A COMPARISON OF STRENGTH CHARACTERISTICS OF THE MORTISE AND TENON JOINT AND DOWEL JOINT

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This report is submitted as partial fulfillment of the requirements for the degree of Master of Wood Technology.

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Ann Arbor, Michigan, 1949

ACKNOWLEDGEMENTS

The research necessary for this project was conducted at the Wood Utilization Laboratory of the School of Forestry and Conservation of the University of Michigan, with Mr. Louis A. Patronsky, Assistant Professor of Wood Technology as advisor.

The author is grateful to Professor Patronsky for his interest and suggestions, which aided greatly in the completion of this work.

The author is also grateful to the John Widdicomb Furniture Company of Grand Rapids, Michigan, and the Peter Cooper Corporations of Gowanda, New York. The John Widdicomb Furniture Company supplied all of the wood material used in the project, and performed a large amount of the machining. The glue was furnished by the Peter Cooper Corporations.

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A COMPARISON OF STRENGTH CHARACTERISTICS OF THE MORTISE-AND-TENON AND DOWEL JOINT

INTRODUCTION

In the manufacture of wood furniture and many other wood products, the joining together of two members may be accomplished by any one of several techniques or devices. The principal factors usually involved in the selection of which to use are cost, strength required, and shape and function of the members to be joined.

At those points of assembly where one member is relatively long and with relatively small end dimensions, the selection usually involves a choice between a dowel joint or a mortise-and-tenon joint. Lack of authentic data has resulted in an inability to properly evaluate and compare strength characteristics of the two joints. The basic purpose of this problem has been to provide some of the necessary strength information as a selective aid when the use of this type of joint is indicated.

PROCEDURE

Presumably, strength superiority between the two joints could be determined by gluing up a sufficient number of test specimens of the two joints to obtain a reliable average, eliminating other possible variables, and subjecting all the specimens to the same test. However, it was decided to determine the strength of the joints under as wide a range of controlled variables as practical. Selection of variables was with the intent of including those most apt to affect the strength of the joint and most generally encountered in the manufacturing process and in use of the finished product.

The variables selected were tightness of joint fit, moisture content of the joint members, and the type of strain applied to the joint. The following is a discussion of these variables and an explanation of the method of their application:

A. Joint Fit

The tightness or looseness of the joint fit will undoubtedly affect the strength or holding power of that joint. The extent to which it does affect the strength should determine the degree of control that must be maintained over the two principal causes of improper joint fit, namely (a) relative moisture content of the members at the time of machining and the time of assembly and (b) machining accuracy. In this problem, differences in joint fit were by machining. The variance of the moisture content of the members at the time of machining and assembly were controlled sufficiently to make this factor negligible. Measurements for the three joint fits used are as follows:

Mortise-and-tenon

(a) The size of the mortise was held constant at .75" x .75".

(b) The length of the tenon was held constant at 7/8". Cross-sectional dimensions varied as follows:

JF_1 - .75" x .75"

JF_2 - .735" x .735"

JF_3 - .72" x .72"

<u>Dowel</u>

(a) The size of the dowel was held constant at 7/16" (28/64") x 1½".

(b) Only one dowel hole per assembly was varied. It was in the member corresponding to the mortise member.

JF_1 - 28/64"

JF_2 - 29/64"

JF_3 - 30/64"

B. Moisture Content

Three different moisture contents were used:

MC_1 - 4%

MC_2 - 8%

MC_3 - 12%

C. Strain Applied

Two tests were used:

T_1 - tension

T_2 - bending

All wood members were straight grained, kiln dried mahogany (<u>Swietenia macrophylla</u>). No attempt was made to select boards on the basis of density or to match members of similar densities in the same assembly. Commercial, spiral-grooved hardwood dowels were used.

A group of 25 to 30 similar test specimens was prepared for each possible combination of variables. There was a total of 36 groups, with each group differing from all other groups by at least one variable. Each group had identifying letters (examples - $MJF_2MC_3T_1$, $DJF_1MC_2T_2$) which were printed on each specimen of that group. A data sheet was prepared for each group on which was recorded the individual test results and other relevant information and observations (Fig. 9).

The steps necessary to complete the test will be discussed in the order of their occurrence. They were machining, gluing and assembling, conditioning, and testing.

A. Machining

With the exception of the tenon pieces, all members were 1¼" x 1¼" and either 6" or 7" in length. These pieces were reduced to net overall dimensions and the tenons cut at the John Widdicomb Furniture Company plant with normal factory production equipment. Inasmuch as extreme precision was not required on these pieces, machining accuracy was checked by means of a ruled metal tape and a tolerance of ± 1/32" was maintained.

The two shoulder cuts on the tenon shown below were made on the double-end tenoner. A 10% check was made by the writer with a micrometer as the pieces came from the machine to assure maintenance of a tolerance of ±.005" for measurements A and B. (Fig. 1).

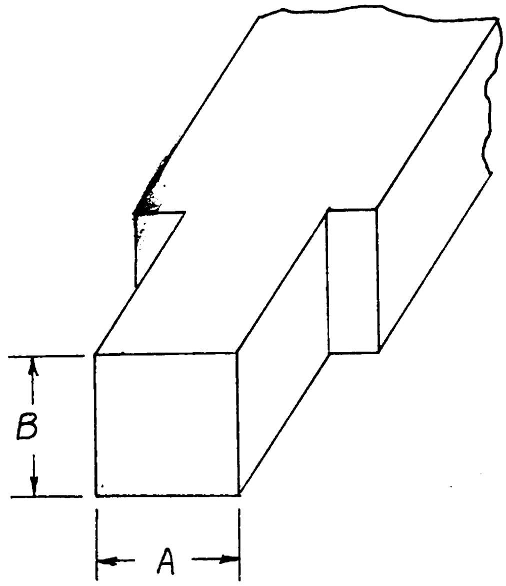


Figure 1. Tenon

All mortising was done with a 3/4" hollow-chisel mortising bit.

Boring was done on a double-spindle vertical boring machine. High-speed steel twist bits were used. Before boring of dowel holes, the bored ends of the dowel members corresponding to the tenon members were trimmed off by circular saw. A fine-toothed cross-cut blade and a slow feed speed were used to insure a smooth end surface free from saw marks. These ends were then carefully checked for perfect squareness to the sides. A heavy, steel boring jig, which supported the entire length of the member, was devised and clamped securely in place. Special care was given to the preparation and alignment of this jig to prevent any vibration in the member during the boring operation and to assure a dowel hole that was exactly at right angles to the end of the member.

The dowel joints, as originally designed, were square and the full dimensions of the block (1¼" x 1¼").

In order to make the strength figures for the two types of joints more directly comparable, square notches were cut in opposite edges of the bored ends of the dowel specimens (Fig. 2).

B. Gluing and assembling

A high quality animal hide glue (Peter Cooper's A Extra, ground) was used to eliminate any variations in test results due to a poor quality glue. It is classified as a grade 14 glue, with a jelly strength of 374 grams and a viscosity of 135 millipoises. The water to glue ratio was 2½/1. A fresh batch of glue was heated each day, after a 3 to 10 hour soak, in a water-jacketed glue pot. A thermometer suspended in the glue was used as a check to keep the working temperature between 135° and 145° F. The members were stored and glued at a room temperature of approximately 75° - 80° F. A moderately heavy spread of glue was brushed on all contact surfaces of both pieces and the members immediately assembled and placed under clamping pressure for ten minutes.

Assemblies were individually clamped in standard wooden hand clamps. (See Fig. 2). No accurate measurement of the clamping pressure was obtained, but it will be noted that psi pressure was greater for the mortise-and-tenon joints because of the smaller shoulder area receiving the pressure.

C. Conditioning

All test specimens were conditioned for a minimum of ten days.

Moisture content for each group was determined by placing approximately 20 gram cross-section pieces from two specimens of each group, immediately after testing, in a drying oven for 24 hours. Moisture content calculation was by the formula:

$$\text{Moisture content} = \frac{W_1 - W_2}{W_2} \times 100$$

where W_1 = weight at time of test.

W_2 = weight oven dry.

D. Testing

Tension

All tension tests were made on the 5000 lb. Dillon Tensile Tester (Fig. 3, 4). The head speed for the test was .25 of an inch per minute.

The accuracy of the gauge on the machine was not checked prior to starting tests. It was assumed that any error that might be present would be in direct proportion to the indicated strength. The object was to obtain an accurate relative difference, even though the recorded strength of the specimen was slightly in error.

Bending

All of the bending tests were made on the 60,000 lb. Universal Riehle Testing Machine (Fig. 5). Prior to making any recorded tests on the machine, an accuracy chart was made for the machine from 0 to 400 lbs. This was done by piling steel blocks, previously weighed on an accurate scale, on the table of the machine and recording, in approximately 20 lb. increments, the actual weight and the machine-indicated

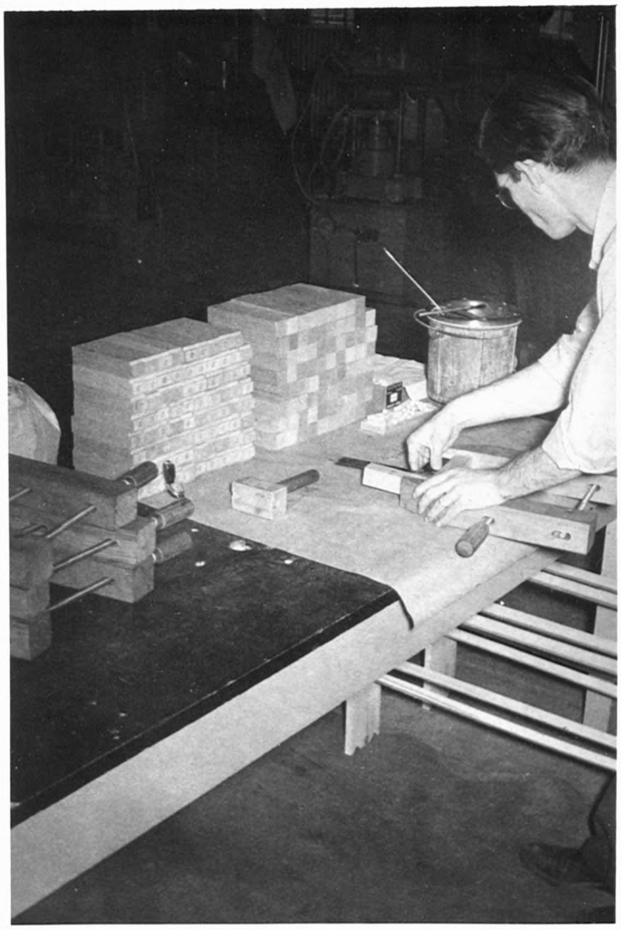


FIGURE 2

GLUING OPERATION

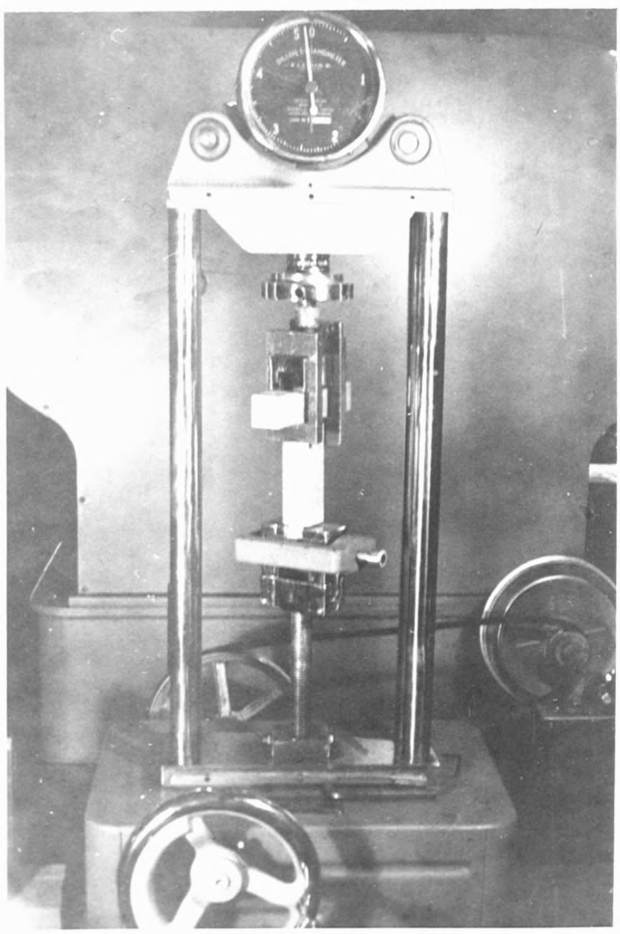


FIGURE 3

TENSION TEST

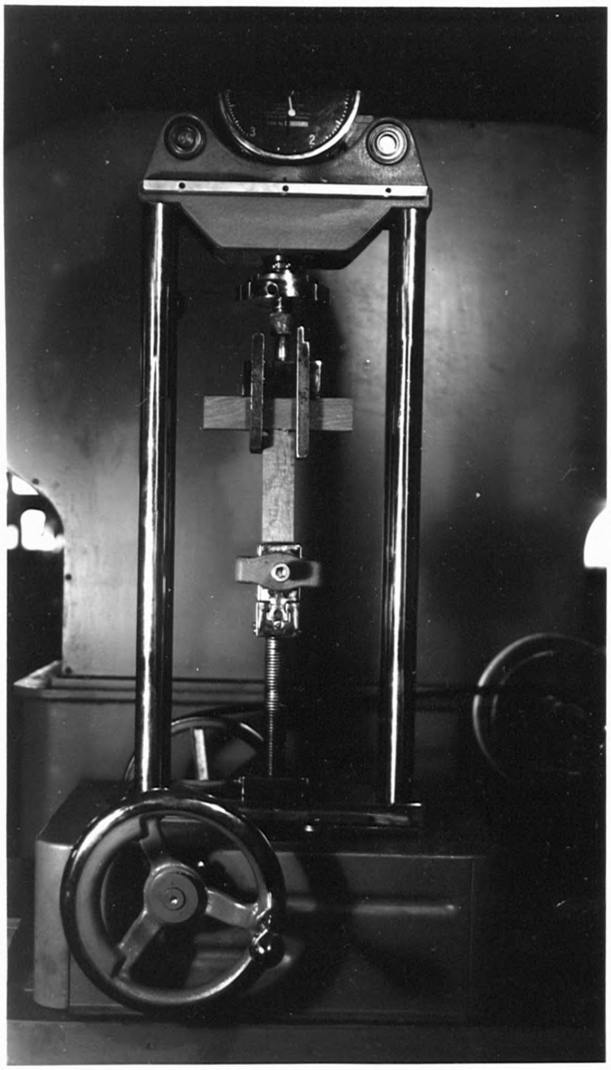


FIGURE 4

TENSION TEST

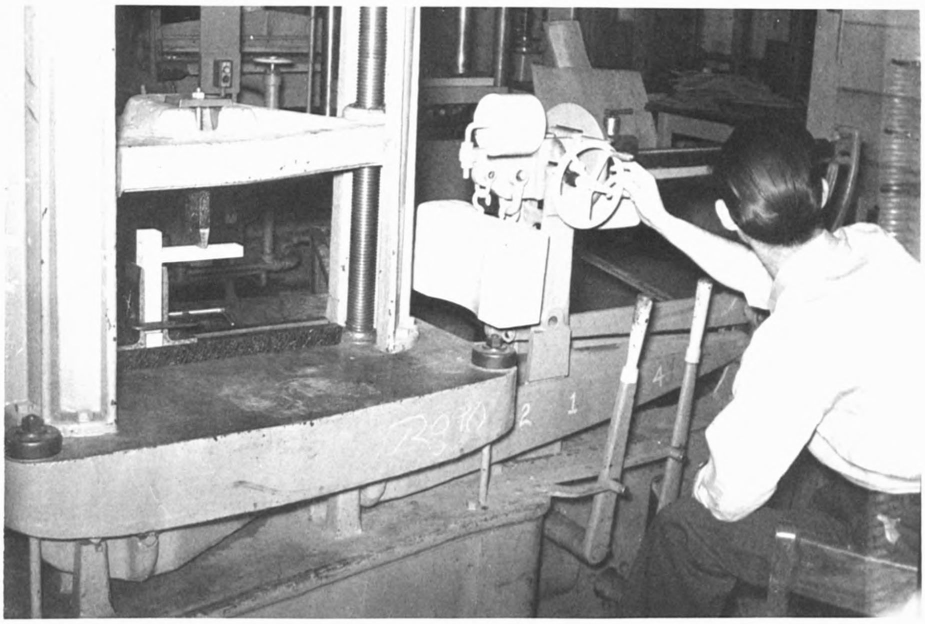


FIGURE 5

60,000 LB. UNIVERSAL RIEHLÉ TESTING MACHINE

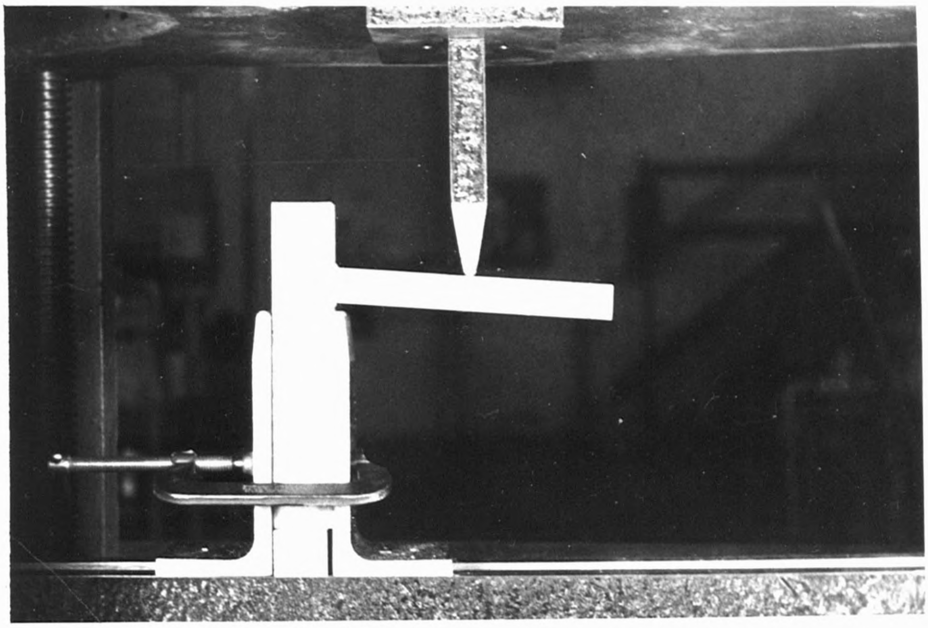


FIGURE 6
BENDING TEST
(POSITION - a)

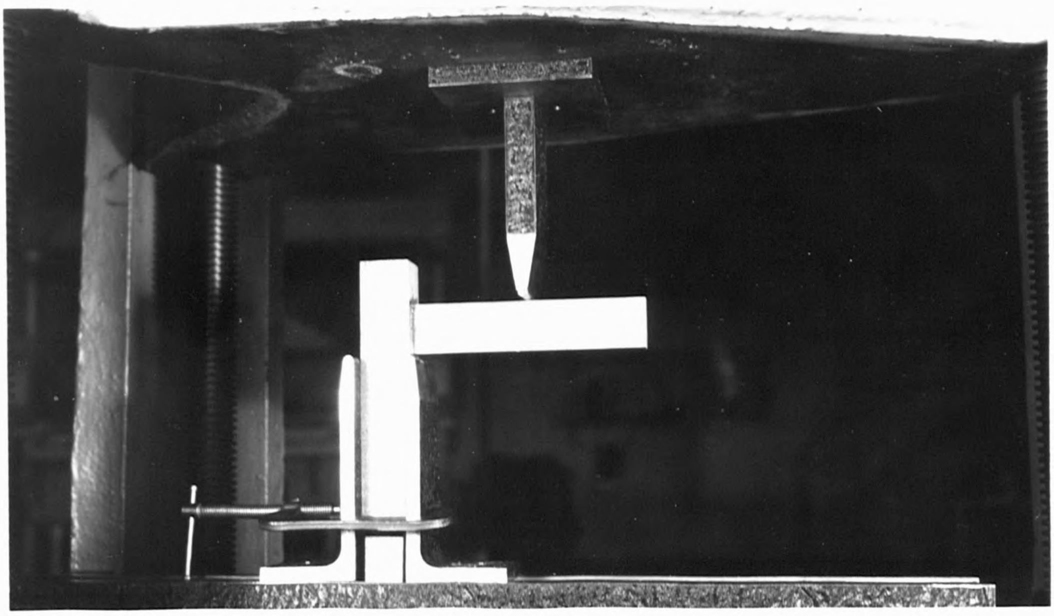


FIGURE 7
BENDING TEST
(POSITION b)

weight of the blocks. Between 60 and 300 lbs., the range within which all bending failures occurred, the error did not exceed 2% of the actual weight and averaged about 1%.

The head speed for all tests was .25 of an inch per minute. The span or lever arm was 3 inches.

The testing set-up is illustrated in Figures 5, 6 and 7. The small C-clamp seen in the picture furnished added support to the holding jaws. The horizontal member of the device was centered on the table and securely clamped to prevent any lateral or lengthwise shifting.

The specimen was tested as a cantilever beam. By this method of testing, the maximum stress was placed on the specimen at the joint. The effect of this stress was both to withdraw and bend the dowel and tenon, thereby simulating racking of a case. Tensile stresses were produced in the upper half of the tenon and the dowel and compressive stresses in the lower half. It was apparent that as the lever arm began to depress, the bottom edge of the lower shoulder would act as a fulcrum. Because the length and relative position of the fulcrum would be a definite factor in the strength ofthe joint, one half of the specimens in each group were tested with the 1¼" dimension aligned horizontally (position a)(Fig. 6), and the other half aligned vertically (position b) (Fig. 7). The purpose of this was to provide more detailed information on the strength characteristics of the joint.

RESULTS

The test results for the thirty-six groups are given in Table I. Table II shows the strength comparison of the mortise and tenon joint and dowel joint on a percentage basis. Tables III and IV are designed to show the effect ofjoint fit and moisture content on the strength of the mortise and tenon and dowel joints respectively. Graphs I and II depict the effect of the shoulder on bending strength for the mortise and tenon and dowel joint respectively. Graph III exhibits the correlation between joint strength and moisture content.

TABLE I

STRENGTH AVERAGES FOR ALL GROUPS TESTED

(a) Tension

	Joint Fit (tight)				Joint Fit (medium)				Joint Fit (loose)			
	Mort. & Tenon Max. Load (lbs)	MC*	Dowel Max. Load (lbs)	MC*	Mort. & Tenon Max. Load (lbs)	MC*	Dowel Max. Load (lbs)	MC*	Mort. & Tenon Max. Load (lbs)	MC*	Dowel Max. Load (lbs)	MC*
4% Moisture Content	953	4.6%	602	4.4%	616	4.1%	686	4.9%	596	4.4%	460	4.1%
8% Moisture Content	1341	8.2%	840	7.8%	1048	9.8%	946	7.4%	1130	8.6%	882	7.2%
12% Moisture Content	1056	12.0%	1059	11.5%	1083	12.6%	981	10.0%	991	10.9%	921	9.8%
Average	1117		834		916		871		906		754	
(b) Bending												
4% Moisture Content	200	5.7%	138	4.5%	212	4.4%	104	5.3%	170	4.5%	96	4.3%
8% Moisture Content	238	8.8%	147	7.8%	246	8.9%	132	7.3%	194	8.1%	131	8.1%
12% Moisture Content	224	12.3%	146	11.6%	210	10.9%	138	10.3%	186	12.2%	142	11.4%
Average	221		144		222		125		183		123	

MC* - Actual moisture content (oven dry basis) at time of test.

~~SUMMARY~~

TABLE II

SUMMARY OF TEST RESULTS

(a) Percent of greater strength for mortise and tenon joint based on joint fit. Three groups (4%, 8% and 12% moisture content) tested for each grade of joint fit for each joint.

VARIABLE	STRENGTH PROPERTY	
	Tension	Bending
Joint Fit (tight)	34%	53%
Joint Fit (med.)	5%*	78%
Joint Fit (loose)	20%	49%

*Moisture content of these specimens at time of testing was in error and resulted in abnormally high strength figures for the dowel joint specimens (See Table I).

(b) Percent of greater strength for mortise and tenon joint based on moisture content. Three groups (tight, medium and loose joint fit) tested at each moisture content for each joint.

VARIABLE	STRENGTH PROPERTY	
	Tension	Bending
4% Moisture Content	23%	72%
8% Moisture Content	32%	89%
12% Moisture Content	8%	46%

TABLE III

STRENGTH AVERAGES FOR MORTISE AND TENON JOINT GROUPS

(a) Tension

	Joint Fit (tight)	Joint Fit (Medium)	Joint Fit (loose)	Average
4% Moisture Content	953	616	596	722
8% Moisture Content	1341	1048	1130	1173
12% Moisture Content	1056	1083	991	1043
Average	1117	916	906	

(b) Bending

	Joint Fit (tight)	Joint Fit (medium)	Joint Fit (loose)	Average
4% Moisture Content	200	212	170	194
8% Moisture Content	238	248	194	226
12% Moisture Content	224	210	186	207
Average	221	222	183	

GRAPH I

EFFECT OF SHOULDER ALIGNMENT ON JOINT STRENGTH
(MORTISE AND TENON)

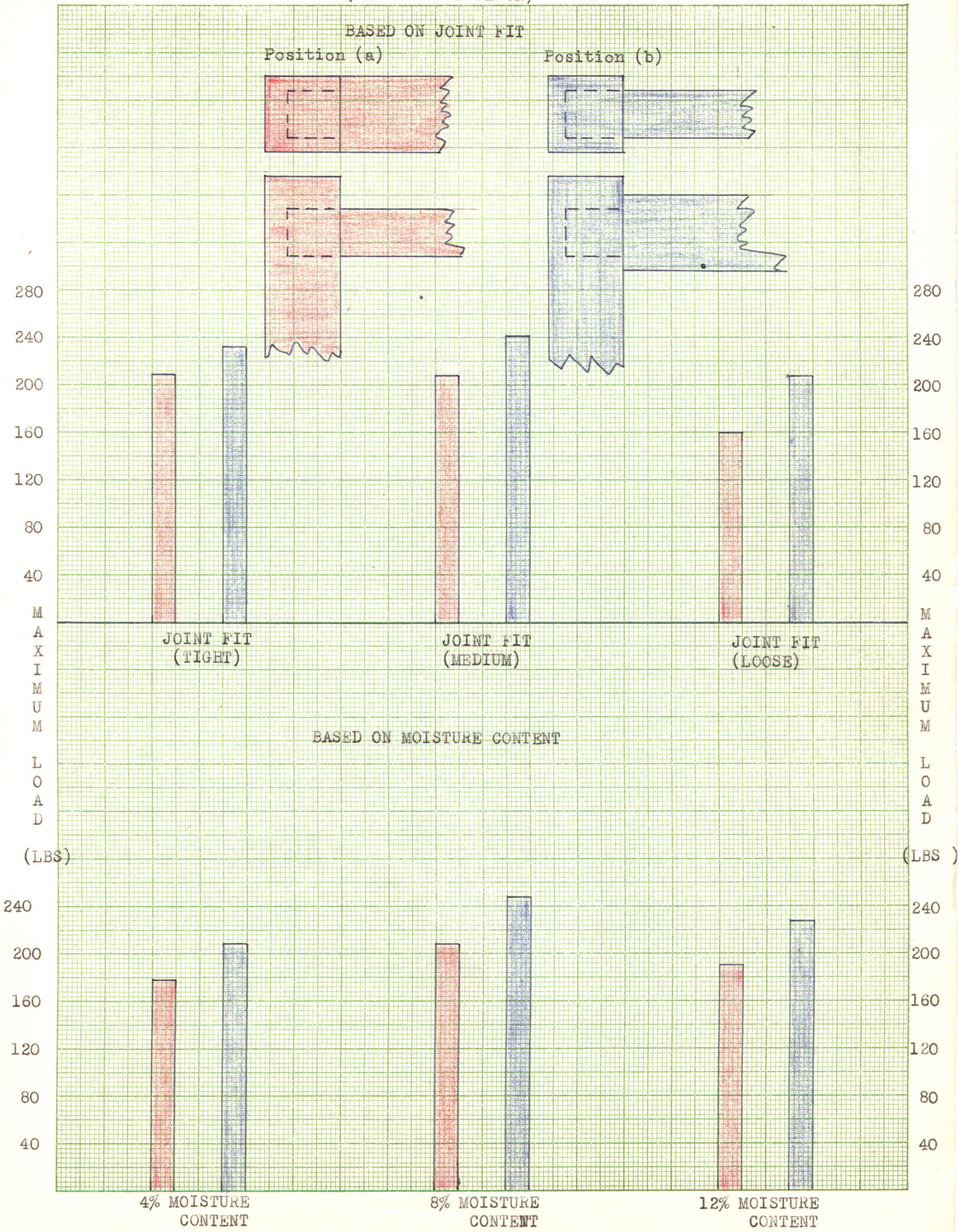


TABLE IV

(a) Tension

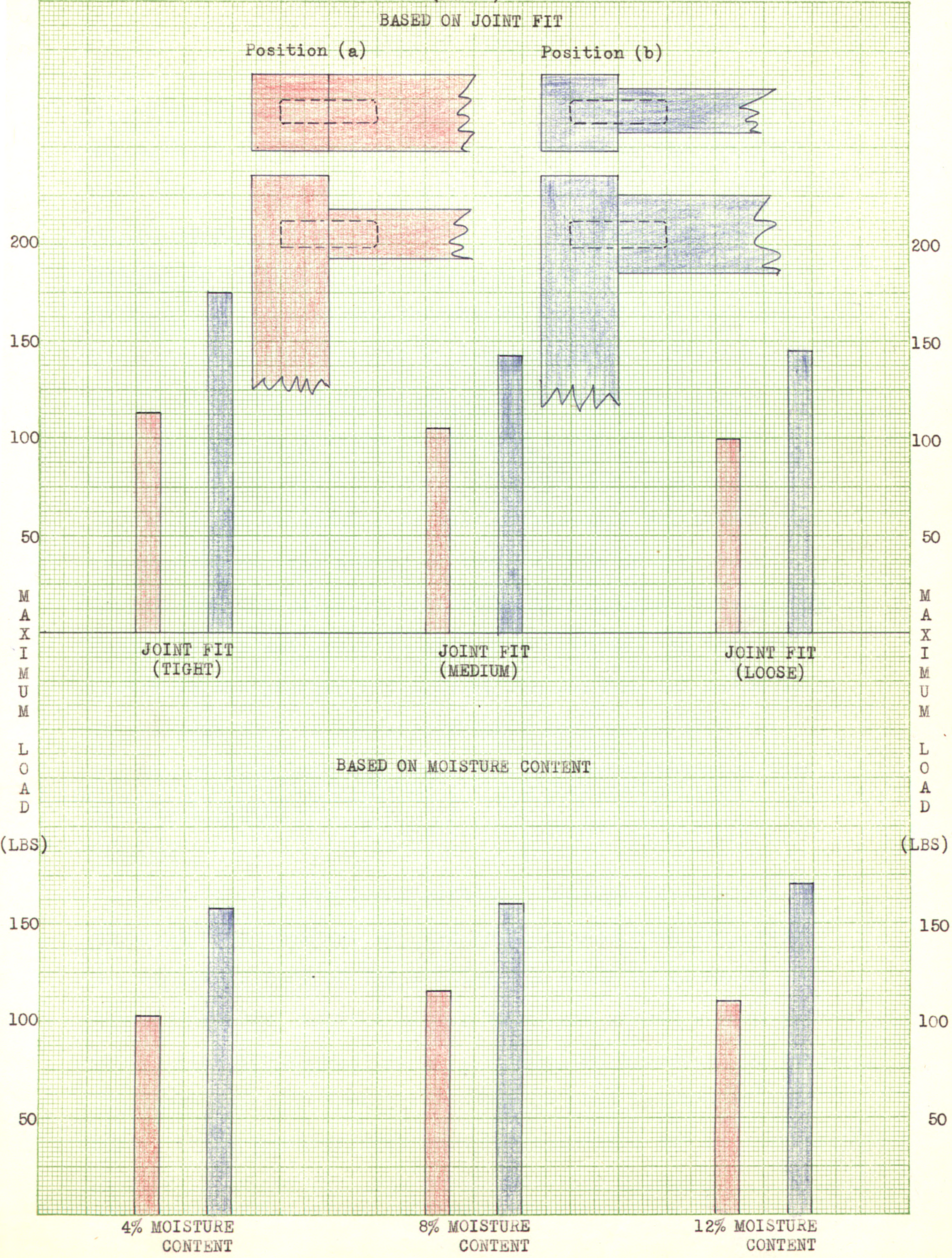
	Joint Fit (tight)	Joint Fit (medium)	Joint Fit (loose)	Average
4% Moisture Content	602	686	460	583
8% Moisture Content	840	946	882	889
12% Moisture Content	1059	981	921	987
Average	834	871	754	—

(b) Bending

	Joint Fit (tight)	Joint Fit (medium)	Joint Fit (loose)	Average
4% Moisture Content	138	104	96	113
8% Moisture Content	147	132	131	137
12% Moisture Content	146	138	142	142
Average	144	125	123	—

GRAPH II

EFFECT OF SHOULDER ALIGNMENT ON JOINT STRENGTH
(DOWEL)



DISCUSSION OF RESULTS

The strength limit of either joint is in the combined strength of the glue line and the strength of the smallest wood member. Although the glue line area for both joints was $3 \pm .05$ square inches, different types of glue line were present in varying proportions. For these specimens tested in tension, the shoulder represents a relatively weak end grain to side grain gluing in tensile stress. The remainder of the glue line is subjected to a shear stress, approximately half of which is a cross-lapped side grain to side grain and half end grain to side grain. Although the shear strength of joints is not comparable to that of standard solid wood shear test specimens, the amount of wood failure on the shear surfaces of the joint is indicative of a greater strength in shear than in end grain to side grain gluing. An important factor in the greater strength of the mortise and tenon joint is the fact that it has considerably more shear area and correspondingly less end grain to side grain intension than the dowel joint.

Tension

The mortise and tenon specimens showing the highest strength were observed to have considerable wood failure on the end grain part of the mortise. A patch or clump of fibrous material adhered to the tenon and gouged a deep groove in the side of the mortise as the specimen proceeded to failure. The lower strength specimens showed no wood failure of this type. It is possible that such failure would not be characteristic of a harder and less brash wood than mahogany.

An end grain wood failure was consistently observed in the dowel hole but it apparently bore no correlation to joint strength. Even those specimens having 100% wood failure on the dowel showed low strength as often as high strength. Record was kept of whether the vertical or horizontal member retained the dowel after failure. Results were erratic in this respect and revealed no strength correlation.

Bending

The high strength superiority of the mortise and tenon joint is further accented by the much greater strength retained by the joint after passing maximum load. Upon removal from the testing machine, an attempt was made to complete the failure by hand pressure. Few of the mortise and tenon joints could be broken in this manner, while the reverse was true for the dowel joint.

High strength mortise and tenon specimens exhibited a relatively long fibrous failure in the upper half of the tenon. The lower strength specimens showed a relatively brash failure completely across the tenon. Considering this observed feature, and the location and nature of the stresses in the tenon, it would appear that the strength of the joint would be largely dependent on the modulus of rupture of the wood of which the tenon was made.

The dowel joints, particularly those aligned vertically (see position b, Graph II), gave indication of an internal failure at about two-thirds of the maximum strength. Several specimens were removed from the testing machine at this point of preliminary failure. They were cut open (Fig. 8) and closely inspected to determine the nature of this failure. It was suspected that it was caused by failure of the glue line on the upper shoulder which was in tension, but no glue line failure or other disturbance was found.

Effect of Joint Fit

Although certain storage precautions of the blocks after machining were taken to prevent a large fluctuation of moisture content, they were not relied on to maintain the close machining tolerance. A 15% check was made with a micrometer at the time of assembly to determine what dimensional change had occurred. The blocks were within a moisture content range of 6% to 8% at the time of assembly and average measurements were as follows:

Joint Member	Nominal Dimension (inches)	Actual Dimension (inches)	Joint Tolerance (inches)	Joint Fit
Mortise	.750	.759	---	---
Tenon	.750	.747	.012	tight
Tenon	.735	.732	.027	medium
Tenon	.720	.718	.041	loose

The following figures show that a definite strength decrease resulted from the loose joint fit, but the strength of the medium joint fit varied from 4% greater than the tight joint fit to approximately equal to that of the loose joint fit.

Mortise and tenon joint

Tension

Joint fit (tight) - 22% stronger than joint fit (medium)
- 23% stronger than joint fit (loose)

Bending

Joint fit (tight) - same as joint fit (medium)
- 21% stronger than joint fit (loose)

Dowel joint

Tension

Joint fit (tight) - 4% weaker than joint fit (medium)
- 11% stronger than joint fit (loose)

Bending

Joint fit (tight) - 15% stronger than joint fit (medium)
- 17% stronger than joint fit (loose)

Effect of Moisture Content

The lack of precise control over the moisture content of the specimens was the principal cause of error in the results. Formulas to calculate strength corrections for moisture content would not apply in the case of glued joints because of other factors involved. However, the existence and nature of this error should be considered when comparing the strength figures. It is this writer's opinion that, in the absence of moisture content error, the strength superiority of the mortise and tenon joint in tension would be 25% to 30% instead of 19%.

Graph III is based on a combined average of strength and moisture content and would be completely accurate only if the

the strength-moisture content relationship were a straight line function--an unproven assumption. However, the writer believes that the graph is sufficiently accurate to furnish an indication of the moisture content at which the greatest joint strength occurs, which, under the conditions of this investigation, is in a 9% to 9½% range. This moisture content range of greatest joint strength would change with a change in moisture content at the time of machining and assembly and perhaps with the use of a different type of adhesive.

A relatively high strength was maintained at 12% moisture content, but the difference in strength between the two joints was less. This would indicate that the effect of moisture content on strength is not as pronounced at a high moisture content.

Effect of Shoulder Alignment in Bending

For the mortise and tenon joint, position (b) (Graph I) is 18% stronger than position (a). Position (b) (Graph II) for the dowel joint is 45% stronger than position (a).

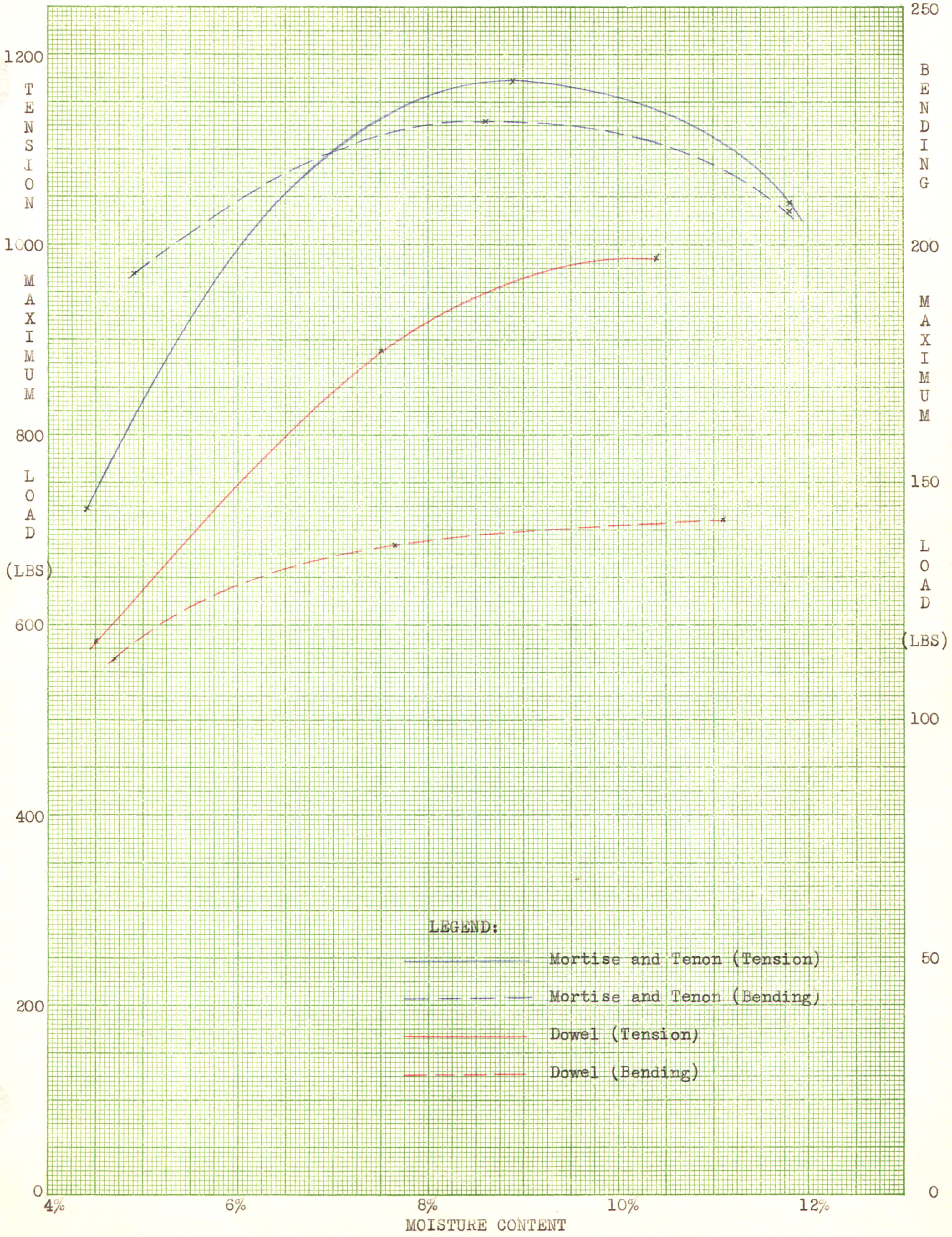
By lowering the position of the fulcrum, position (b) develops more of the tensile strength parallel to the grain. The lower or 'complete failure' specimen of Figure 8, in which the dowel has been partially withdrawn from the dowel hole, exhibits this tension effect.

CONCLUSIONS

The final averages, based on all groups tested, show that the mortise and tenon joint is 19% stronger than the dowel joint

GRAPH III

EFFECT OF MOISTURE CONTENT ON JOINT STRENGTH



in tension, and 68% stronger in bending, which is the strain to which it is most often subjected in service.

To gain and maintain the maximum strength inherent in the joint:

1. The joint tolerance should not exceed .02" in any dimension when the members are at a moisture content of 7% to 9%.
2. Where design permits, the shoulders should be aligned in the plane of greatest stress.

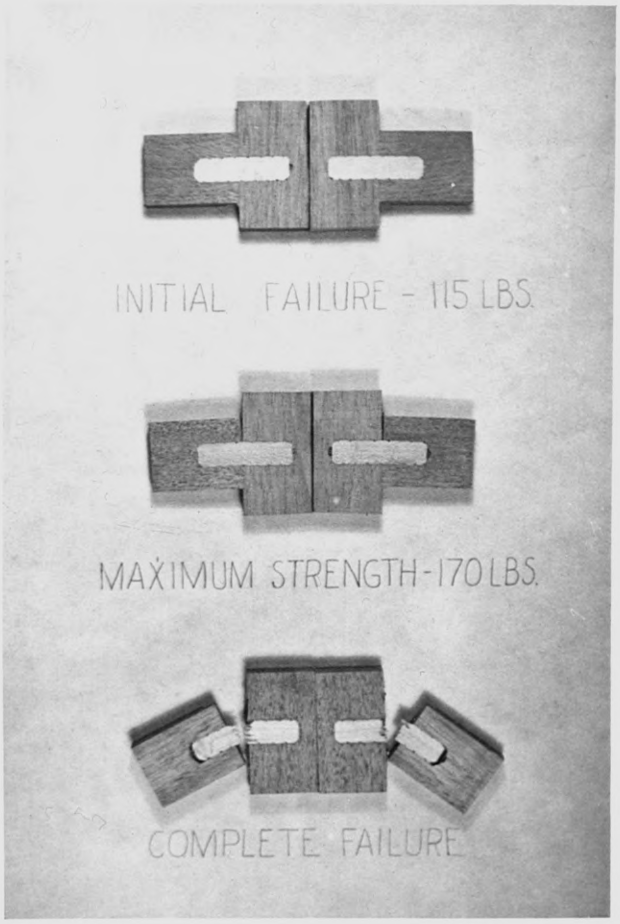


FIGURE 8

BENDING FAILURE OF DOWEL JOINT

42

Group No. 42- DJF$_2$MC$_2$T$_3$

Glued 3-12-49
In CTH Room
from 3-12-49
to 4-6-49
Tested 4-6-49

REMARKS: Tested at 7.3%.
At about 2/3 max strength test piece showed a sudden decrease in strength (no visible failure) but quickly regained strength.

No.	Max. Stress (lbs)	Type of Failure	No.	Max. Stress (lbs)	Type of Failure
1	(a) 120		16	(b) 155	
2	100		17	155	
3	125		18	190	
4	140		19	160	
5	115		20	175	
6	120		21	170	
7	135		22	190	
8	135		23	205 X	
9	105		24	105	
10	125		25	160	
11	75 X		26	155	
12	110		27	130	
13	115		28	135	
14			29		
15	ave 120		30	ave 144	

Average Max. Stress: lbs. 132

psi ______

FIGURE 9

DATA SHEET