint. It may not be appropriate to assume that a joint is pinned. Massé and Salinas (1988) reported that the best representation of an actual truss joint is to assume that it is semi-rigid. They concluded that traditional design methods over-design the top chords and under-design the bottom chords. Maragechi and Itani (1984) tested tension splice joints in pure axial tension, pure shear, and pure bending to obtain

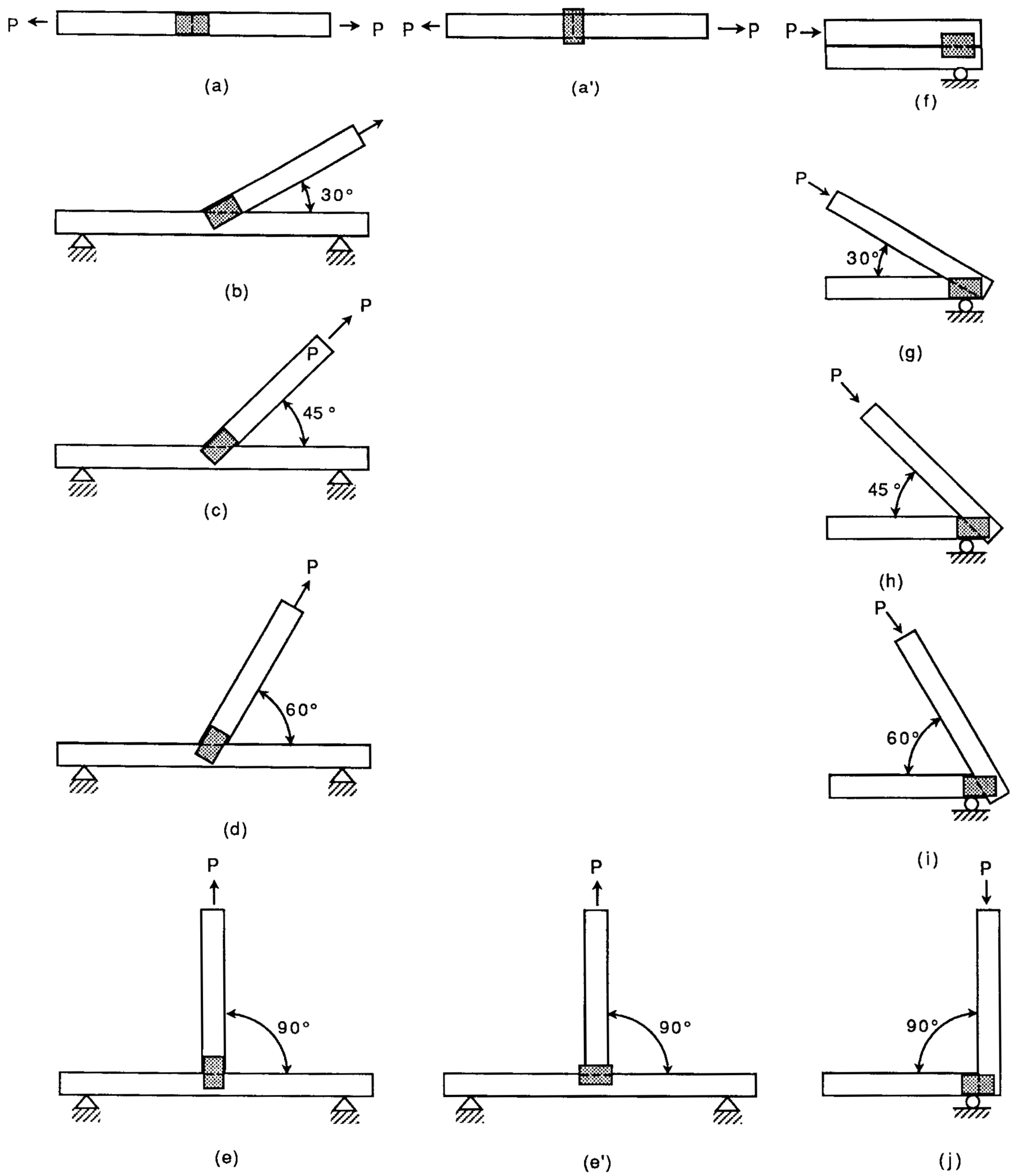

FIG. 1. Joint orientations. Joints (a) to (e') were tested in tension, and (f) to (j) were tested in shear.

stiffnesses for truss joints. They reported that axial and rotational stiffnesses had appreciable influences on member end forces, while shear stiffness had little effect.

The orientation of the metal connector plate affects the mode of failure of joints. McMartin et al. (1984) reported that improving designs of heel joints resulted in a 40% increase in the load carrying capacity of trusses. Sheppard (1969) tested heel joints fabricated using six different sizes of metal connector plates. The most common mode of failure of the joints was tooth withdrawal.

MATERIALS AND METHODS

Material and fabrication

All lumber used for this study was purchased from a local lumber yard and was No. 2 Southern Yellow Pine KD 15. The modulus of elasticity (MOE) and moisture content (MC) of each specimen were determined prior to fabrication of the joints. To determine the MOE, the 8-ft-long piece was placed flatwise and simply supported 6 ft apart. Dead weight was applied at the center in increments of 10 lb (up to 50 lb). Deflection was measured at midspan by a linear variable differential transducer (LVDT) and was recorded by a computer.

The moisture content of each piece was determined according to the ASTM D 2016-74, Method A (ASTM 1974). In this procedure, a 1-inch cross section was cut from each piece of lumber and weighed. All of the specimens were then placed in an oven and heated at 103 ± 2 C temperature for approximately 24 h until they reached a constant weight. Upon removal from the oven, the specimens were weighed immediately and the MC was calculated. The specific gravity (SG) of the specimens was not determined.

The metal connector plates were procured from an industry metal connector plate manufacturer. The specifications of the connector plates are given in Table 1.

TABLE 1. *Metal plate connector specifications.*

Plate size (inch)	3 × 5
Plate thickness (gauge)	20
Tooth density (teeth/sq. in.)	8
Tooth length (inch)	⅜
Teeth configuration	In-line
Modulus of elasticity (psi)	29.5×10^6
Yield strength (psi)	36×10^3

Joint fabrication and testing procedures

A total of 36 joints were fabricated and tested. These joints consisted of the four Canadian Standard orientations and three intermediate (30, 45, and 60°) orientations tested in tension, and five orientations (0, 30, 45, 60, and 90°) tested in shear. Each joint was replicated three times. All configurations are shown in Fig. 1.

Each joint was fabricated from a single piece of lumber cut in half and rejoined together by metal connector plates. This procedure would minimize variations in MOE, SG, and MC between the connected pieces. A hydraulic press was used to stamp the metal connector plates to the lumber. Unlike common practice in truss fabrication, only one plate was pressed at a time. Testing was conducted using a recently developed testing frame apparatus. The test frame was laid out horizontally and was bolted to the floor to restrict any movement. Each joint specimen was held in place by and loaded on this test frame. The test frame with a heel joint in place is shown in Fig. 2. The joints were kept at room temperature for 7 days prior to testing.

The load was applied through a hydraulic cylinder. A calibrated force transducer attached to the hydraulic cylinder measured the applied force. The cylinder was actuated by a single variable volume hydraulic pump and was restrained by the test frame to exert pressure on the joint. A proportional solenoid pressure control valve was the "heart" of the hydraulic system, permitting close control of the pressure in the cylinder. Joint slip was measured using LVDTs. The applied force was monitored and recorded by an IBM-PC/XT computer. The analog signals from the load cell and LVDTs were amplified using a signal conditioning unit and then converted into digital signals by an analog to digital (A/D) converter to be recorded by the computer.

The joint specimen was placed in the testing apparatus, and a tensile load (tension test) or a compressive load (shear test) was applied. In each case, the load was applied in a manner such that joint displacement was in the plane of the load. The following steps describe the loading procedure:

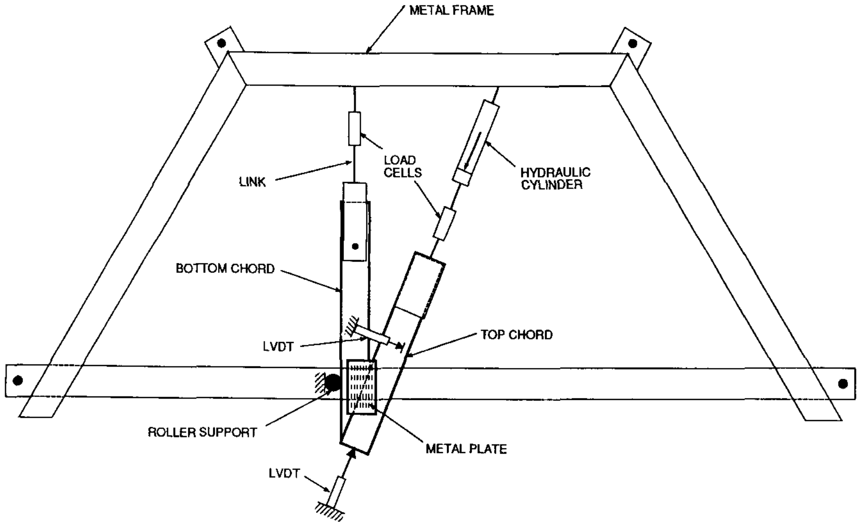

FIG. 2. Test frame with a heel joint in place.

1. Setting up. This included securing the joint specimen in place, positioning the LVDTs, and connecting the load cell and the hydraulic system.
2. Apply an initial load of 50 psi (300 lb) to initialize the system.
3. Read the force applied and the resulting displacements.
4. Increase the applied force every 10 seconds by increasing the hydraulic pressure.
5. Convert readings from voltage into pounds and inches (analog to digital), print and store data at the same time.
6. Repeat Steps 3 to 5 until failure. Failure was defined when deflection increased at no detectable increase in load-cell readings or when a permanent damage to the joint was observed.

Steps 3 to 6 were performed by the computer. Each test lasted between 9 to 20 minutes. This was consistent with the ASTM D 1761-88 recommendation that failure should occur between 5 to 20 minutes (ASTM 1988).

ANALYSIS PROCEDURE

Modeling the P-Δ data

A P-Δ curve was plotted for each set of data. Each data set was curve fitted using a least-squares technique. Several models—polynomial (nonlinear regression), logarithmic, nonlinear three parameter, and nonlinear two parameter—were tried to determine the best fit. The nonlinear three parameter model was of the form:

$$P = (M_0 + M_1\Delta)[1 - \exp(-k\Delta/M_0)] \quad (1)$$

where P = load on the joint, lb
Δ = joint displacement, in.
k, M_0, M_1 = parameters to be determined

The physical significance of the parameters is that k = the initial stiffness; M_1 = the stiffness at large slip; and M_0 = the intercept of the asymptote with slope M_1 (Foschi 1977).

The nonlinear two parameter model was obtained by setting $M_1 = 0$ in Eq. (1), and becomes

$$P = M_0\,[1 - \exp(-k\Delta/M_0)] \quad (2)$$

Setting $M_1 = 0$ is equivalent to setting the slope equal to zero at the ultimate load. Setting $M_1 = 0$ provides two advantages: (1) M_0, the intercept parameter, provides a reasonable appreciation of the maximum load, and (2) one less parameter to consider. In all of the curve fitting procedures, the data curve extending from zero to the ultimate load was used.

Next, the P-Δ data of the three replicates were combined together, and the combined data were curve fitted using the same procedure discussed previously. This procedure provided two or three parameters (depending on whether the 3- or 2-parameter model was used) instead of three times more for the replicates.

Calculating the stiffness values

Two approaches were followed to determine the stiffness values for the joints. One approach was to calculate the stiffness from the slope of the load-deflection curve at the allowable design load. The allowable design load was defined as the ultimate load divided by a factor of three (Truss Plate Institute 1985). The factor of three includes a load duration factor and a factor of safety. The second approach was to calculate the stiffness by dividing the load at the critical slip (=0.015 inch) by 0.015 inch (TPI 1985).

Given the stiffness values for the standard orientations, a procedure is herein suggested to calculate the stiffness values for the intermediate orientations using a Hankinson-type interpolation (Hankinson 1921). Foschi (1977), and McCarthy and Wolfe (1987) suggested similar interpolation schemes for calculating the stiffness for intermediate orientations.

The formula used to determine the stiffness values for the intermediate orientations is expressed as

$$k_\theta = \frac{k_{\parallel} \cdot k_{\perp}}{k_{\parallel} \sin^n\theta + k_{\perp} \cos^n\theta} \qquad (3)$$

where

k_θ = predicted stiffness for an intermediate orientation between 0 and 90°

θ = angle between applied load and grain direction

$k_{\parallel}$ and $k_{\perp}$ = stiffnesses for the standard orientation of 0 and 90°, respectively

n = exponential value

It should be noted that an n = 2 is used in the Hankinson formula for calculating stresses for lumber at intermediate angles between parallel and perpendicular to the grain (NFPA 1986). In this study, exponents of 1.0, 1.25, 1.5, 1.75, 2.0 were considered in the interpolation scheme. McCarthy and Wolfe (1987) used similar exponents to determine k_θ for joints of arbitrary orientations.

RESULTS AND DISCUSSION

Results—material properties

The modulus of elasticity (MOE) of the lumber used for the fabrication of the joints tested in tension ranged from 0.9 to 2.1 × 10^6 psi, and that for the joints tested in shear ranged from 1.2 to 2.2 × 10^6 psi. The lumber used for the fabrication of the joints tested in shear had generally higher MOE values than the lumber used for the joints tested in tension. The moisture content (MC) of each piece of lumber used for the joints tested in tension was between 13.6 and 18.6%. The average MC was 15.9%. The MC of the lumber used for the joints tested in shear was between 11.5 and 13.4%. The average MC was 12.4%.

Mode of failure—joints tested in tension

Three failure modes were possible for the joints tested in tension: (1) tooth withdrawal, (2) wood failure, and (3) connector plate shear failure. Tooth withdrawal and wood failure were most prevalent. These modes of failure accounted for almost 90% of all failures for these joints. Tooth withdrawal was evident mainly for the 30 and 45° joints. For the 60° and 90° joints, failure occurred in the horizontal wood member. The horizontal member was subjected to a force component perpendicular to the grain. The 0° joint failed by plate shear. Evidently, tension parallel to the grain of the lumber was greater than shear of the metal connector plate at the critical section. The connector plate sheared in half at the joint interface where the teeth were punched.

Mode of failure—joints tested in shear

For the joints tested in shear, failures by both tooth withdrawal and plate shear were prevalent. The 0, 30, and 45 degree joints failed

TABLE 2. *Ultimate strength, displacement at failure, joint stiffness, lumber MOE, MC and failure modes for joints tested in tension.*

Test no.	Joint orientation (degrees)	Ultimate load (lb)	Displacement @ failure (in.)	Stiffness @ design load (lb/in.)[1]	Stiffness @ critical slip (lb/in.)[1]	MOE (E + 06) (psi)	MC %	Mode of failure
13	0	5,544	0.059	3.10	2.30	1.1	18.6	Plate shear
17	0	6,213	0.059	3.60	2.60	1.3	17.7	Plate shear
16	0	5,458	0.073	2.10	1.80	0.9	15.8	Wood failure
4	30	5,505	0.149	1.30	1.40	1.1	15.5	Tooth withdrawal
11	30	5,893	0.131	1.50	1.50	1.3	12.8	Tooth withdrawal
8	30	4,786	0.096	1.10	1.10	0.9	14.3	Tooth withdrawal
6	45	6,056	0.116	1.90	1.70	2.1	11.9	Tooth withdrawal
7	45	5,514	0.064	1.50	1.50	1.5	14.0	Tooth withdrawal
10	45	5,455	0.085	1.40	1.40	1.1	18.3	Tooth withdrawal
5	60	3,696	0.071	1.20	1.10	1.0	16.1	Wood failure
9	60	3,339	0.047	1.20	1.10	0.9	14.0	Tooth withdrawal
12	60	7,087	0.099	2.40	2.10	1.7	14.5	Wood failure
20	90	3,398	0.038	1.40	1.30	1.0	18.4	Wood failure
21	90	4,487	0.056	1.80	1.60	1.3	17.6	Wood failure
22	90	4,717	0.053	1.80	1.60	1.3	17.1	Wood failure/Tooth withdrawal

[1] Multiply stiffness values by 10^5.

consistently by tooth withdrawal. In most cases, the mode of failure was symmetrical, i.e., one plate withdrew from the tension member and the other plate withdrew from the compression member. Tooth withdrawal originated at the column of teeth in the compression member farthest from the joint gap.

For the 60 and 90° joints, five out of six tests failed by plate shear at the joint interface. For one 60° joint, failure was by horizontal shear in the compression member. All failures for the joints tested in shear were abrupt and dramatic, and can be characterized as brittle.

P-Δ curves and stiffness values for joints tested in tension

The P-Δ curves exhibited a nonlinear relationship. The lower one-third section of the curve can reasonably be characterized as linear. The slope of the P-Δ curve also seems to approach zero at the ultimate load. This characteristic of the P-Δ curve supports the idea of using a 2-parameter nonlinear model by setting $M_1 = 0$.

The ultimate load, deflection at failure, MC, MOE of lumber, and mode of failure of each test are given in Table 2. The calculated stiffness values (to be discussed later) are also given in Table 2. For the joints tested in tension, the range of the ultimate loads was between 3,339 and 7,087 lb. Deflection at failure was between 0.038 and 0.149 inch. The ultimate loads were within a narrow range for the 0, 30 and 45° joints but dropped for the 60 and 90° joints, with the exception for one 60° test. The exception may be attributed to the higher MOE lumber used for that joint.

As shown in Table 2, no clear trend was observed for the calculated stiffness values for these joints. The stiffness values for the 0° joints were generally higher than the stiffnesses for the other angles. The stiffnesses for the replicates were not quite repeatable. For example, one replicate had a stiffness twice as much as the other replicates. The stiffness values ranged between 1.1 and 2.6 × 10^5 lb/in. for all joints.

P-Δ curves and shear values for joints tested in shear

The P-Δ curves for the joints tested in shear also exhibited a nonlinear relationship, more so than the joints tested in tension. The ultimate loads, deflections at failure, stiffness values, and modes of failure are given in Table

TABLE 3. *Ultimate strength, displacement at failure, joint stiffness, lumber MOE, MC and failure modes for joints tested in shear.*

Test no.	Joint orien-tation (degrees)	Ultimate load (lb)	Displacement @ failure (in.)	Stiffness @ design load (lb/in.)[1]	Stiffness @ critical slip (lb/in.)[1]	MOE (E + 06) (psi)	MC %	Mode of failure
8	0	5,197	0.229	1.57	1.46	1.8	12.6	Tooth withdrawal
6	0	5,863	0.257	1.63	1.54	1.9	13.2	Tooth withdrawal
3	0	4,582	0.092	1.91	1.65	2.2	12.4	Tooth withdrawal
10	30	4,834	0.082	2.30	1.66	2.1	12.5	Tooth withdrawal
16	30	4,505	0.120	1.07	1.05	1.8	12.5	Tooth withdrawal
5	30	5,033	0.108	1.01	1.04	2.1	12.4	Tooth withdrawal
20	45	5,421	0.105	1.81	1.49	2.1	12.2	Tooth withdrawal
11	45	5,890	0.164	1.28	1.29	1.5	13.4	Tooth withdrawal
2	45	6,207	0.171	1.29	1.29	1.8	12.4	Tooth withdrawal
12	60	4,878	0.146	0.90	0.95	1.8	11.9	Wood failure
18	60	5,132	0.180	0.95	0.97	1.9	12.5	Plate shear
15	60	5,590	0.205	0.89	0.98	1.4	11.5	Plate shear
1	90	3,165	0.288	1.32	0.82	1.2	12.4	Plate shear
17	90	3,185	0.289	0.56	0.66	1.3	11.5	Plate shear
13	90	3,775	0.242	0.90	0.85	1.5	12.7	Plate shear

[1] Multiply stiffness values by 10^5.

3. For these tests, the range of the ultimate loads was between 3,165 and 6,207 lb. The ultimate loads for the 90° joints were clearly lower than the loads for the other joints (Table 3).

The 45° joints had the highest ultimate strength (Table 3). When the connector plates are oriented 45° to the shear plane, the major axis of the connector plate coincides with the axis of the principal stress in tension. Also, a 45° orientation contributes to the formation of tension diagonals that takes place after the connector plate has buckled slightly in regions localized near the shear plane. This phenomenon also applies to the 30 and 60° joints. The tension diagonals carry an even higher load and prevent the buckling from propagating. For the 90° joints, the shear plane was perpendicular to the plate major axis and thus no tension was developed. The connector plate failed in shear.

For the shear tests, increasing θ resulted in decreasing the stiffness values, as shown in Table 3. Shear stiffness was highest (average $K = 1.55 \times 10^5$ lb/in.) for $\theta = 0°$ and lowest (average $K = 0.78 \times 10^5$ lb/in.) for $\theta = 90°$. Shear stiffnesses were reasonably repeatable when the tests were replicated. Note that the average shear stiffness for $\theta = 90°$ was half the average stiffness for $\theta = 0°$. This seems to correspond to the difference between the compression strength of lumber parallel to the grain and perpendicular to the grain.

The stiffness values for the joints tested in shear were relatively lower than the stiffness values for the joints tested in tension. However, the lumber used for the fabrication of the joints tested in shear had higher stiffness and lower moisture content than the lumber used for the fabrication of the joints tested in tension (Tables 2 and 3).

Parameter estimation for the P-Δ curves

Several models (polynomial, logarithmic, 3- and 2-parameter nonlinear) were tried to characterize the P-Δ curve. The 3- and 2-parameter nonlinear models, Eqs. (1) and (2), proposed by Foschi (1977) seem to fit the data quite well. The 2-parameter model was as good as the 3-parameter model. The experimental P-Δ curve was plotted along with the P-Δ curves predicted by the 2- and 3-parameter models for comparison. Figures 3 to 7 show these plots for the joints tested in tension, and Figs. 8 to

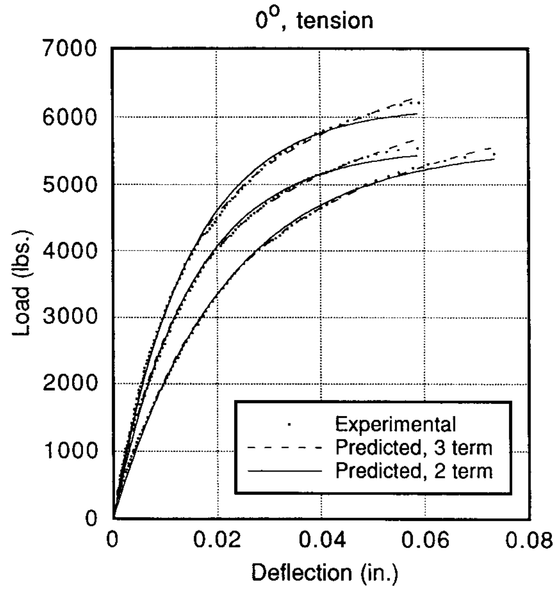

FIG. 3. Experimental and predicted P-Δ curves for θ = 0°, tension test.

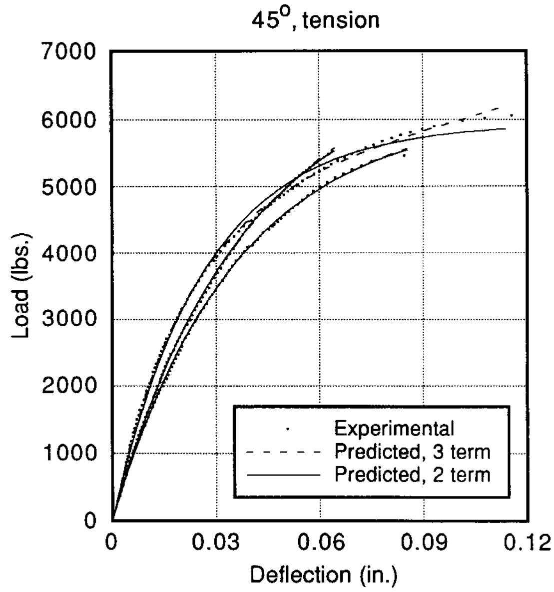

FIG. 5. Experimental and predicted P-Δ curves for θ = 45°, tension test.

12 show the corresponding plots for the joints tested in shear.

Tables 4 and 5 provide the parameters estimated by the 2- and 3-parameter models for the joints tested in tension and shear, respectively. As shown, there was considerable variability in parameter values, and no consistent trend was observed with changing θ. The pa-

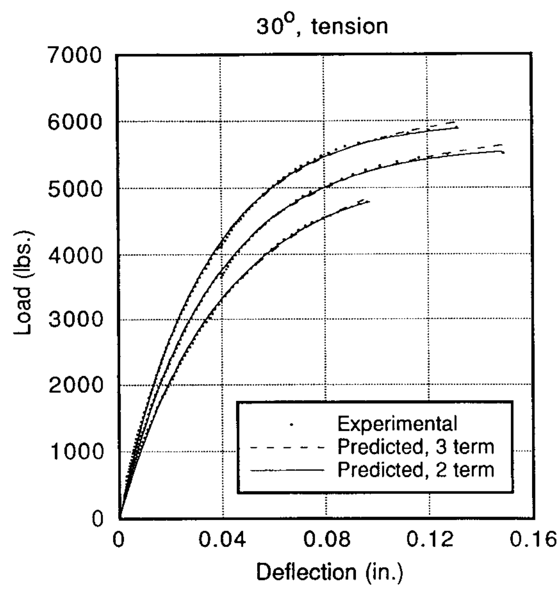

FIG. 4. Experimental and predicted P-Δ curves for θ = 30°, tension test.

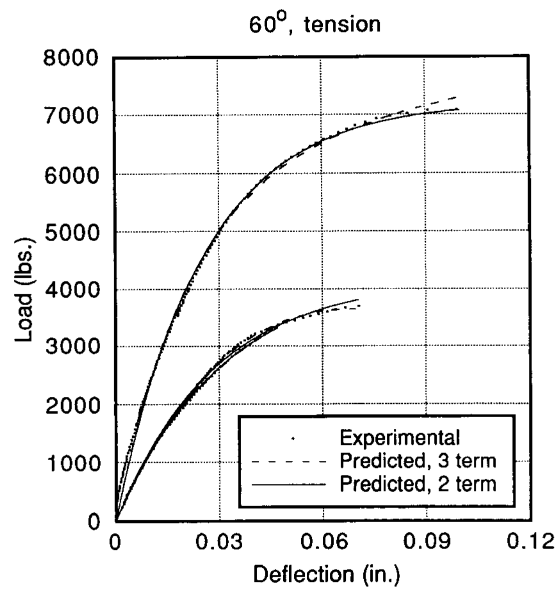

FIG. 6. Experimental and predicted P-Δ curves for θ = 60°, tension test.

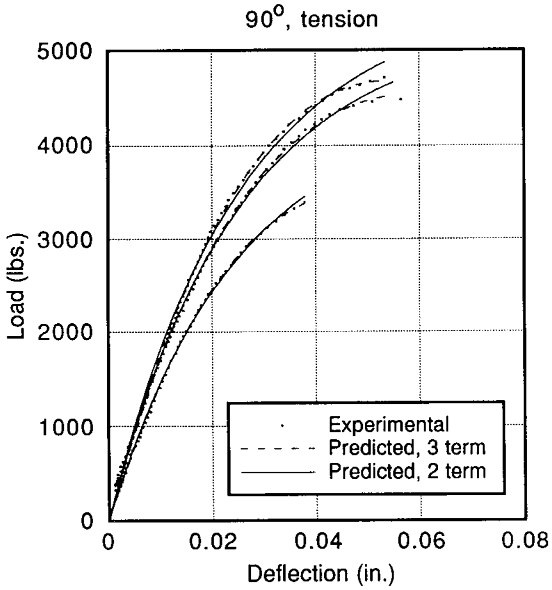

FIG. 7. Experimental and predicted P-Δ curves for θ = 90°, tension test.

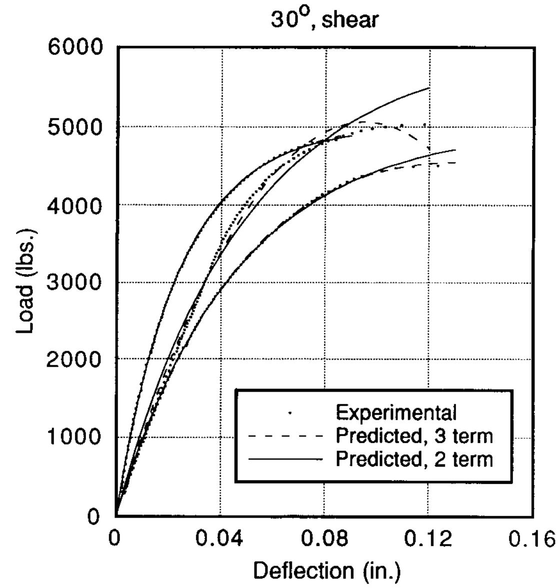

FIG. 9. Experimental and predicted P-Δ curves for θ = 30°, shear test.

rameters M_0 and M_1 were strongly but negatively correlated (coefficient of correlation >0.95), M_0 and k were negatively correlated, and M_1 and k were positively correlated.

When the 3-parameter model was modified to the 2-parameter model, the M_0 values were increased and the k values were decreased (Table 4), indicating the interaction between the parameters.

M_1 values were negative for all 90°, and one

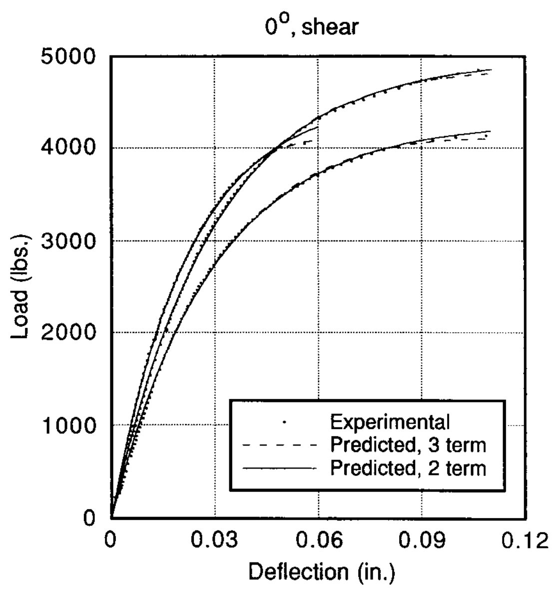

FIG. 8. Experimental and predicted P-Δ curves for θ = 0°, shear test.

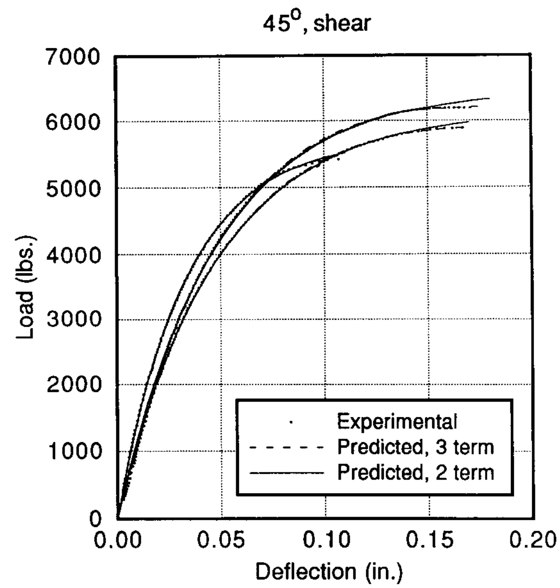

FIG. 10. Experimental and predicted P-Δ curves for θ = 45°, shear test.

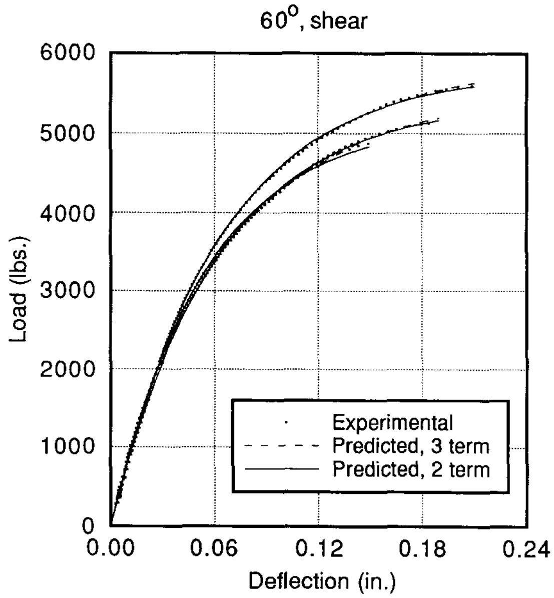

FIG. 11. Experimental and predicted P-Δ curves for θ = 60°, shear test.

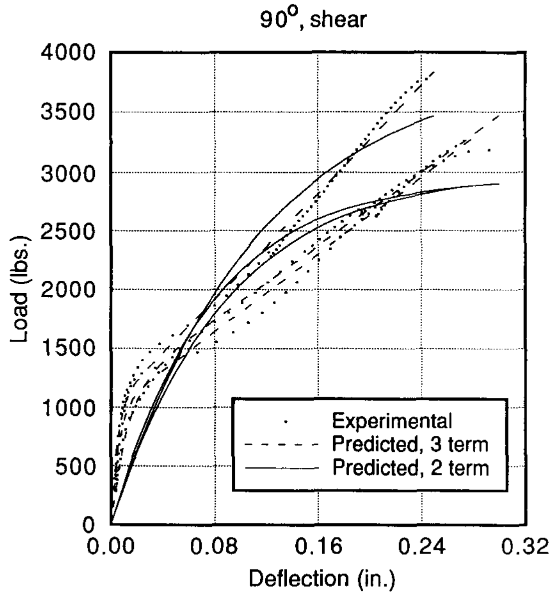

FIG. 12. Experimental and predicted P-Δ curves for θ = 90°, shear test.

60° joint (Table 4). When the P-Δ curve was truncated at the maximum end of the curve, to have a non-negative M_1, the 3-parameter model consistently over-predicted the data at the truncated region. Hence, the parameters should be derived from the entire curve, extending from zero to the ultimate load, letting M_1 become negative. Otherwise, if a 2-parameter model is fitted to a truncated data, the ultimate load, supposedly equal to M_0, may not be estimated accurately. Figure 13 shows the difference between the 2- and 3-parameter models when the P-Δ curve was truncated to avoid negative M_1.

Effect of connector plate orientation on strength and stiffness of joints

The four Canadian standard connector plate test orientations are: (1) Fig. 1a, where the force is applied parallel to the plate major axis and parallel to the wood grain; (2) Fig. 1a′, where the force is applied perpendicular to the plate major axis and parallel to the grain; (3) Fig. 1e, where the force is applied parallel to the plate major axis but perpendicular to the grain, and (4) Fig. 1e′, where the force is applied perpendicular to the plate major axis and the grain.

On the average, the ultimate load reduced almost by one-half for $\theta = 0°$ and decreased by 26% for $\theta = 90°$, when the connector plate major axis was perpendicular to the applied load compared to that when parallel. The stiffness values at the critical joint slip were also lower for the perpendicular orientations (Table 6).

The mode of failure was altered when the connector plate major axis was oriented perpendicular to the applied load. These joints invariably failed by tooth withdrawal. As stated previously, when the connector plate major axis was oriented parallel to the applied load, failure was by plate shear for $\theta = 0°$, and by wood failure for $\theta = 90°$.

When the connector plate major axis was oriented perpendicular to the applied load and grain of wood, the number of teeth that were embedded in the wood was much less than the number of teeth that were embedded when the connector plate major axis was oriented parallel. For the 3″ × 5″ connector plate used in this study, the number of teeth was 120. When

TABLE 4. *Model parameters for the joints tested in tension.*

Test number	Joint orientation (degrees)	3-Parameter model* k (lb/in.)	3-Parameter model* M_0 (lb)	3-Parameter model* M_1 (lb/in.)	2-Parameter model* k (lb/in.)	2-Parameter model* M_0 (lb)
13	0	389,767	4,395	22,291	365,509	5,548
16	0	267,211	4,487	15,603	255,635	5,573
17	0	446,649	5,024	22,024	422,207	6,160
4	30	157,636	5,243	2,979	155,163	5,620
8	30	135,403	4,184	9,049	131,458	5,236
11	30	183,862	5,550	3,816	180,648	5,991
6	45	237,457	4,631	13,832	220,968	5,936
7	45	183,530	4,994	17,876	179,514	6,731
10	45	171,621	5,744	3,351	170,499	6,095
5	60	134,132	8,758	−45,900	143,531	4,180
9	60	141,539	2,002	31,717	135,260	4,279
12	60	293,170	6,257	11,123	284,229	7,220
20	90	167,553	15,895	−148,449	175,958	4,457
21	90	200,177	9,364	−51,087	209,794	5,250
22	90	205,577	15,195	−114,150	220,099	5,542

* The coefficient of determination of statistics (R^2) of each model was greater than 0.998.

the connector plate was oriented perpendicular, only 36 teeth per plate were embedded in the wood for the 0° joints versus 120 when parallel. For the 90° joints, 60 teeth were embedded in the horizontal member and 36 teeth were embedded in the vertical member, and tooth withdrawal occurred in the vertical member.

Prediction of stiffness for intermediate orientations

The average stiffness values for $\theta = 0°$ and for $\theta = 90°$ were used in a Hankinson-type interpolation procedure [Eq. (2)] to determine the stiffness values for the intermediate orientations. The range of exponential values

TABLE 5. *Model parameters for the joints tested in shear.*

Test number	Joint orientation (degrees)	3-Parameter model* k (lb/in.)	3-Parameter model* M_0 (lb)	3-Parameter model* M_1 (lb/in.)	2-Parameter model* k (lb/in.)	2-Parameter model* M_0 (lb)
3	0	142,832	4,755	−4,581	145,618	4,279
6	0	195,211	6,368	−25,329	202,415	4,537
8	0	166,193	5,228	−2,377	167,771	4,980
5	30	108,446	139,981	−722,813	122,953	6,011
10	30	207,654	4,830	2,160	206,196	5,007
16	30	104,260	6,895	−12,383	108,209	5,016
2	45	132,470	7,315	−4,679	135,762	6,496
11	45	126,612	6,686	−3,213	128,692	6,143
20	45	171,112	5,933	−1,882	172,174	5,724
12	60	97,541	4,048	6,863	93,741	5,178
15	60	93,543	5,468	1,517	92,543	5,786
18	60	88,577	5,155	1,286	87,875	5,410
1	90	174,255	982	8,237	34,081	3,021
13	90	221,299	1,014	11,282	34,279	3,900
17	90	98,281	1,114	7,851	38,538	2,969

* The coefficient of determination of statistics (R^2) of each model was greater than 0.97.

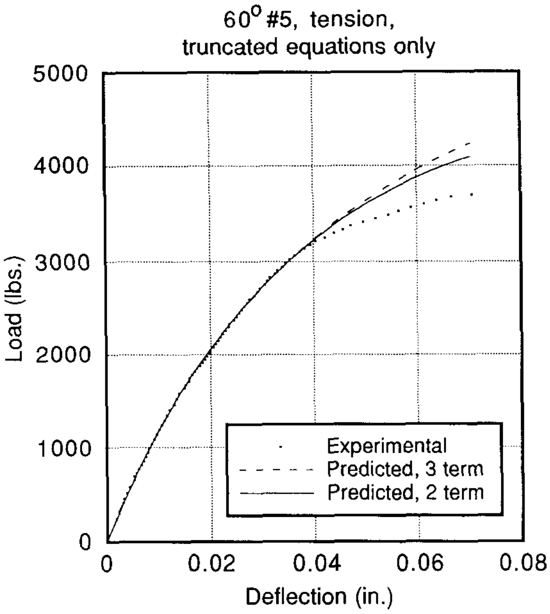

FIG. 13. Effect of truncating the P-Δ data at the upper end (to avoid negative M_1) on prediction of stiffness.

TABLE 7. *Prediction of stiffness for intermediate angles from the standard tests for joints tested in tension.*

Joint orientation (degrees)	Average exp. stiffness (lb/in.)	Predicted stiffness values (lb/in.)			
		n = 1.0	n = 1.25	n = 1.5	n = 1.75
0	2.23				
30	1.34	1.39	1.53		
45	1.54	1.27	1.38	1.52	1.64
60	1.44	1.25	1.35	1.44	1.54
90	1.50				

Multiply all stiffness values by 10^5.

considered was 1.0 to 3.0. The stiffness values predicted by Eq. (2) were compared to the experimental values. The results are tabulated in Tables 7 and 8 for the joints tested in tension and shear, respectively. Not a single exponent (n) seems appropriate for accurately predicting the stiffnesses for the intermediate angles. For the joints tested in tension, an n = 1.5 seems to predict the stiffness for $\theta = 45°$ and for $\theta = 60°$, and an n = 1.0 for $\theta = 30°$. An n = 2, used for intermediate angles of lumber compressive stresses (NFPA, 1986), overpredicted the stiffness values considerably.

For the joints tested in shear, not a single exponent seems appropriate for predicting the stiffnesses for the intermediate angles. For $\theta = 30$, 45, and 60°, an n = 2.0, 2.5 and 2.75, respectively, predict the stiffness values fairly well (Table 8).

TABLE 6. *Effect of connector plate orientation on stiffness and mode of failure for joints tested in tension.*

Test no.	Joint orientation (degrees)	Ultimate load (lb)	Displacement @ failure (in.)	Stiffness @ critical slip (lb/in.)[1]	MOE (E + 06) (psi)	MC %	Mode of failure
13	0 ⊥⊥	5,544	0.059	2.30	1.1	18.6	Plate shear
17	0 ⊥⊥	6,213	0.059	2.60	1.3	17.7	Plate shear
16	0 ⊥⊥	5,458	0.073	1.80	0.9	15.8	Wood failure
14	0 ⊥	3,004	0.048	1.48	0.9	15.7	Tooth withdrawal
18	0 ⊥	2,713	0.076	1.05	1.5	16.6	Tooth withdrawal
19	0 ⊥	2,506	0.078	0.91	1.1	18.7	Tooth withdrawal
20	90 ⊥⊥	3,398	0.038	1.30	1.0	18.4	Wood failure
21	90 ⊥⊥	4,487	0.056	1.60	1.3	17.6	Wood failure
22	90 ⊥⊥	4,717	0.053	1.60	1.3	17.1	Wood failure/Tooth withdrawal
23	90 ⊥	3,298	0.054	1.35	1.7	18.4	Tooth withdrawal[2]
24	90 ⊥	2,992	0.060	1.32	1.5	16.8	Tooth withdrawal[2]
25	90 ⊥	3,019	0.064	1.19	1.8	20.1	Tooth withdrawal[2]

[1] Multiply stiffness values by 10^5.
[2] Tooth withdrawal in the vertical member.
⊥⊥ Denotes applied load parallel to connector plate major axis.
⊥ Denotes applied load perpendicular to connector plate major axis.

TABLE 8. *Prediction of stiffness for intermediate angles from the standard tests for joints tested in shear.*

Joint orientation (degrees)	Average exp. stiffness (lb/in.)	Predicted stiffness values (lb/in.)				
		n = 1.5	n = 2.0	n = 2.5	n = 2.75	n = 3.0
0	1.55					
30	1.25	1.03	1.24	1.47		
45	1.36	0.87	1.04	1.23	1.35	1.47
60	0.97	0.79	0.89	0.99		
90	0.78					

Multiply all stiffness values by 10^5.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Tooth withdrawal and wood failure were most prevalent for the joints tested in tension. For $\theta = 0°$, failure was by plate shear; for $\theta = 30$ and $45°$, failure was by tooth withdrawal; and for $\theta = 60$ and $90°$, failure was in the wood.
2. For the joints tested in shear, failure was consistently by tooth withdrawal for $\theta = 0$, 30, and 45°. For $\theta = 60$ and for $\theta = 90°$, failure was by plate shear and occurred at the joint interface.
3. All P-Δ curves exhibited a nonlinear relationship. The P-Δ curves for the joints tested in tension were more linear at the bottom one-third section than those for the joints tested in shear.
4. The range of ultimate strength for the joints tested in tension was between 3,339 and 7,087 lb, and that for the joints tested in shear was between 3,165 and 6,207 lb. The range of stiffness values for the joints tested in tension was between 1.1 and 2.6 × 10^5 lb/in., and that for the joints tested in shear was between 0.78 and 1.55 × 10^5 lb/in. Stiffness decreased with increasing θ for the joints tested in shear.
5. For joints tested in tension, the strength and stiffness values were lower when the connector plate major axis was oriented perpendicular to the applied load compared to those when parallel.
6. A 2-parameter nonlinear model predicted the P-Δ curve quite well. The difference between the 2- and 3-parameter models was negligible. If the 2-parameter model is adopted, the intercept parameter, M_0, would provide a reasonable appreciation of the ultimate load. Given the ultimate load, a reasonable stiffness value can be calculated by dividing one-third of the ultimate load (M_0) by the critical joint slip (=0.015 inch, TPI 1985).
7. When characterizing the P-Δ curve for parameter estimation, the entire curve extending from zero to the ultimate load should be used. Truncating the data to avoid negative M_1 would result in overpredicting the P-Δ curve at the truncated region.
8. The stiffnesses of the intermediate orientations were predicted from the stiffnesses of the standard tests ($\theta = 0°$ and $\theta = 90°$) using a Hankinson-type formula. An exponent, n = 1.5, gave reasonable predictions for the joints tested in tension, especially for $\theta = 45$ and for $\theta = 60°$. For the joints tested in shear, exponents between 2.0 and 2.75 gave reasonable predictions of stiffness.

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