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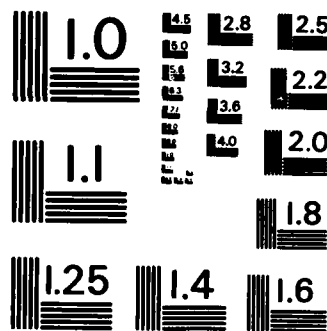
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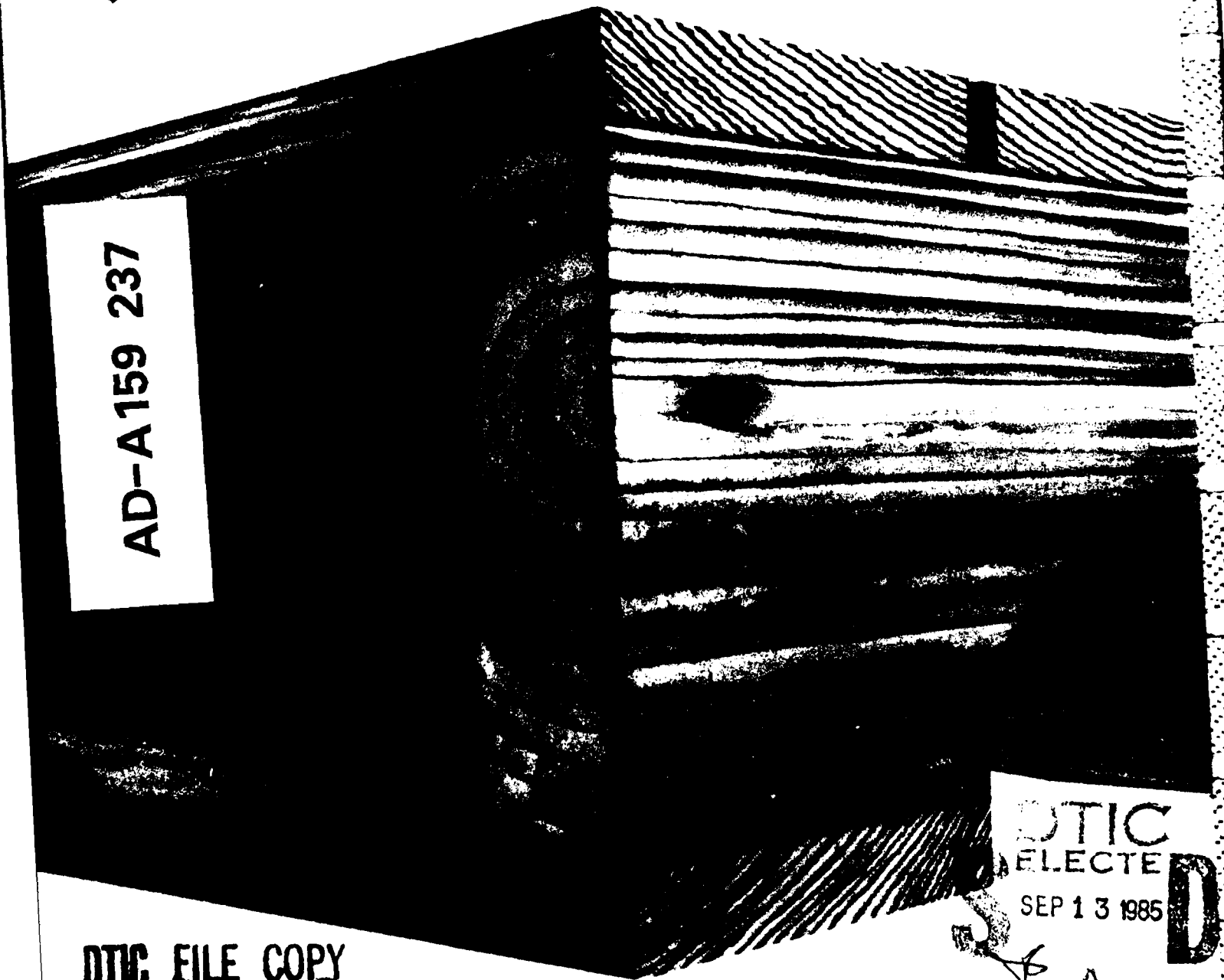
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# Rotational Characteristics of Pallet Joints

Thomas Lee Wilkinson



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# Abstract

During its lifespan, a pallet must withstand its imposed load without endangering its contents or the people handling it. To determine the amount of load a pallet will withstand requires a sound engineering analysis. The moment-rotation behavior of the joints between deckboards and stringers is needed for input to such an analysis. This report describes the joint behavior as affected by (1) deckboard species, (2) stringer species, (3) type of fastener, and (4) fastener pattern. The behavior is described by a mathematical model.

Keywords: Pallets, nails, staples, moment-rotation.

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# Rotational Characteristics of Pallet Joints

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## Introduction

Wood pallets, a major use of U.S. hardwood lumber, are employed for handling and storage of many commodities. During its lifespan, a pallet must withstand its imposed load without endangering its contents or the people handling it. Determining the load a pallet will withstand requires a sound engineering analysis. For such an analysis, the behavior of the pallet components is used as input.

An important pallet component is the joints between the deckboards and stringers. The joint stiffness influences the deflection characteristics and load carrying capacity of the pallet. The greatest impact of joint stiffness is on pallet deflection when the pallet is racked across the deckboards in racked storage. At worst, this deflection can create a life-threatening situation due to load instability; however, it is more likely to create severe serviceability problems.

This report describes the behavior of the joints between deckboards and stringers. The particular behavior described is the rotational resistance as affected by (1) deckboard species, (2) stringer species, (3) type of fastener, and (4) fastener pattern. Results reported here provide necessary pallet joint behavior to predict pallet strength and stiffness of green pallets when employed with computerized pallet analyses.

## Past Work

Several studies (Stern 1971, 1974, 1978; Stern and Wallin 1976) have determined the strength and stiffness of wood pallets. Stern dealt with overall pallet performance as affected by species of wood or type of fastener.

Stern (1976) determined the ultimate withdrawal resistance of nails and staples in deckboard-stringer joints assembled from 22 southern hardwoods. McLain and Stern (1978) likewise found the delayed withdrawal resistance of similar pallet joints of five western woods.

Mack (1975) predicted pallet behavior from the characteristics of the pallet parts. He characterized the joints by the relative separation of the deck and stringer obtained in a withdrawal test. Kyokong (1979) developed a relation between separation modulus and rotation modulus. He showed that the rotation modulus is easy to determine and is less variable than the separation modulus. Kyokong's study is limited in scope. Considerable additional work is needed to evaluate all possible pallet joint variables. A linear modulus value is used in these studies to describe the joint behavior; however, pallet joint behavior is nonlinear. To predict maximum pallet strength, the joint behavior needs to be described to maximum load.

## Experimental Design

### Variables

Combinations of several construction variables affect pallet joint behavior. The range of variables in industry practice is described in specifications produced by the National Wooden Pallet and Container Association (1962a, 1962b, 1974). The particular variables I selected for this study are as follows:

**Wood species.**—All wood had a moisture content above the fiber saturation point at the time specimens were assembled and tested. The deckboard, stringer species combinations were as follows:

- (a) oak deckboard with oak stringer
- (b) yellow-poplar deckboard with yellow-poplar stringer
- (c) Douglas-fir deckboard with Douglas-fir stringer
- (d) oak deckboard with yellow-poplar stringer
- (e) yellow-poplar deckboard with oak stringer

**Fasteners.**—Physical properties were determined for a 25-nail sample. The average physical properties (table 1) are representative of high quality pallet nails. The 2-1/2-inch staples were made of 15-gage round wire with a 7/16-inch crown width. The staples were coated. The four fasteners (fig. 1) were as follows:

- (a) 2-1/4- × 0.112-inch hardened nail
- (b) 3- × 0.120-inch hardened nail
- (c) 2-1/2- × 0.120-inch stiff-stock nail
- (d) 2-1/2-inch staple

**Fastener pattern.**—Patterns I, II, and III (fig. 2) represent the most commonly used patterns and were evaluated with all fasteners and species combinations. Patterns IV and V (fig. 2) were evaluated with the 2-1/4- × 0.112-inch hardened nail in yellow-poplar deckboard with yellow-poplar stringer. Patterns IV and V were included to determine if the behavior of two- and three-nail patterns can be predicted from the behavior of one-nail patterns.

**Deckboard thickness.**—All the hardwood deckboards were 3/4 inch thick. The Douglas-fir deckboards were 11/16 inch thick.

**Replications.**—Nine replications were evaluated for each combination of variables. A total of 518 specimens were tested.

### Specimens

The deckboards were fastened in the center of 12-inch-long stringers (fig. 3). Deckboard widths (fig. 2) varied with the number of fasteners. All specimens were assembled with green material and tested within 10 minutes of assembly. The fasteners were driven flush with the deckboard surface. Staples were driven with the crown at a 45° angle to the grain of the wood.

**Table 1.—Average physical properties of nails based on a sample of 25 nails**

Property	3-inch hardened nail	2-1/4-inch hardened nail	2-1/2-inch stiffstock nail
Length, inches	2-7/8	2-1/8	2-7/16
Wire diameter, inches	0.120	0.113	0.122
Thread-crest diameter, inches <sup>1</sup>	0.138	0.127	0.135
Number of flutes <sup>2</sup>	4	4	5
Thread length, inches	2.0	1.50	1.69
Number of helix per inch	5.00	5.33	4.74
MIBANT bend angle, degrees <sup>3</sup>	15	21	48
Head diameter, inches	0.288	0.282	0.259

<sup>1</sup>The diameter measured on the thread crest.

<sup>2</sup>Number of continuous symmetrical depressions along the nail shank.

<sup>3</sup>A measure of the nail stiffness as obtained following ASTM standard F680, Testing Nails.

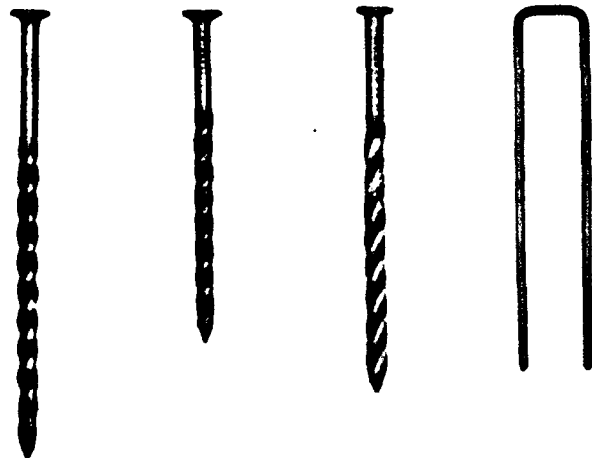


Figure 1.—Fasteners studied are (left to right) 3- × 0.120-inch hardened nail; 2-1.4- × 0.112-inch hardened nail; 2-1/2- × 0.120-inch stiff-stock nail; and 2-1/2-inch staple. (M150 944)

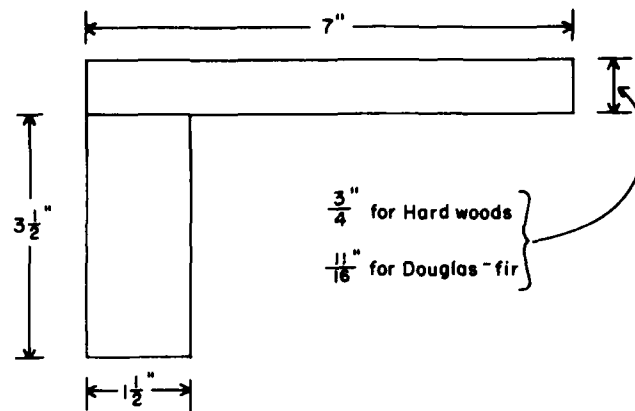


Figure 3.—Joint geometry. (ML85 5016)

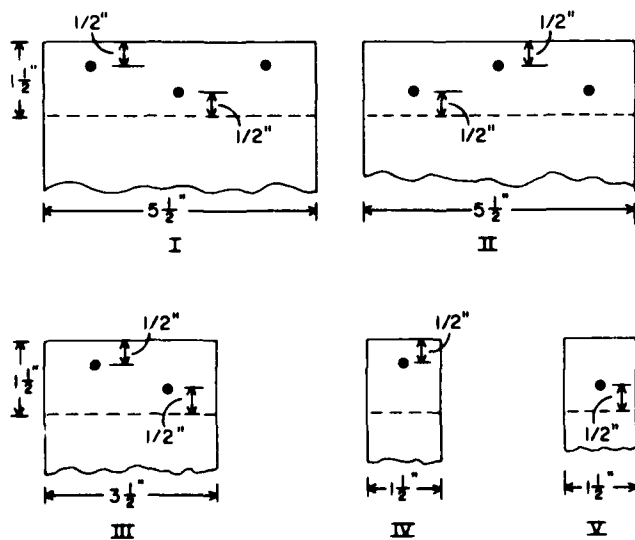


Figure 2.—Top view of fastener patterns. (ML85 5015)

## Experimental Procedure

The stringer was securely clamped in a vice secured to the base of the testing machine (fig. 4). Load was applied to the deckboard 4-1/2 inches from the inside edge of the stringer through a knife edge attached to a load cell. Deflection at the point of applied load was measured by the head movement of the testing machine. The loading rate was 0.10 inch per minute. Specimens were loaded to a deflection of 0.40 inch, which represents the usable rotation range for pallet joints.

Digital load-deflection data were recorded on tape. This was later transferred to a computer for data analysis. A hard copy of the load-deflection curve was also made. This was used to detect any irregularities in the testing.

The effective moment arm was assumed to be from the inside of the stringer to the load point. Thus the moment equaled 4.5 times the load and, for small deflections, the rotation equaled the deflection divided by 4.5.

Moisture and specific gravity sections were cut from each deck and stringer.

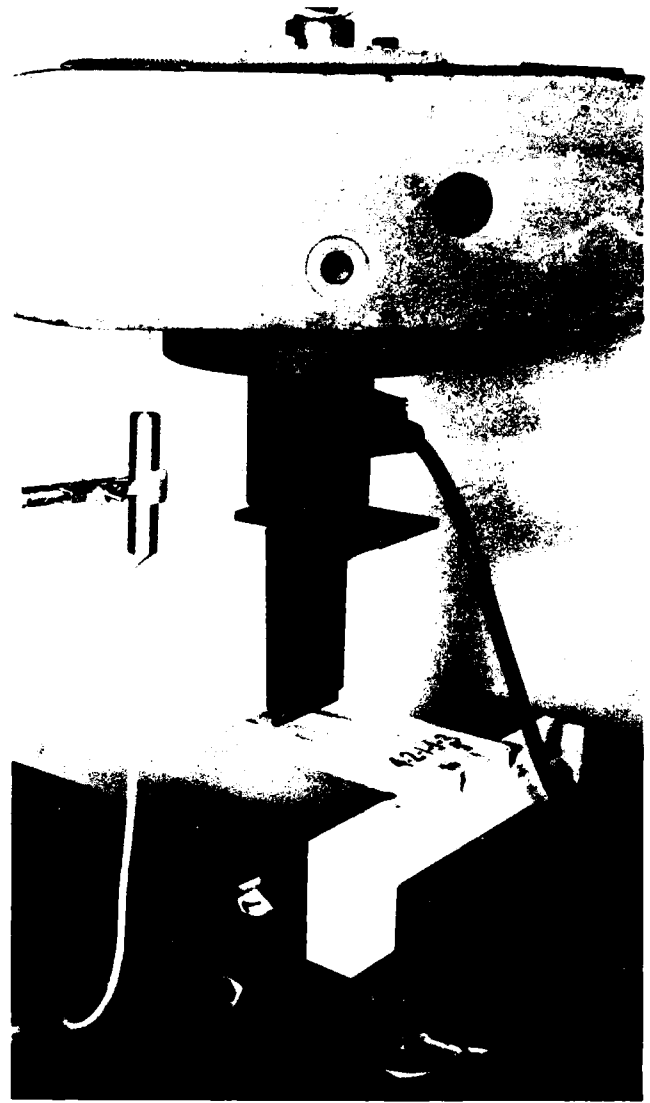


Figure 4.—Experimental setup to obtain moment-rotation curves of pallet joints. (M84 0043)



## Results and Discussion

To describe the moment-rotation curves mathematically, the following two functions were fitted to the data using a nonlinear least squares routine.

$$M = A \tanh(\theta B) \quad (1)$$

and

$$M = A\theta^B \quad (2)$$

where

$M$  = moment, inch-pounds

$\theta$  = rotation, radians ( $\theta \leq 0 \leq 0.09$ )

$A$  = equation parameter, inch-pounds

$B$  = equation parameter

Nonlinear models were fitted to the moment-rotation data because the computer analysis requires a secant modulus at various levels of rotation. The measured rotation was not corrected for any bending of the deckboard.

The residual sum of squares for equation (1) was less than for equation (2) for 493 of the 518 curves. A typical fit (fig. 5) shows equation (1) closely follows the data points, whereas equation (2) does not. Visual examination of the fitted curves with the experimental data in cases where equation (2) had lower residual sum of squares shows equation (1) fits the initial portion of the moment-rotation nearly as well as equation (2), figure 6. Therefore, equation (1) describes pallet joint moment-rotation more appropriately than equation (2).

The  $A$  parameter of equation (1) relates to the amount of moment carried by the joint, i.e. the larger  $A$  is, the more moment carried. The  $B$  parameter relates to the amount of curvature in the moment-rotation curve, i.e. the larger  $B$  is, the more curvature there is. The mean values for the parameters are presented in tables 2 through 6 along with the standard deviation, maximum, and minimum values. Some general observations are as follows:

1. **Fastener effect.**—The  $A$  parameters are highest for the 3- × 0.120-inch nails. In general, the staples have the second highest  $A$  values, followed by the 2-1/2- × 0.120-inch nails. The  $B$  parameters are generally highest for the staples. The three nails have nearly equal  $B$  parameters.

2. **Pattern effect.**—The  $A$  parameters are highest for pattern I and lowest for pattern III. The  $B$  parameters are nearly equal for all patterns.

3. **Species effect.**—The  $A$  parameters are highest for the all oak specimens. The next highest values are for the yellow-poplar stringers with oak decks and then the oak stringers with yellow-poplar decks. This indicates the density of the deck is more important than the density of the stringer in giving high  $A$  values. The lowest  $A$  values are for the all Douglas-fir specimens. The  $B$  values vary between species groups, but are considerably lower for the Douglas-fir specimens. As mentioned, the Douglas-fir specimens had thinner deckboards. They also had slightly rounded corners on the stringers while the other species had sharp corners.

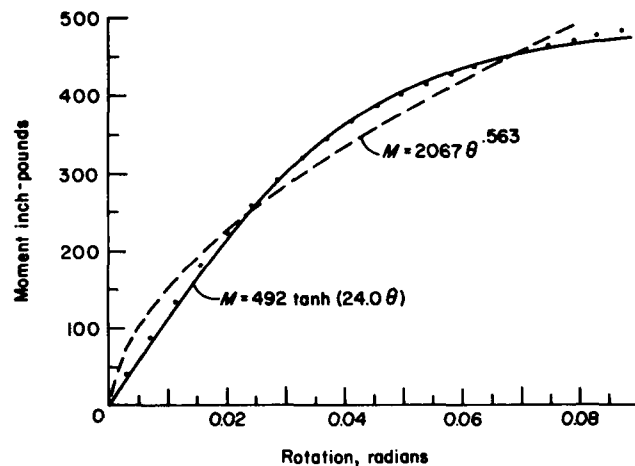


Figure 5.—Typical fit of hyperbolic tangent and power functions. (ML85 5017)

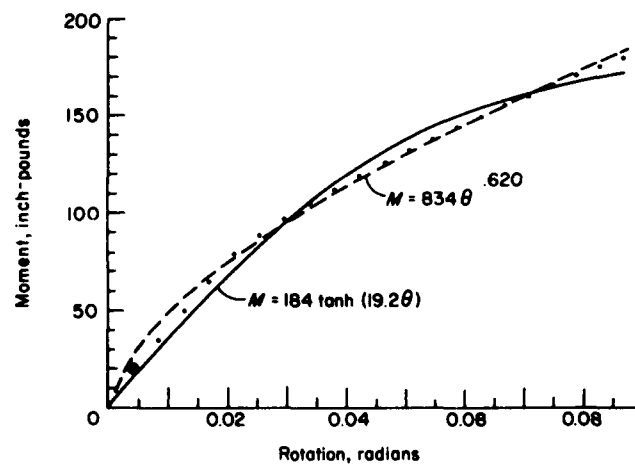


Figure 6.—Typical fit of hyperbolic tangent and power functions when the power function had the smaller residual sum of squares. (ML85 5018)

From the observation that the  $B$  parameters are nearly equal for all the patterns and for all the nails within each species combination, a single  $B$  value for each species combination seems justified to simplify the functions. Therefore, each experimental curve was refitted with the restriction that  $B$  be held constant for (1) all patterns with all nails within a species combination and (2) all patterns with staples within a species combination. The average  $A$  values and single  $B$  values, table 7, produce average curves which vary by less than 10 percent from those given by the previous average parameters as demonstrated in figure 7 for pattern II with 3- × 0.120-inch nails in all Douglas-fir specimens.

Statistical analysis of all the  $A$  parameters in table 7 for patterns I, II, and III provided the following expression for estimating  $A$ .

$$A = e^{[6.044 \cdot F_P + F_F + 0.165R]} \quad (3)$$

where

$F_P$  = factor for fastener pattern:

Fastener pattern	Pattern factor
I	0.287
II	.008
III	-.295

$F_F$  = factor for fastener type, table 8

and

$R$  = normal random variable with mean of zero and variance of one. Values given by equation (3) are within plus or minus 10 percent of the average  $A$ 's in table 7.

Nail patterns IV and V were included in this study to see if a relation existed between one-nail joints and multiple-nail joints. Statistical analysis of the  $A$  parameters in table 7 for the joints of yellow-poplar decks and stringers with 2-1 4- × 0.112-inch nails provided the following expression for estimating  $A$ .

$$A = e^{[5.780 \cdot F_Y + 0.175R]} \quad (4)$$

where

$F_Y$  = factor for fastener pattern:

Fastener pattern	Pattern factor
I	0.276
II	.018
III	-.294
IV	-.580
V	-1.348

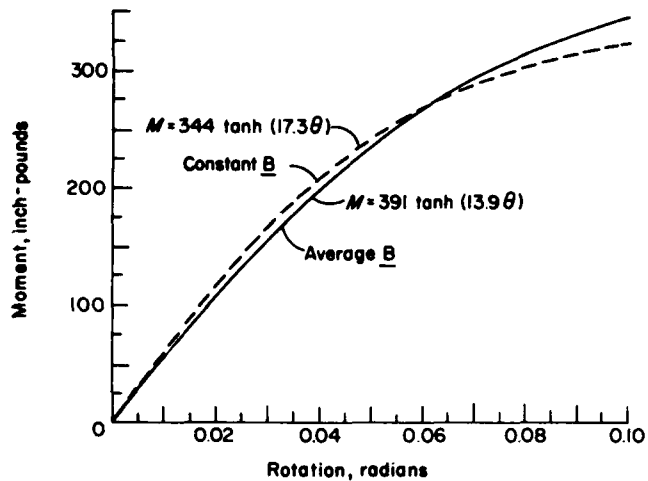


Figure 7.—Comparison of curves using average parameter values and parameter values obtained assuming  $B$  constant. Curves are for Douglas-fir deck and stringer with 3- × 0.120-inch nails and pattern II. (ML85 5019)

Thus, a relation does exist between 1-, 2-, and 3-nail patterns. For 2- and 3-nail patterns, the  $A$  parameters given by equation (4) are within 2 percent of those given by equation (3).

Attempts to predict the parameters for 2- and 3-nail patterns from the 1-nail patterns are inconclusive.  $A$  parameters of similar magnitude to test values can be obtained by addition of the  $A$  parameters of the 1-nail patterns. The  $B$  parameters for the 1-nail patterns, table 5, are higher than for the 2- and 3-nail patterns. These tests were limited to one fastener type and one species. Evaluation of additional joint variables might indicate that behavior of multiple-nail patterns can be predicted from test of one-nail patterns.

**Table 2.—Parameter values for specimens with oak stringers and oak decks. Parameters determined by fitting  $M = A \tanh(\theta B)$  to the experimental moment-rotation data (sample sizes are 9)**

Fastener	Pattern <sup>1</sup>	Specific gravity		A, inch-pounds				B			
		Stringer	Deck	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
<b>Inches</b>											
2-1/4 × 0.112	I	0.61	0.64	997	96	834	1117	21.6	3.8	15.9	26.1
	II	.63	.63	770	114	560	907	22.2	3.7	18.5	28.8
	III	.60	.64	563	55	475	646	22.0	3.2	18.4	28.3
3 × 0.120	I	.63	.62	1122	171	914	1432	19.9	3.5	17.1	25.9
	II	.63	.64	905	96	790	1124	21.1	3.0	14.9	24.6
	III	.62	.63	595	65	499	709	23.0	2.4	18.8	25.4
2-1/2 × 0.120	I	.61	.60	806	130	677	1119	23.0	2.5	20.2	26.3
	II	.61	.64	651	141	466	921	23.5	3.4	17.6	29.0
	III	.60	.63	490	33	451	549	25.6	3.6	19.1	30.2
2-1/2 staple	I	.63	.63	913	146	706	1198	25.0	1.9	22.3	28.0
	II	.62	.63	641	69	553	756	29.7	2.7	25.8	33.4
	III	.63	.62	463	80	362	596	30.7	4.9	22.0	34.8

<sup>1</sup>See figure 2.

**Table 3.—Parameter values for specimens with oak stringers and yellow-poplar decks. Parameters determined by fitting  $M = A \tanh(\theta B)$  to the experimental moment-rotation data (sample sizes are 9)**

Fastener	Pattern <sup>1</sup>	Specific gravity		A, inch-pounds				B			
		Stringer	Deck	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
<b>Inches</b>											
2-1/4 × 0.112	I	0.60	0.39	486	137	323	749	26.3	3.7	21.0	32.1
	II	.62	.39	362	65	245	434	27.2	2.1	23.2	30.4
	III	.61	.39	277	37	227	331	27.6	2.8	24.0	32.7
3 × 0.120	I	.62	.40	576	86	447	767	28.3	3.0	23.5	33.6
	II	.62	.40	404	82	248	506	30.8	2.4	26.8	35.8
	III	.62	.40	298	34	236	340	29.9	2.3	26.6	33.4
2-1/2 × 0.120	I	.62	.39	497	78	357	610	30.6	4.8	24.3	40.4
	II	.61	.39	361	70	253	458	29.3	3.0	23.1	33.2
	III	.61	.41	302	56	254	426	29.6	3.2	24.1	33.0
2-1/2 staple	I	.61	.41	509	133	325	691	34.1	4.4	28.2	41.0
	II	.60	.38	377	73	252	464	37.2	8.0	27.5	46.4
	III	.61	.39	234	51	160	324	44.7	11.9	32.8	65.1

<sup>1</sup>See figure 2.

Table 4.—Parameter values for specimens with yellow-poplar stringers and oak decks. Parameters determined by fitting  $f = A \tanh(\theta B)$  to the experimental moment-rotation data (sample sizes are 9)

Fastener	Pattern <sup>1</sup>	Specific gravity		A, Inch-pounds				B			
		Stringer	Deck	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
<b>Inches</b>											
-1/4 × 0.112	I	0.39	0.62	550	76	426	685	26.3	3.5	20.0	31.8
	II	.38	.62	440	85	347	631	20.1	3.3	15.8	25.7
	III	.40	.62	292	55	193	379	28.6	3.2	23.4	33.0
× 0.120	I	.38	.65	648	143	495	919	24.6	4.1	18.2	30.3
	II	.39	.61	485	104	334	690	25.9	4.0	18.5	31.2
	III	.37	.64	375	66	286	457	24.3	3.0	19.2	28.3
-1/2 × 0.120	I	.40	.62	615	90	477	757	24.9	5.0	17.9	31.8
	II	.39	.61	496	102	389	706	26.1	2.5	20.8	29.5
	III	.39	.64	329	70	237	449	26.6	4.4	19.4	32.9
-1/2 staple	I	.39	.65	611	90	460	735	25.7	2.9	19.6	29.3
	II	.41	.64	433	64	346	539	26.6	5.3	19.6	36.9
	III	.39	.64	343	41	311	436	25.4	2.3	21.7	28.9

See figure 2.

Table 5.—Parameter values for specimens with yellow-poplar stringers and yellow-poplar decks. Parameters determined by fitting  $M = A \tanh(\theta B)$  to the experimental moment-rotation data (sample sizes are 9)

Fastener	Pattern <sup>1</sup>	Specific gravity		A, Inch-pounds				B			
		Stringer	Deck	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
<b>Inches</b>											
-1/4 × 0.112	I	0.36	0.41	423	98	243	530	26.2	4.9	19.7	33.7
	II	.38	.41	343	48	280	419	25.1	3.3	19.9	30.6
	III	.39	.41	251	76	161	398	25.1	4.6	18.3	32.4
	IV	.39	.38	171	24	135	216	31.0	2.9	26.3	34.5
	V	.40	.39	83	9	70	97	26.4	3.8	21.0	31.0
× 0.120	I	.37	.41	520	70	412	608	23.2	4.1	18.4	29.6
	II	.39	.40	367	50	308	435	22.7	3.1	16.7	27.5
	III	.38	.41	286	59	226	416	25.0	2.7	22.5	29.6
-1/2 × 0.120	I	.39	.39	431	65	321	528	26.2	4.1	20.2	31.7
	II	.37	.41	360	48	290	423	23.4	4.4	17.2	30.1
	III	.37	.40	235	46	151	301	27.6	4.0	22.7	30.0
-1/2 staple	I	.39	.41	515	100	384	656	31.1	5.3	23.8	41.8
	II	.40	.40	330	56	261	438	31.6	3.1	27.1	37.4
	III	.38	.40	255	46	189	314	30.9	5.4	22.0	38.3

See figure 2.

**Table 6.—Parameter values for specimens with Douglas-fir stringers and Douglas-fir decks. Parameters determined by fitting  $M = A \tanh(\theta B)$  to the experimental moment-rotation data (sample sizes are 9)**

Fastener	Pattern <sup>1</sup>	Specific gravity		A, inch-pounds				B			
		Stringer	Deck	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
<b>Inches</b>											
2-1/4 × 0.112	I	0.45	0.43	419	85	335	611	18.7	3.0	14.1	22.1
	II	.45	.46	351	52	275	409	15.3	3.9	11.7	22.9
	III	.41	.42	228	35	185	281	18.2	4.1	12.8	25.1
3 × 0.120	I	.41	.46	490	81	363	625	17.0	1.7	14.7	20.1
	II	.42	.45	391	63	323	526	13.9	1.9	10.8	16.3
	III	.43	.40	283	34	230	341	16.4	3.7	11.5	22.1
2-1/2 × 0.120	I	.43	.43	430	82	342	566	21.2	4.9	12.8	28.0
	II	.45	.44	396	47	325	487	15.1	3.4	10.0	19.0
	III	.43	.40	256	42	199	321	17.1	3.0	11.7	21.1
2-1/2 staple	I	.45	.42	421	130	217	672	23.1	5.2	13.6	31.0
	II	.45	.41	334	39	273	388	23.5	5.5	15.9	32.5
	III	.44	.40	247	42	163	309	23.3	5.6	17.1	35.4

<sup>1</sup>See figure 2.

species combination

Parameter values for species combinations of

Fastener	Pattern <sup>1</sup>	Oak stringer and oak deck			Oak stringer and yellow-poplar deck			Yellow-poplar stringer and oak deck			Yellow-poplar stringer and yellow-poplar deck			Douglas-fir stringer and Douglas-fir deck			
		Constant $\beta$ parameter	A parameter Mean	Standard deviation	Constant $\beta$ parameter	A parameter Mean	Standard deviation	Constant $\beta$ parameter	A parameter Mean	Standard deviation	Constant $\beta$ parameter	A parameter Mean	Standard deviation	Constant $\beta$ parameter	A parameter Mean	Standard deviation	
Inches			- Inch-pounds -														
	2-1/4 x 0-112	I	21.6	982	84	28.6	468	125	24.3	559	58	24.6	424	86	17.3	427	60
		II	21.6	768	99	28.6	356	64	24.3	402	77	24.6	345	56	17.3	320	57
		III	21.6	563	50	28.6	274	38	24.3	306	52	24.6	247	64	17.3	228	32
		IV	..	..	..	..	..	..	..	..	..	24.6	163	26	..	..	..
3 x 0-120																	
		I	21.6	1065	109	28.6	573	86	24.3	633	114	24.6	503	70	17.3	482	72
		II	21.6	889	104	28.6	412	86	24.3	488	87	24.6	354	51	17.3	344	67
		III	21.6	607	54	28.6	301	36	24.3	372	69	24.6	287	61	17.3	269	38
		I	21.6	823	135	28.6	503	75	24.3	610	86	24.6	436	60	17.3	460	60
2-1/2 x 0-120																	
		II	21.6	664	121	28.6	364	74	24.3	506	104	24.6	348	42	17.3	356	40
		III	21.6	519	40	28.6	303	50	24.3	333	59	24.6	243	47	17.3	250	33
Staple																	
		I	26.9	887	123	34.9	502	126	25.5	610	79	30.5	512	93	22.3	409	91
		II	26.9	659	80	34.9	378	76	25.5	433	64	30.5	332	55	22.3	333	38
	III	26.9	477	78	34.9	241	49	25.5	342	47	30.5	253	45	22.3	245	36	

<sup>1</sup>See figure 2

Table 8.—Fastener type factors for equation (3)

Stringer	Deck	Fastener factor, $F_F$ , for			
		1-1/4 x 0-112-inch nail	3- x 0-120-inch nail	2-1/2- x 0-120-inch nail	2-1/2-inch staple
Oak	Oak	0.573	0.674	0.434	0.428
Oak	Yellow-poplar	-.184	-.030	-.114	-.188
Yellow-poplar	Oak	-.040	.128	.092	.054
Yellow-poplar	Yellow-poplar	-.264	-.140	-.248	-.198
Douglas-fir	Douglas-fir	-.303	-.185	-.208	-.284

## Summary of Findings

This report describes the behavior of one pallet component, the joints between deckboards and stringers for green pallets. The particular behavior described is the rotational resistance as affected by (1) deckboard species, (2) stringer species, (3) type of fastener, and (4) fastener pattern. The primary findings are:

1. Moment-rotation of pallet joints is best described by a two-parameter hyperbolic tangent of the form

$$M = A \tanh (\theta B)$$

where

$M$  = moment, inch-pounds  
 $\theta$  = rotation, radians ( $0 \leq \theta \leq 0.09$ )

and

$A$  and  $B$  = equation parameters, table 7.

2. The  $B$  parameter is independent of nail type and fastener pattern. It differs for staples and nails, and depends upon species of deckboard and stringer.

3. The  $A$  parameter depends on all joint variables.

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