THE EFFECT OF DOWEL DIAMETER AND DOWEL PENETRATION ON JOINT STRENGTH

Thesis for the Degree of M. S.

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Donald Lewis Crews

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THE EFFECT OF

DOWEL DIAMETER AND DOWEL PENETRATION

ON JOINT STRENGTH

By

DONALD LEWIS CREWS

AN ABSTRACT

Submitted to the College of Agriculture
Michigan State University of Agriculture and
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Approved Aubrey E. Wylie

Abstract

The research reported here was primarily to study the effect of dowel penetration and dowel diameter on joint strength. To show this effect, two tests were employed. One test was a standard withdrawal test and the other was a test in which "in use" stresses were developed.

The dowels were matched for replications of the two tests. As a check on the matching, specific gravity specimens were measured. The test specimens were loaded to failure and the maximum loads recorded.

The results of the research are summarized in the following list:

1. The withdrawal test gives a good measure as to the strength of a dowel joint.
2. The use of the withdrawal test is highly recommended. Its simplicity of design makes it a desirable test of dowel joint strength.
3. For a given dowel diameter, there is a limit to the effect of dowel penetration on joint strength. The final determinant of joint strength is the strength of the wood dowel.

4. Until the strength of the wood is reached, there is a linear relationship between glue line area and maximum load.
5. In order to develop maximum joint strength, the depth of the dowel hole should be four to six times the diameter of the dowel.
6. Maximum load at failure rather than stress should be used as a criterion of joint strength.

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INTRODUCTION

One of the most difficult problems encountered in the furniture industry was that of joining end grain to side grain surfaces of wood. Numerous joint designs have been developed as a solution to the problem. Some of the more common end-to-side-grain joints are the miter, dowel, mortise-and-tenon, dado tongue and rabbet, slip or lock corner, dovetail, plain, blocked, and tongued-and-grooved (4). If one of these joints were to be selected on the basis of performance, simplicity of design, and ease of construction and assembly, the dowel joint would certainly be the choice.

A dowel joint may be defined as a joint which has one or more pins called dowels joining its two members. These dowels reinforce the joint by bringing side grain into contact with side grain and by increasing the glue line area.

There are several types of dowels manufactured for use in the furniture industry. The dowel most commonly used is one having a small groove spiraling the length of the dowel. It is thought that the spiral groove insures a quick and even distribution of adhesive away from the bottom of the dowel hole. In industry the adhesive is usually applied to the bottom of the hole before the dowel is inserted.

Another dowel type which has come into use in recent years is the compressed dowel. The compressed dowel is a smooth dowel which has been compressed to reduce its diameter. When an adhesive is applied to the dowel and it is inserted into the dowel hole, the dowel expands in diameter. This expansion is due to the intake of moisture from the adhesive. The increase in dowel diameter results in a high pressure between the surfaces of the dowel and the dowel hole.

A third type is the uncompressed smooth dowel. It is seldom used in the furniture industry.

Dowels are manufactured in diameters ranging from 1/8 inch to one inch by 1/64 inch increments. Beech, birch, hard maple, and white pine are the most common species of wood used for dowels.

In the assembly of dowel joints, animal glue and polyvinyl resin adhesive are used almost exclusively. This is probably due to their relatively low cost, high initial bond strength, and ease of application and preparation.

Some of the factors that may affect the strength of a dowel joint are wood species, wood density, dowel type,

dowel length, and dowel diameter, diameter of dowel hole, type of adhesive, and method of application. If all of these variables were controlled and a withdrawal test of some design were employed, the strength of the joint would depend solely on the tensile strength of the wood dowel and, or the shear strength of the glue line.

Purpose of Study

Since the tensile strength of the dowel is a function of dowel diameter and the shearing strength of the glue line is a function of the glue line area, it would seem logical to assume that dowel length and dowel diameter are most important factors in evaluating the strength of a dowel joint.

The stresses developed in a withdrawal test are easily defined but, at the same time, these stresses are seldom encountered in the practical application of the joint. It is the author's opinion that a test in which "in use" stresses are developed should be employed. If a high correlation between the "in use" test and the withdrawal test results, the simpler of the two tests should become the standard.

The objectives of this study were:

1. To evaluate two tests of dowel joint strength;

one a standard withdrawal test and the other, a test in which "in use" stresses are developed.

2. To determine the correlation, if any, between the two tests.
3. To determine a joint strength equation for dowel joints in terms of glue line area of the dowel.
4. To determine a dowel length-dowel diameter ratio for maximum joint strength.

Previous Work

One of the earliest investigations into dowel joint strength was in 1939 when Rosser (10) determined that the method in which the glue was applied to the dowel had an effect on the strength of the joint. He found that a stronger joint resulted when the glue was spread on both the dowel and in the dowel hole. He also established that insertion of the dowel parallel to the grain resulted in a stronger joint than insertion perpendicular to the grain. Rosser's data were based on tests performed using the specimen shown in Figure 1-A.

According to Nearn, Norton, and Murphey (7), when a dowel is incorporated into a joint it does three things. First, it increases the area of the original glue line by an area equal to the surface area of the dowel cylinder.

Secondly, it reduces the area of the original glue line by an area equal to the area of the dowel hole. Thirdly, a dowel may present a more favorable gluing surface than was previously available to the joint. The latter is especially important when joining end grain to edge grain and end grain to end grain.

Nearn, Norton, and Murphey (7), varying the size of the dowel hole and the type of dowel, found that the spiral and standard (smooth) dowels produced joints of equal strength. Their data also indicated that superior joints resulted when the dowel hole was 1/64 or 2/64 inch larger than the diameter of the dowel. The test specimen employed in this particular study was a modification of the test piece that is standard for tests in tension perpendicular to the grain. (Fig. 1-B).

Nearn and Clarke (6) found that a compressed dowel gives a stronger joint than a spiral dowel, and the spiral dowel makes a stronger joint than a regular (smooth) dowel. This is in contradiction to the study of Nearn, Norton, and Murphey. However, the test specimen in this report is different from that used in the previous work. This may be the reason for the difference in the conclusions. The specimen used by Nearn and Clarke is shown in Fig. 1-C. It was also established that the use of a dowel hole slightly larger in diameter than the dowel pin would tend to increase

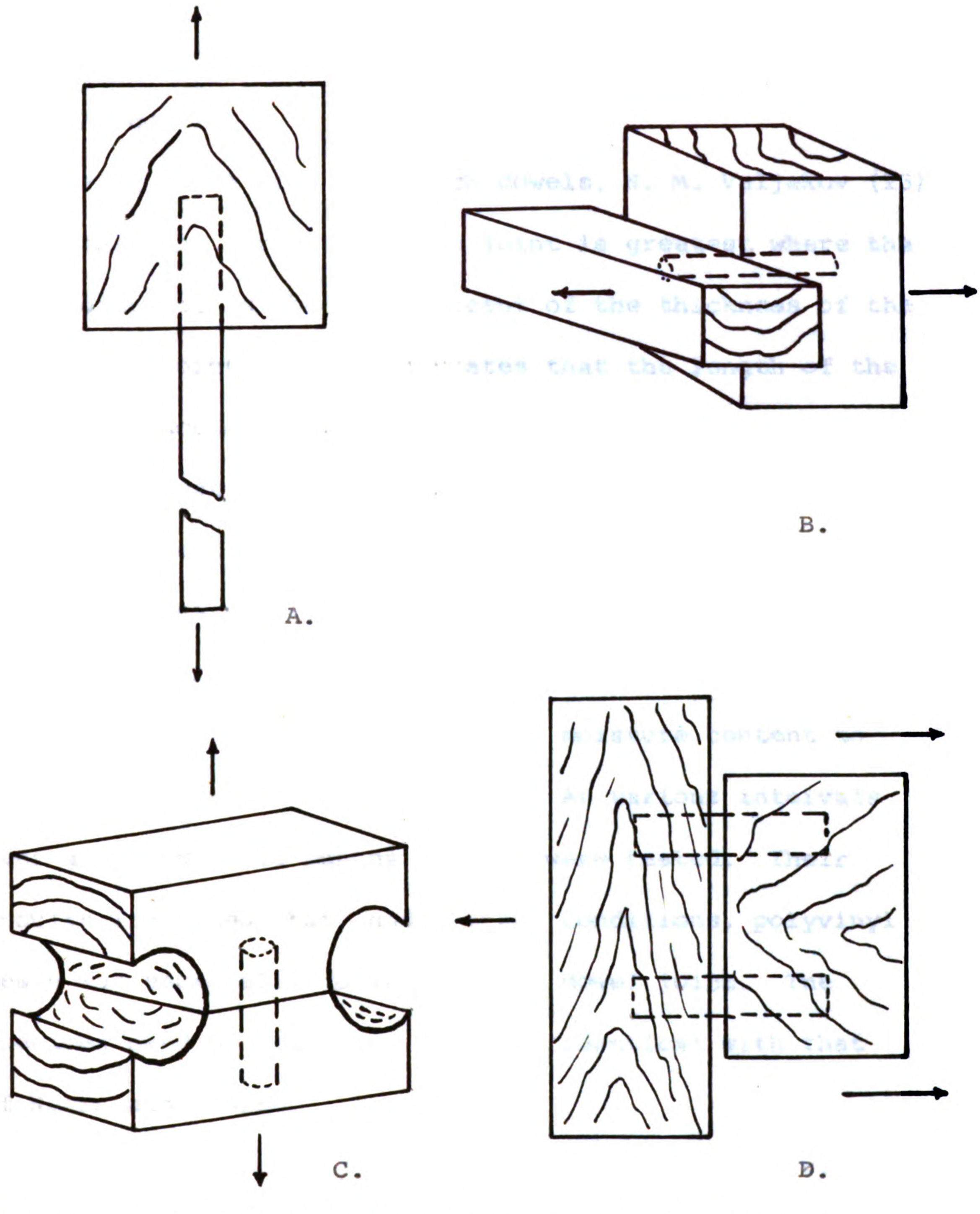

Fig. 1. Test specimens used to determine dowel joint strength. Arrows indicate direction of load application. A. Rosser B. Nearn and Clarke C. Nearn, Norton, and Murphey D. Veljakov

joint strength. It is felt that if the dowel hole is too small, there is a tendency for the adhesive to be stripped from the dowel.

Using Scots pine and birch dowels, N. M. Veljakov (13) noted that the strength of the joint is greatest where the dowel diameter is about 50 percent of the thickness of the wood being joined. He also states that the length of the dowel pin should be from 5.5 to 6.5 times its diameter. Veljakov's test specimen is shown in Figure 1-D.

In respect to assembly joint adhesives, Selbo and Olson (11) tested seven types of assembly joints, each with 11 different adhesives. The samples were exposed to repeating cycles that caused the moisture content to vary from 6 percent to 20 percent. At various intervals over a period of 36 months samples were tested. Their results indicated that, under these conditions, polyvinyl resin was especially durable in the dowel joint. The specimen used by Selbo and Olson is identical with that of Nearn and Clarke.

In a paper in which they evaluate several polyvinyl emulsion adhesives, Olson and Blomquist (9) verified the work of Selbo and Olson (11). Using identical test specimens and a number of polyvinyl emulsion adhesives, they confirmed that polyvinyl resin adhesives perform very well in dowel joints.

PROCEDURE

Description and Preparation of Samples

Two test specimen designs were used in this study. The withdrawal specimen (Fig. 2, Fig. 4) was described by Selbo and Olson (11). This is the specimen type which has been used in most of the recent research on dowel joint strength. It consists of two blocks of wood jointed together, side grain to side grain, with a dowel. The grain directions of the two blocks are perpendicular.

The final selection of an "in use" test specimen (Fig. 3, Fig. 5) resulted in the construction of an extreme modification of a block joint such as the one used to test the durability of certain woodworking glues by Selbo and Olson. This test specimen will be referred to in this paper as the bending test specimen. It consists of two blocks of wood jointed together, side grain to end grain, with a dowel. It was felt that this design would put the dowel under certain stresses that are encountered in its typical applications. It should be noted that the bending specimen represents a corner joint. This should be considered if comparisons are to be made with other tests of dowel joint strength.

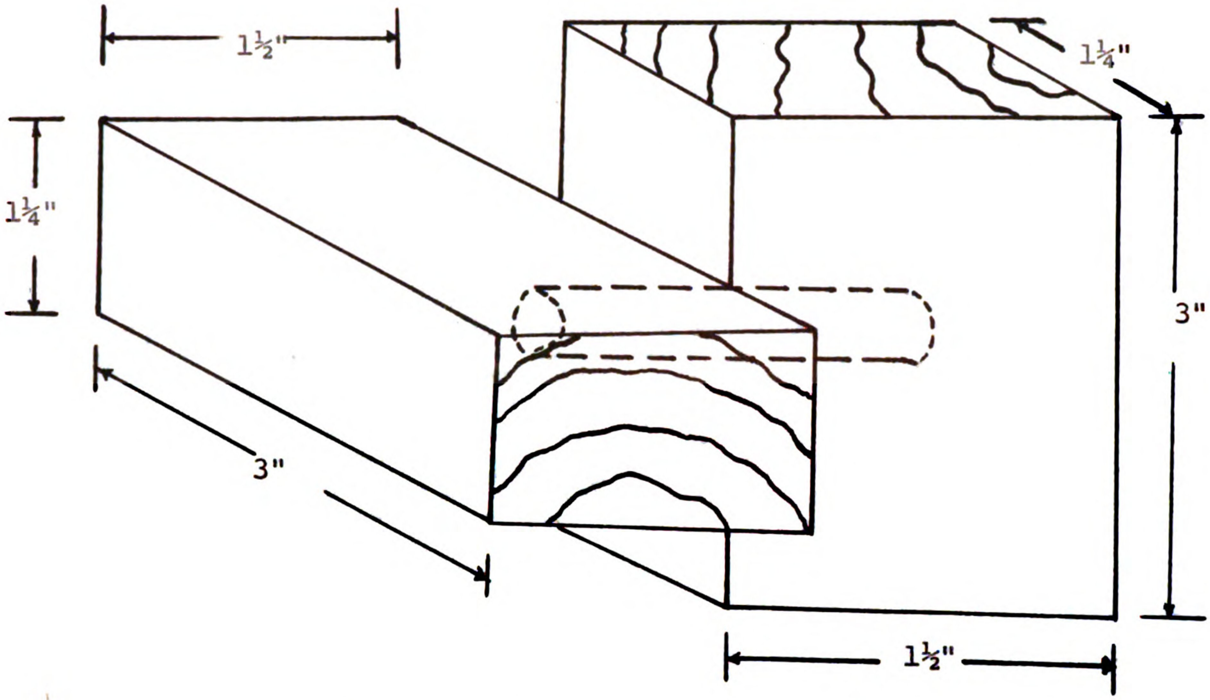

Fig. 2. Withdrawal Specimen

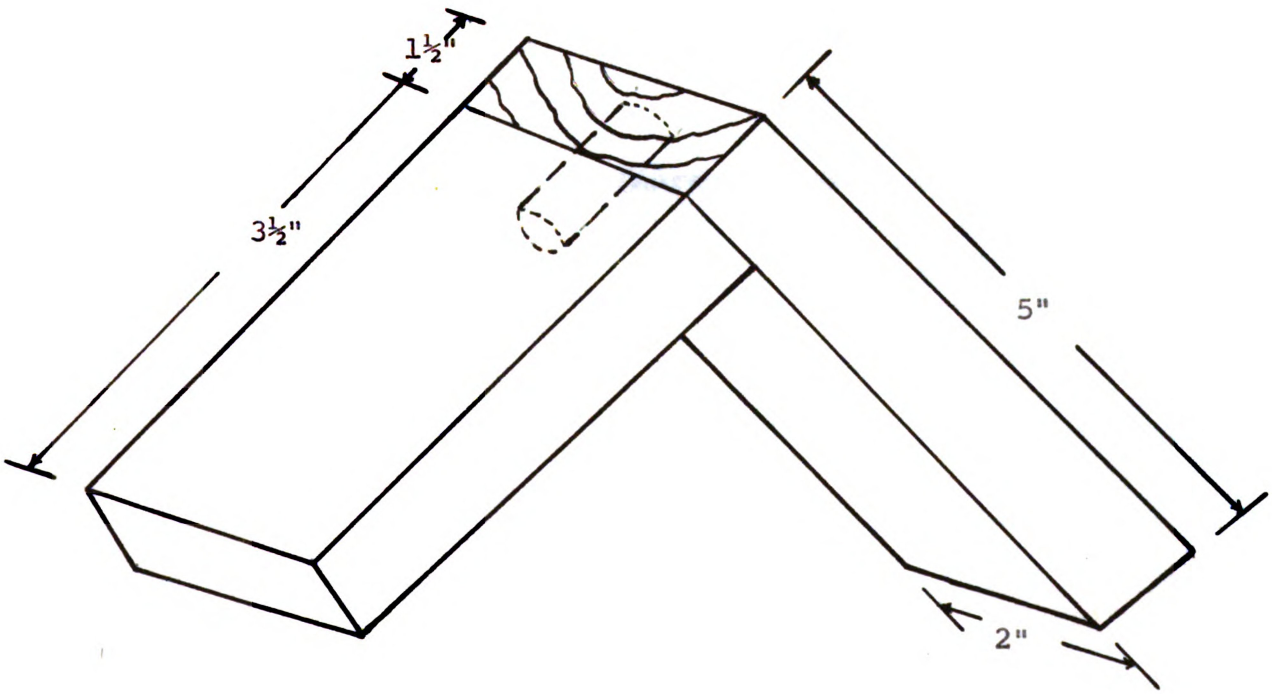

Fig. 3. Bending Specimen

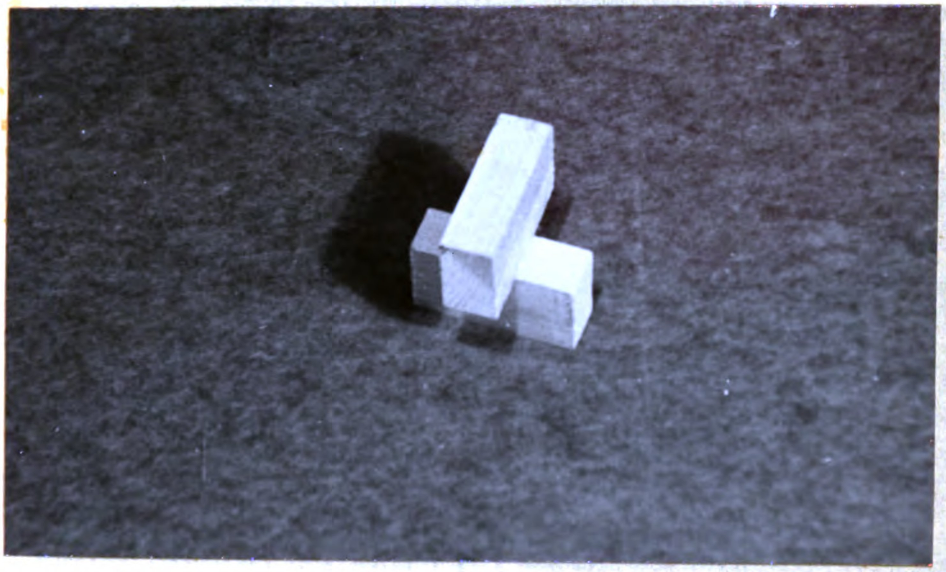

Fig. 4. Withdrawal Specimen

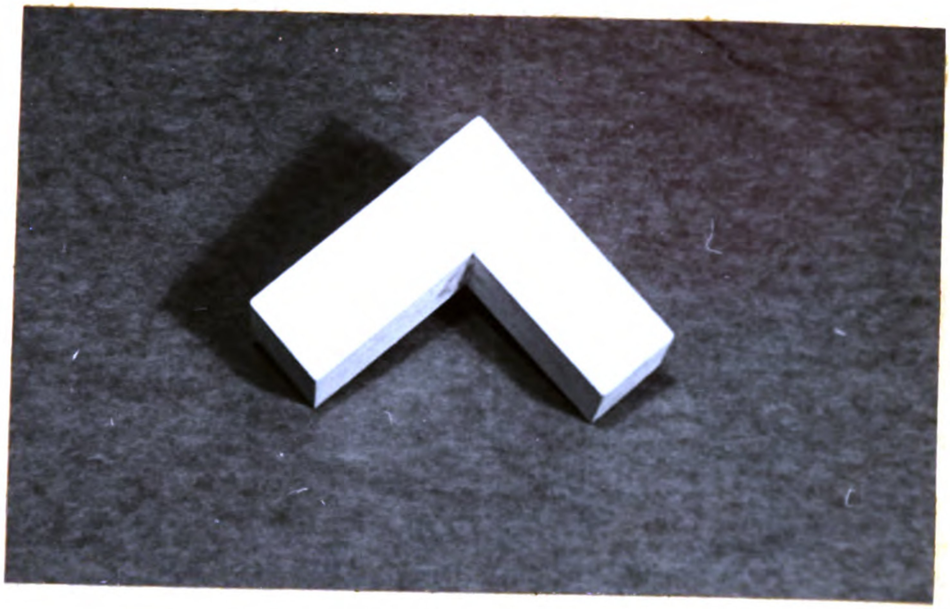

Fig. 5. Bending Specimen

The dowels and test blocks used in this study were hard maple (Acer saccharum Marsh. and Acer nigrum Michx. f.). Maple was selected because it serves as a standard in most types of shear tests for adhesives, and because of its commercial importance in the furniture industry in the form of dowels. The blocks used in the two tests were machined from clear, straight-grained, kiln-dried hard maple. They were planed and cut to the proper dimensions using conventional woodworking machinery. Each set of blocks was marked with a marking gauge to determine the exact centering of the dowel hole. Five different hole diameters were drilled, each having four depth classes. There were four replications for each combination of hole depth* and hole diameter with the exception of the 1/2 inch dowel. Two additional hole depth classes were added to this diameter class. This experimental design (Fig. 6) resulted in a total of 88 observations for each of the two tests.

Since the dowels were the most critical portion of the test specimen, a great deal of care was taken in their selection. From previous research (6) (7), it was determined that spiral dowels give the best performance of any dowel type. Spiral grooved dowels having six spirals per inch

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* In this study, the terms "hole depth", "dowel length", and "dowel penetration" are used interchangeably.

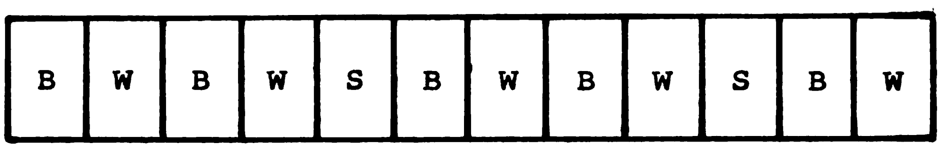
	Withdrawal Test						Bending Test					
	Hole Depth						Hole Depth					
Dowel Dia.	1/4	1/2	3/4	1	5/4	6/4	1/4	1/2	3/4	1	5/4	6/4
1/4	4	4	4	4	-	-	4	4	4	4	-	-
5/16	4	4	4	4	-	-	4	4	4	4	-	-
3/8	4	4	4	4	-	-	4	4	4	4	-	-
7/16	4	4	4	4	-	-	4	4	4	4	-	-
1/2	4	4	4	4	4	4	4	4	4	4	4	4

Fig. 6. Design of experiment. Numbers in cells indicate number of replications.

were chosen for study. In addition to the spiral grooves, there were two straight grooves running the length of the dowel. These straight grooves were not as deep as the spiral ones but they may have had some effect on the movement of the adhesive.

In order to assure as close a match as possible between the replications of the two tests, the following sampling plan was employed. A commercial dowel manufacturer was visited and clear, straight-grained hard maple was selected from the rough stock. This select stock was then passed through the dowel lathes. The resulting five-foot dowel rods were carefully inspected for any excessive tearing of the grain, deviations of the spiral groove, or defects which may have been uncovered by the final machining. From these dowel rods, the individual dowels were cut to length on a band-saw and the ends chamfered to blunt points on a belt sander. Adjoining dowels were matched for replications of the two tests (Fig. 7). Every fifth dowel was set aside for specific gravity measurement. The length of each dowel was measured to the nearest 1/64 inch. Only that portion of the dowel which was to come in contact with the side of the hole was considered for the length measurements.

Various studies (6) (7) have shown that a hole size 1/64 or 1/32 inch larger than the dowel will give the



B = Bending Specimen

W = Withdrawal Specimen

S = Specific Gravity Specimen

Fig. 7. Sampling design from five-foot dowel rods.

strongest joint. The dowel holes bored for this study were 1/64 inch larger than the nominal size of the dowel. The depth of each hole was measured to the nearest 1/64 inch. Since the bottom of the dowel hole is not flat but rounded (Fig. 8), the depth of the hole is slightly deeper at the center than at the side. The hole depth was measured at the side because it was felt that the strength of the glue bond between the end grain of the dowel and the side grain or end grain of the block would be negligible.

Standard deviations for both the dowel diameters and hole diameters were found to be very small. The averages and standard deviations for the various classes of these two variables are listed in Table 1.

Table 1. Nominal diameters, Actual diameters, and Standard deviations of dowels.

Nominal Diameter	Actual Diameter	Standard Deviation
.250	.253	.003
.313	.316	.003
.375	.377	.003
.438	.441	.003
.500	.503	.003

In the fabrication of the specimens, a polyvinyl resin (Peter Coopers Type PV-1) was used. The adhesive

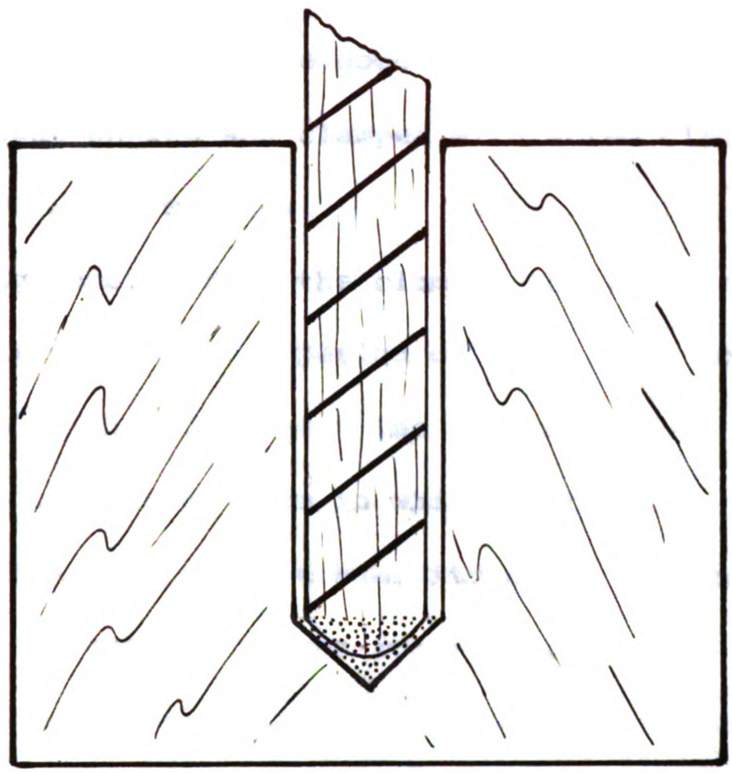


Fig. 8. Cut-away view of dowel hole. Note rounding at bottom of hole. Dotted area was omitted in glue line area calculations.

was applied to both the dowel and the dowel hole. A piece of saran-coated cellophane, with a hole to permit passage of the dowel, was placed between the two joint members. This was done to prevent any further bonding of the two blocks other than that of the dowel. The two members were aligned at right angles and clamped with screw clamps for approximately twenty minutes.

Following removal from the clamps, the joint specimens were left undisturbed for a period of seven days to allow complete cure of the adhesive. The specimens were then placed in a conditioning room in which there was a temperature of 76° F and a relative humidity of 30 percent. They remained under these conditions for a period of at least twenty days. During this time, the samples attained an equilibrium moisture content of about six percent. The specific gravity specimens were also subjected to these exact conditions.

Testing of Specimens

The withdrawal samples were tested using a Baldwin-Emery SR-4 Universal Testing Machine. The specimens were mounted on a special fixture which allowed a tensile force to be applied to the glued dowel joint as shown in Figure 9. The specimens were tested with a machine speed of 0.025

inch per minute. All of the specimens were loaded until failure occurred in the joint.

The bending specimens were tested with the same testing machine. The sample was placed on grooved roller plates as shown in Figure 10. A vertical load was applied at the apex of the joint until failure of the dowel or failure of the glue line occurred. The speed of the loading head for this test also was 0.025 inch per minute.

As the load was applied to the samples, the joints were carefully inspected for any irregularities occurring around the critical failure area. These irregularities were noted along with the maximum load.

Determination of Specific Gravity

As stated previously, the sampling plan of this study was such that specific gravity specimens were taken at regular intervals. Since the individual dowels were cut from a single dowel rod, it was felt that one specific gravity measurement for every four dowels was a representative sample. In total, there were 22 specific gravity specimens.for each test type.

A mercury displacement volumeter was used to determine the volume of the dowel specimens. This method was employed in place of the conventional procedures because of the

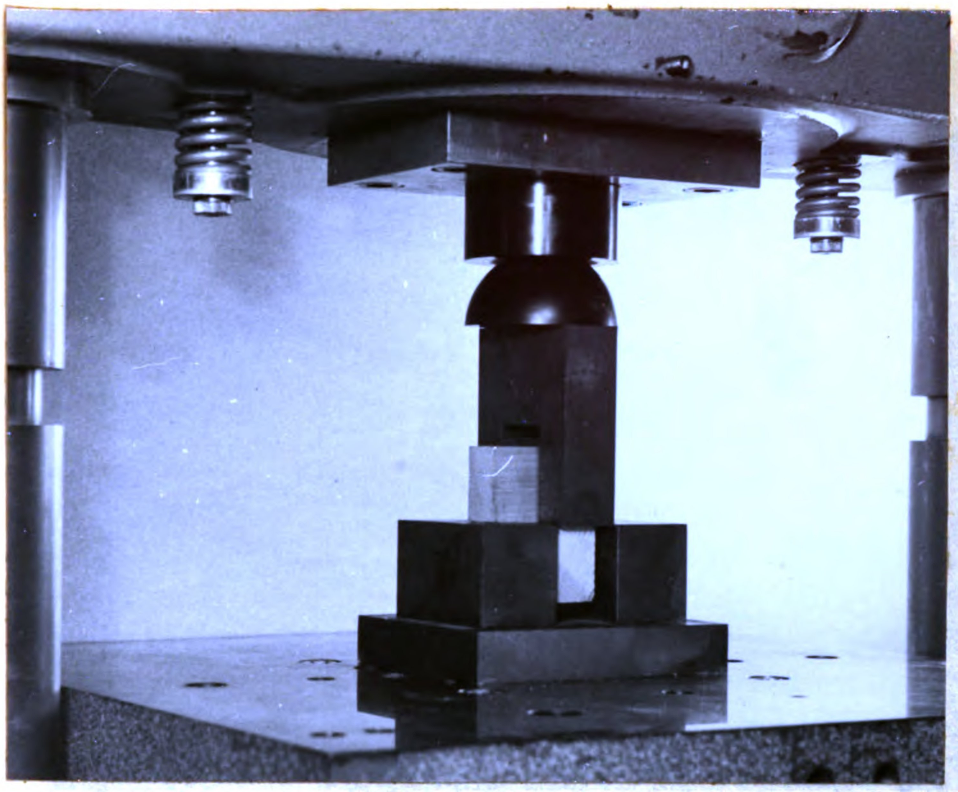


Fig. 9. Withdrawal specimen mounted in testing machine.

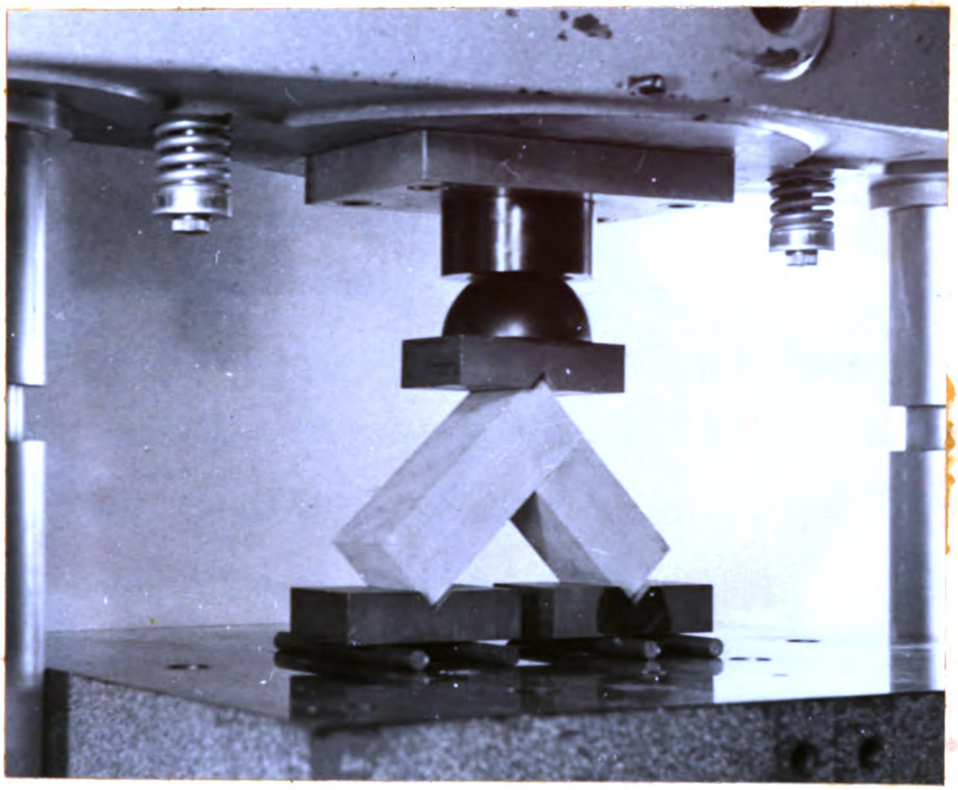


Fig. 10. Bending specimen mounted in testing machine.

irregular surface of the dowels due to the spiral groove. Although the high surface tension of mercury limits the size of the void it will fill to two-thousandths inch, the volumetric measurements by this method were considered sufficiently accurate.

Following the volumetric determination, the samples were oven-dried and their weights determined using a grammatic balance. The specific gravity as referred to in this paper is based on the oven dry weight and the volume at six percent moisture content. Specific gravity comparisons from other work should not be made unless they are made at the same conditions.

RESULTS AND ANALYSIS

Withdrawal Test

The effect of dowel penetration on joint strength can best be illustrated by the use of maximum load - dowel penetration curves and analysis of variance. For each dowel diameter class, the maximum load observations were plotted over the corresponding hole depth. A curve was plotted through the points. It will be noted that on most of the curves (Figs. 16-20, Appendix A) there is a point where the curve tends to level off. Below this point, the line approaches exact linearity. Because of this linearity, it was felt that regression calculations were unnecessary.

The joint failures in the withdrawal test were of two types; a failure in the glue line and complete dowel failure. The failure of the glue line (Fig. 11-A) resulted at all points below the leveling-off point on the curves. There was very little wood failure on these specimens. The failure which occurred in the joints above the break in the curves was complete dowel failure in tension (Fig. 11-B).

Analysis of variance computations for the maximum loads were then made for each of the dowel diameter classes. In all cases (Tables 3-7, Appendix A) there was a statistically

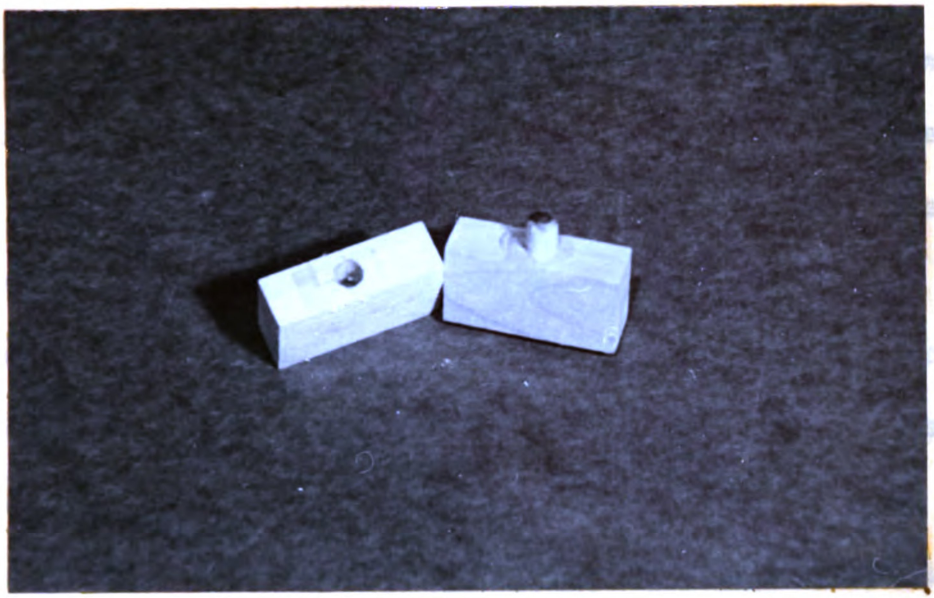


Fig. 11-A. Typical failure of withdrawal specimen in linear portion of curve.

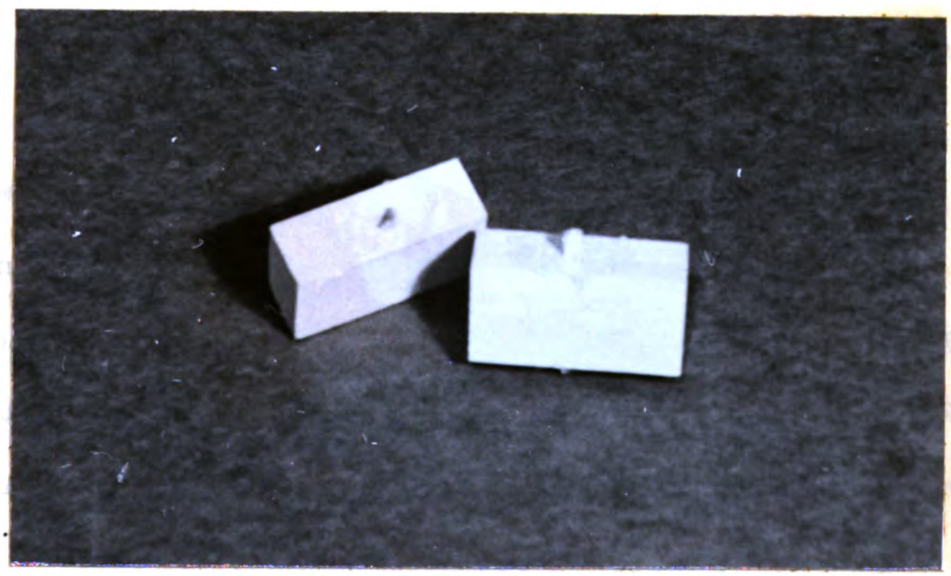


Fig. 11-B. Typical failure of withdrawal specimen above linear portion of curve.

significant difference at the one percent level between the maximum load averages. By the studentized range test, it was determined which of the individual averages were different from one another. For the withdrawal test, there was no significant difference between the one inch and 3/4 inch hole depths in the 1/4 and 5/16 inch diameter classes. In the 1/2 inch diameter class, there was no significant difference between the 6/4 and 5/4 inch hole depths. The results of the studentized range tests are summarized in Table 8, Appendix A. In the particular diameter classes where there was no significant difference between the hole depths, it was concluded that this was the point where hole depth ceased to be a factor governing joint strength.

Analysis of the data shows that one, and possibly two, hole depth classes should have been added to the experimental design for the 3/8 inch and 7/16 inch diameter classes. Had these depth classes been added, it is presumed that a break point in the curve would have been indicated.

Table 2. Equations, Correlations Coefficients, Standard errors of estimate, and Confidence limits for regression Curves.

Curve	Equation*	Standard Error of Estimate	Correlation Coefficient	Confidence limits
Withdrawal	Y=40 3456DL	88	.986	.978-.992
Bending	Y=335 3786DL	318	.872	.801-.919
Both tests	Y=295 1.09x	307	.881	.815-.925

* D= Dowel diameter
L= Dowel length
x= Maximum withdrawal load

A second effect which may be shown by further analysis of the data is that of glue line area as related to joint strength. Since the curves of load over hole depth indicate that there is a point where depth is no longer a factor in joint strength, it is surmised that a plot of load over glue line area would be similar. Therefore, only those values which fell on the curves below the break in the curve were considered for the glue line area calculations. The glue line area for each combination of dowel length and dowel diameter was calculated. The corresponding maximum loads were plotted over these areas. By the method of linear regression, a line was plotted among the points (Fig. 12) and a correlation coefficient was calculated. The correlation coefficient as well as the standard error of estimate for the linear equation and the confidence limits of the correlation coefficient are summarized in Table 2. The regression was tested for linearity by analysis of variance (Table 9, Appendix A) and was found to be highly significant.

Bending Test

The analysis of the bending test followed the same procedure as the analysis of the results of the withdrawal test. The maximum loads were plotted over the corresponding dowel penetrations and the curves were drawn among the points. Once again, because of the linearity of the points, regression calculations were omitted. Analysis of variance computations were made and the individual maximum load averages for the various hole depth classes were tested using the studentized range test.

The resulting failures of the bending test were similar to those in the withdrawal test. In the linear portion of the curve, there was failure in the glue line. It was noted that the initial glue line failure occurred in the member which had the dowel perpendicular to the grain. Complete dowel failure occurred in the samples above the

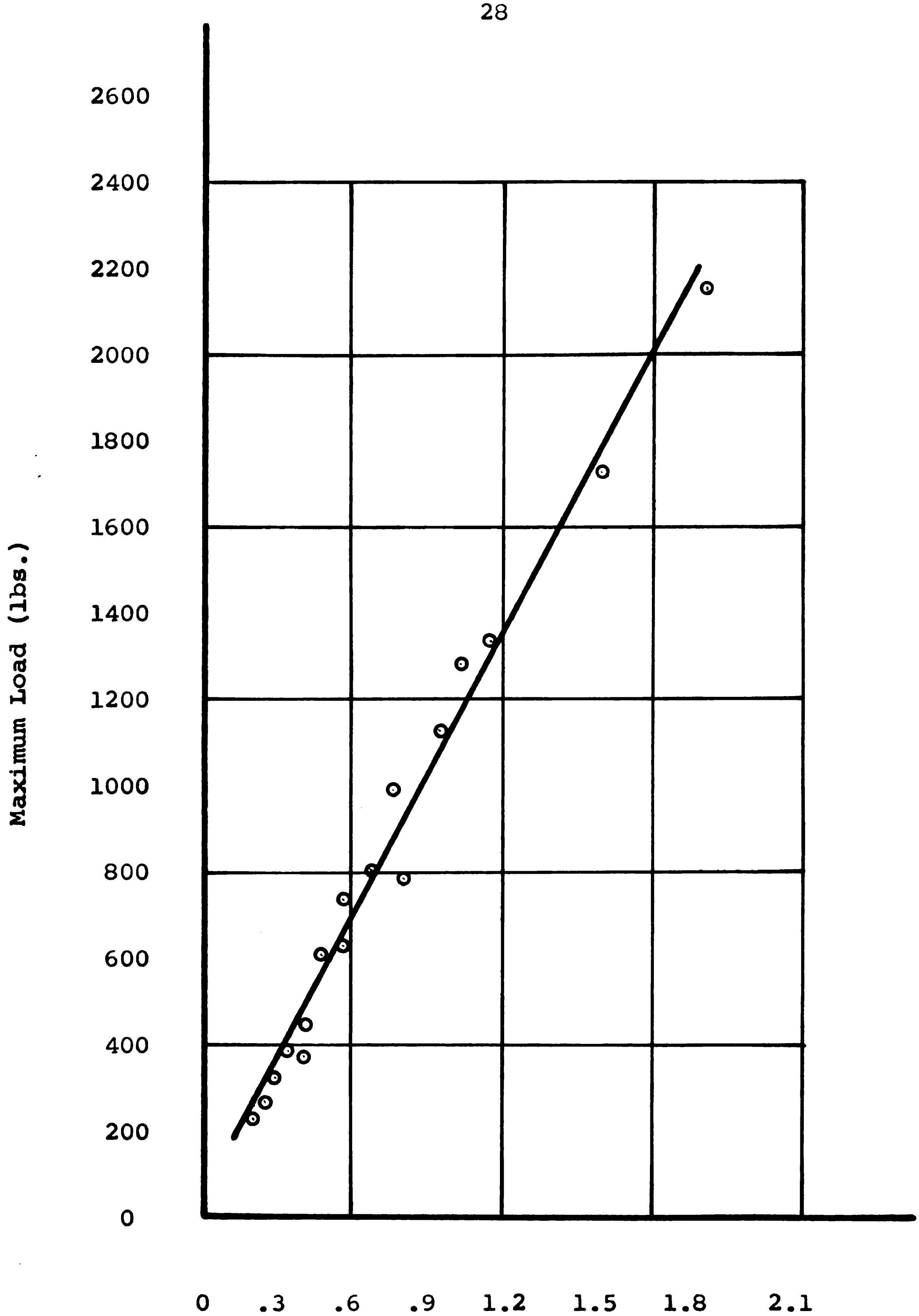


Fig. 12. Regression of maximum load over glue line area for withdrawal test.

linear portion of the curve. It will be noted (Fig. 13-A) that there is evidence of a shearing failure parallel to the grain in that portion of the member between the end of the dowel and the end of the member. Careful inspection of the bending specimen during the course of loading showed that this shear failure occurred after a maximum load had been attained.

For the bending test, there was no significant difference between the one inch and 3/4 inch hole depths in the 1/4 inch diameter class. However, in the 5/16 inch diameter class, there was no difference between the one inch and 3/4 inch hole depths or between the 3/4 and 1/2 inch hole depths. A similar situation will be noted (Table 15, Appendix B) in the 1/2 inch diameter class. Compared to the withdrawal test, the results of this analysis are rather erratic and inconclusive. However, a similar trend may be noted by comparing the curves of the two tests.

In the analysis of the effect of glue line area on joint strength, the maximum loads were plotted over the same areas used in the withdrawal curve (Fig. 14). The regression equation and correlation coefficient were computed. These and their standard errors are shown in Table 2. The regression was tested for linearity and was found to be highly significant.

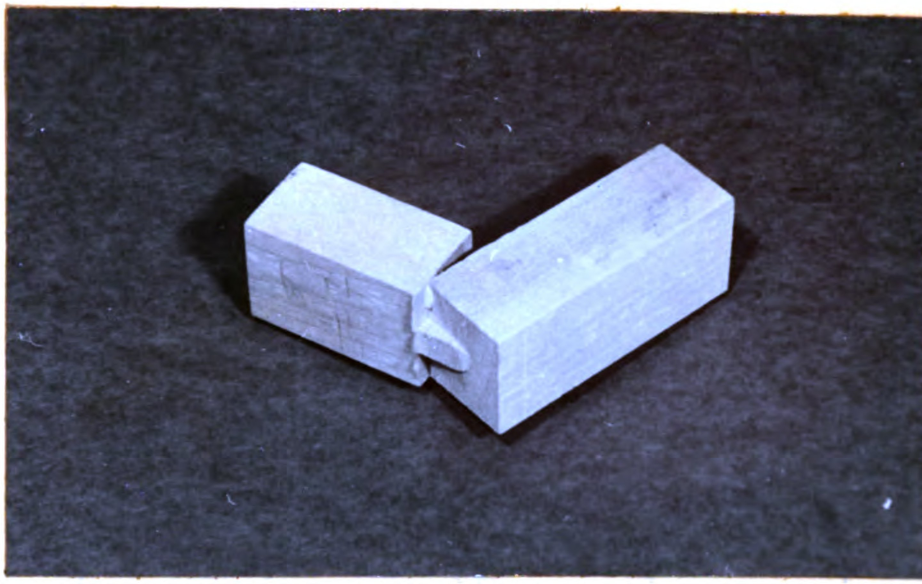


Fig. 13-A. Typical failure of bending specimen in linear portion of curve. Note shear failure parallel to grain on end of member.

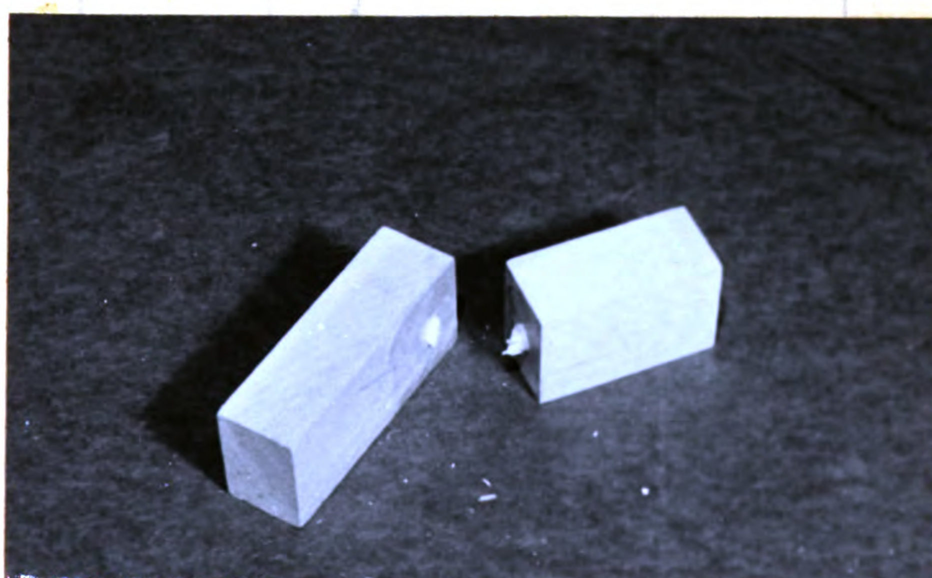


Fig. 13-B. Typical failure of bending specimen above linear portion of curve.

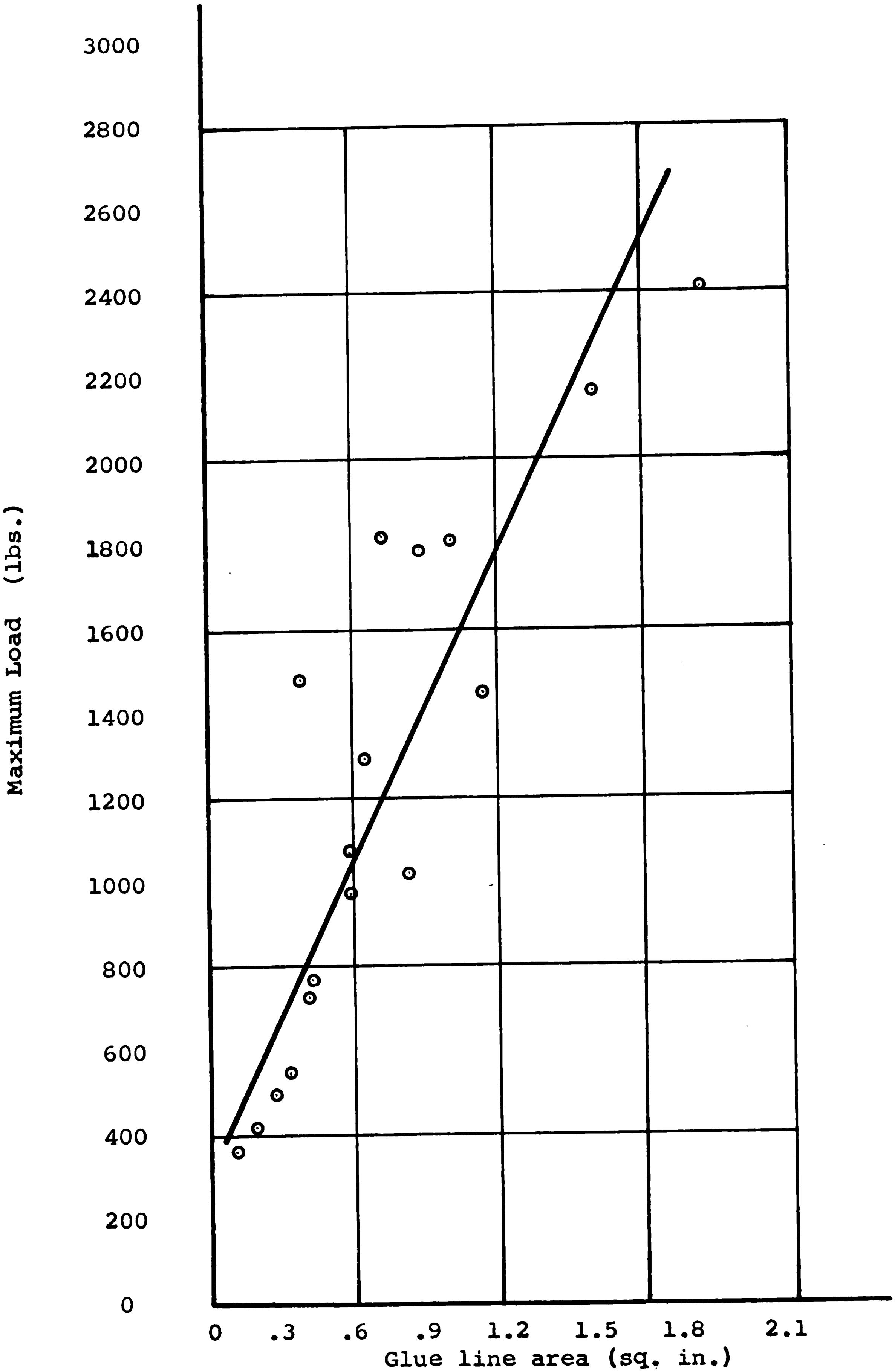


Fig. 14. Regression of maximum load over glue line area for bending test.

Correlation of the Two Tests

One of the primary objectives of this study was to determine if the withdrawal test of dowel joints was a good indication of the strength of the same joint subjected to the stresses encountered in its practical application. Since the dowels used in the two tests were matched specimens, it was felt that a linear regression curve of the two test types would show the correlation if it existed.

Once again, the loads used in the computation of the regression equation were those which occurred before the flattening of the maximum load - hole depth curves. The maximum load of the bending test was plotted over the maximum load of the withdrawal test (Fig. 15). The regression equation and the correlation coefficient was calculated. The standard error of estimate and confidence limits were calculated and are listed in Table 2. The regression was tested for linearity and found to be highly significant (Table 18, Appendix C).

Specific Gravity Determination

The specific gravity samples were analyzed to determine the variability between the two tests and between the five dowel diameters. The range of the specific gravity

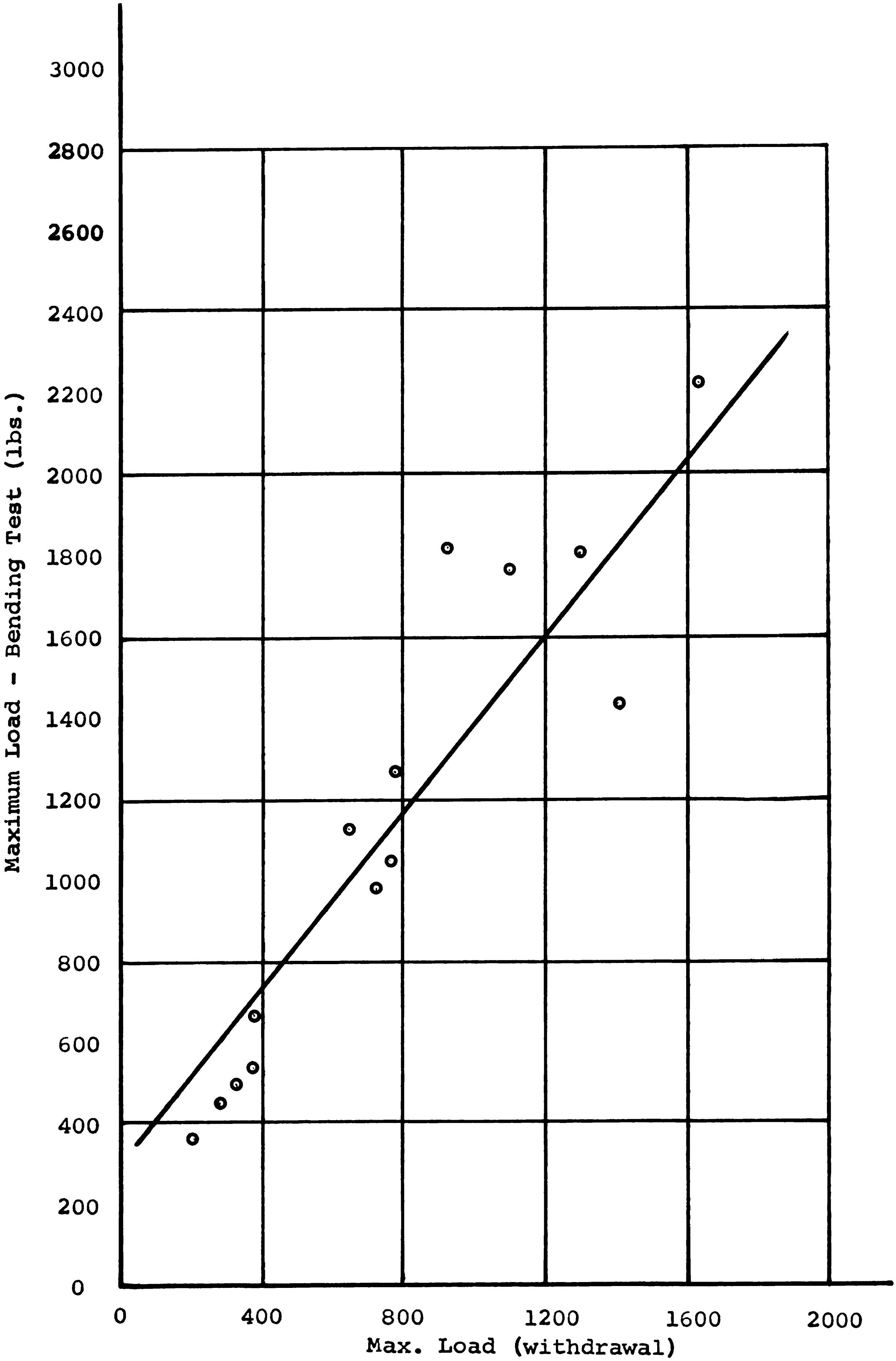


Fig. 15. Regression of bending test over withdrawal test.

was from a low of 0.586 to a high of 0.884. The average of all the specimens was 0.744. An analysis of variance (Table 17, Appendix C) showed that there was not a sif- nificant difference between the two tests. It also showed no significant difference between the diameter classes.

DISCUSSION

The results of the two tests seem to indicate that two of the factors that determine the strength of a dowel joint are the glue line area and the strength of the wood dowel.

The analysis of the individual diameter classes showed that, for a given diameter of dowel, there was a high correlation between maximum load and hole depth. This relationship was linear up to the point where failure of the dowel occurred. From this point, there was no significant increase in the maximum load required to bring about failure in the joint. This phenomenon occurred in nearly all of the diameter classes. An increase in dowel diameter resulted in an increase in the ultimate strength of the joint. From this analysis, it was possible to make an estimate of what the hole depth should be in order to develop the full strength of the dowel. The hole depth should be approximately four to six times the diameter of the dowel. Naturally, if the hole depths in the two members being joined were not equal, this ratio would apply to the shallowest hole.

Since glue line area is a function of diameter and length, the correlation between maximum load and glue line

area was calculated. Glue line area in this paper refers to that area in which the surfaces of the dowel and the dowel hole are in contact. It omits the area at the bottom of the dowel hole. For simplicity, the glue line area was computed by calculating the cylindrical area of the dowel. It was assumed that the spiral grooves performed in the same manner as the surface of the dowel.

The results show that below the point of dowel failure, there is a linear relationship between the area of the glue line and maximum load. For example, a 1/4 inch dowel 3/4 inch long and a 3/8 inch dowel 1/2 inch long have the same surface area. The maximum loads of the four test specimens for this 1/4 inch class averaged 656 pounds while the average for this 3/8 inch class averaged 737 pounds. These averages are for the withdrawal test. For the same two dowels in the bending test, the averages were 1094 pounds for the 1/4 inch class and 989 pounds for the 3/8 inch class. Within the two tests, the loads for these two dowel classes are well within the one-sigma limits of confidence.

Because of the linear relationship between the load and glue line area, it does not seem practical to express the strength of the joint in terms of stress on the dowel. As the glue line area increases, the load at failure increases. Consequently, the stress does not change.

Yavorsky (15) and Marra (5) in their investigations into factors affecting glue line strength, recommend that load at failure, rather than stress, be employed as the criterion of joint strength. This recommendation was made partly because it was found that non-uniform stress distributions occurred in the test specimens which they employed. It is the authors opinion that these recommendations be extended to include the dowel joint.

The results of the bending test compared very favorably with those of the withdrawal test. In all of the curves plotted, the points for the bending test exhibited more scatter than the points for the withdrawal test. However, the correlation coefficients for the bending test were excellent and very highly significant.

In this study, no attempt was made to define the complex stresses which evolve in the failure of the bending specimen. However, an attempt was made to determine if the withdrawal test was a good measure of the strength of the joint when subjected to these complex stresses. The high correlation between the tests showed that the withdrawal test gives a good estimate of the strength of the dowel joint under certain stresses encountered in its practical application.

Further study as to the exact effect of the spiral groove of the dowel might be made. It is now assumed that the spiral groove aids in the movement of the adhesive. The effect of the slope of the groove and the depth of the groove should be investigated. It would be assumed that an optimum groove slope and depth would produce a joint of maximum strength. Certain machining problems would have to be considered in a study of this type.

CONCLUSIONS

Several conclusions may be drawn from the results and analysis of this study.

1. The withdrawal test gives a good measure as to the strength of a dowel joint.
2. The use of the withdrawal specimen is highly recommended. Its simplicity of design makes it a more desirable test of dowel joint strength.
3. For a given dowel diameter, there is a limit to the effect of hole depth on joint strength. The final determinant of joint strength is the strength of the wood dowel.
4. Until the strength of the wood is reached, there is a linear relationship between glue line area and maximum load.
5. In order to develop maximum joint strength, the depth of the dowel hole should be four to six times the diameter of the dowel.
6. Maximum load at failure rather than stress should be used as a criterion of dowel joint strength.

Appendix A

Withdrawal Test

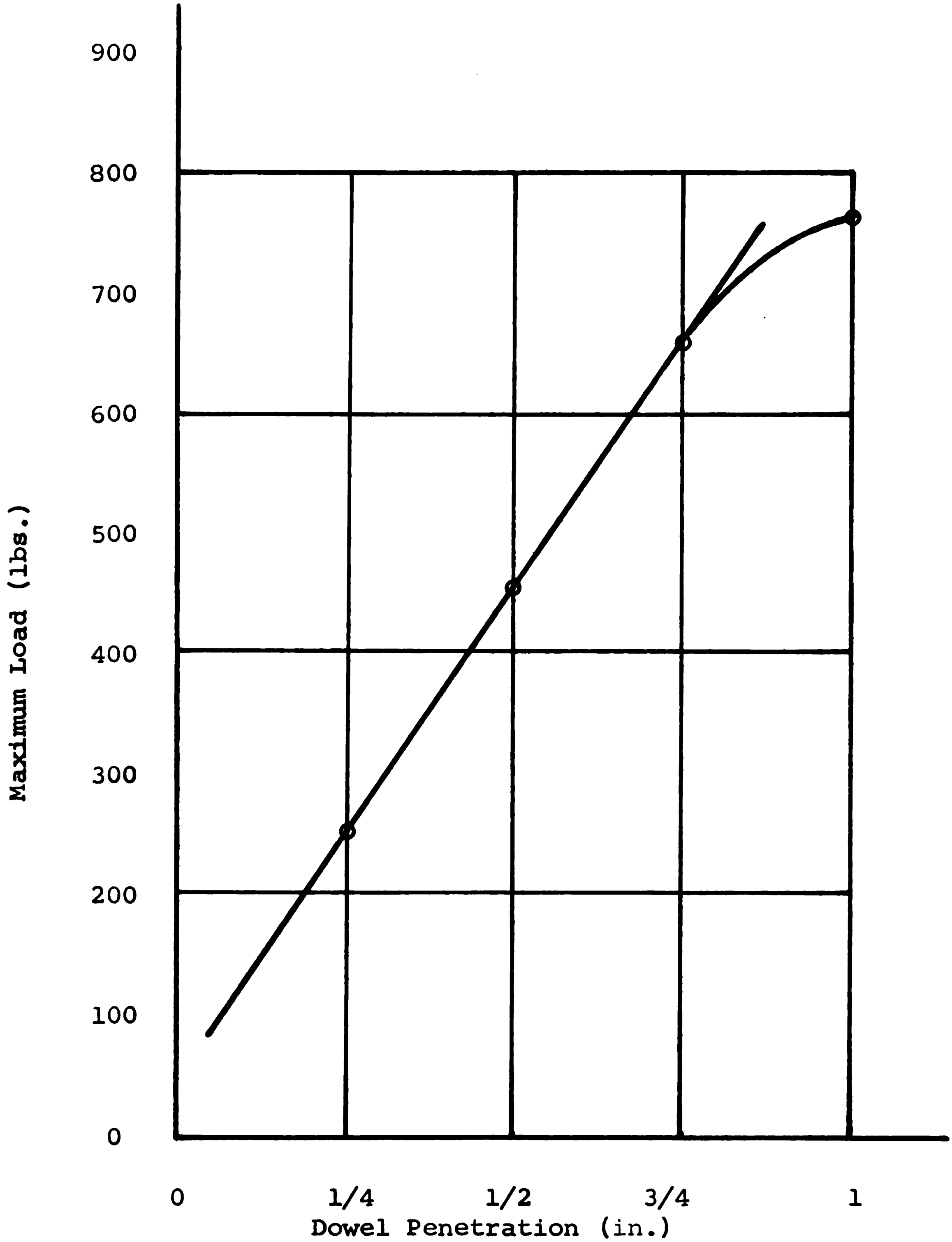


Fig. 16. Maximum load over dowel penetration for 1/4 inch diameter class.

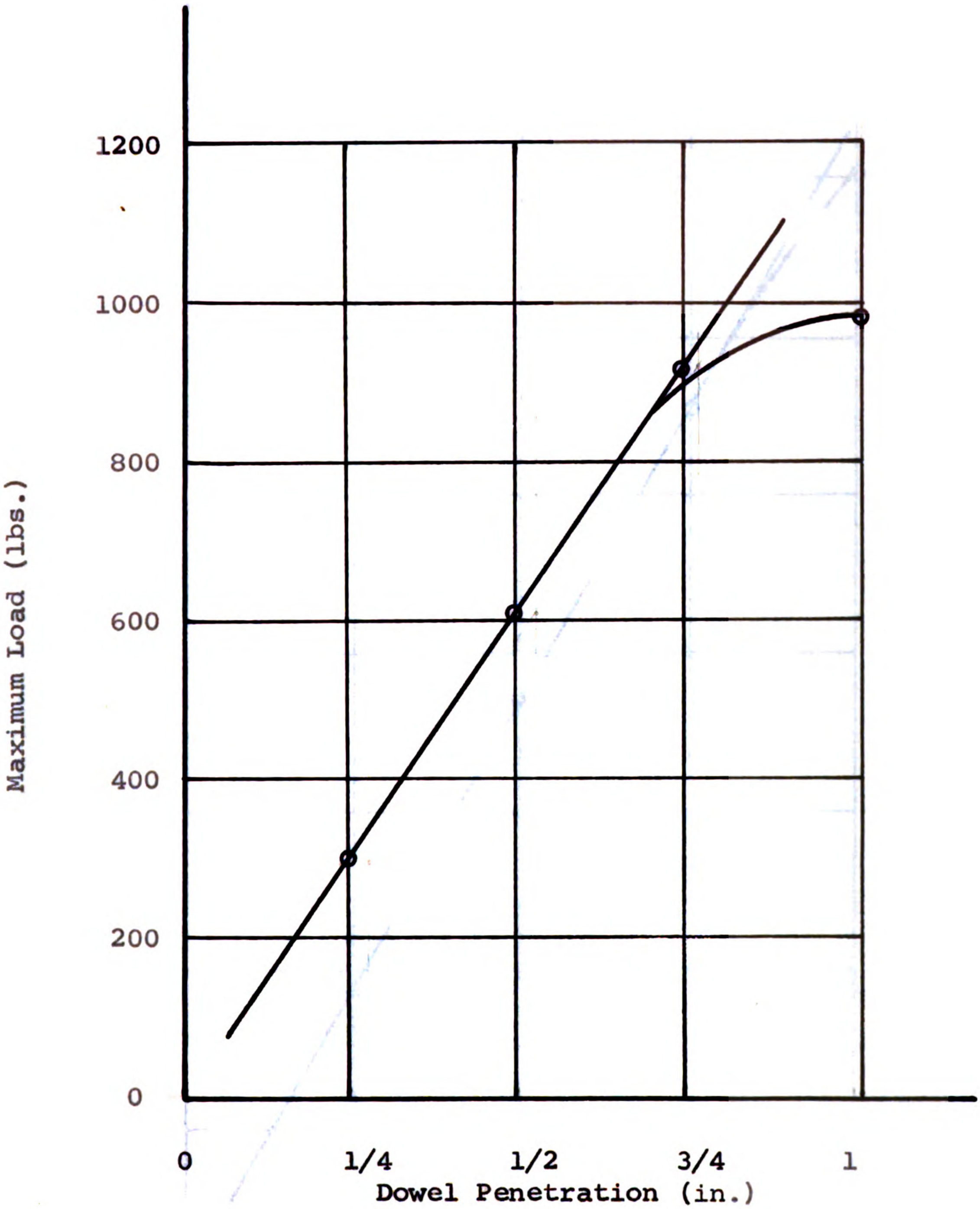


Fig. 17. Maximum load over dowel penetration for 5/16 inch diameter class.

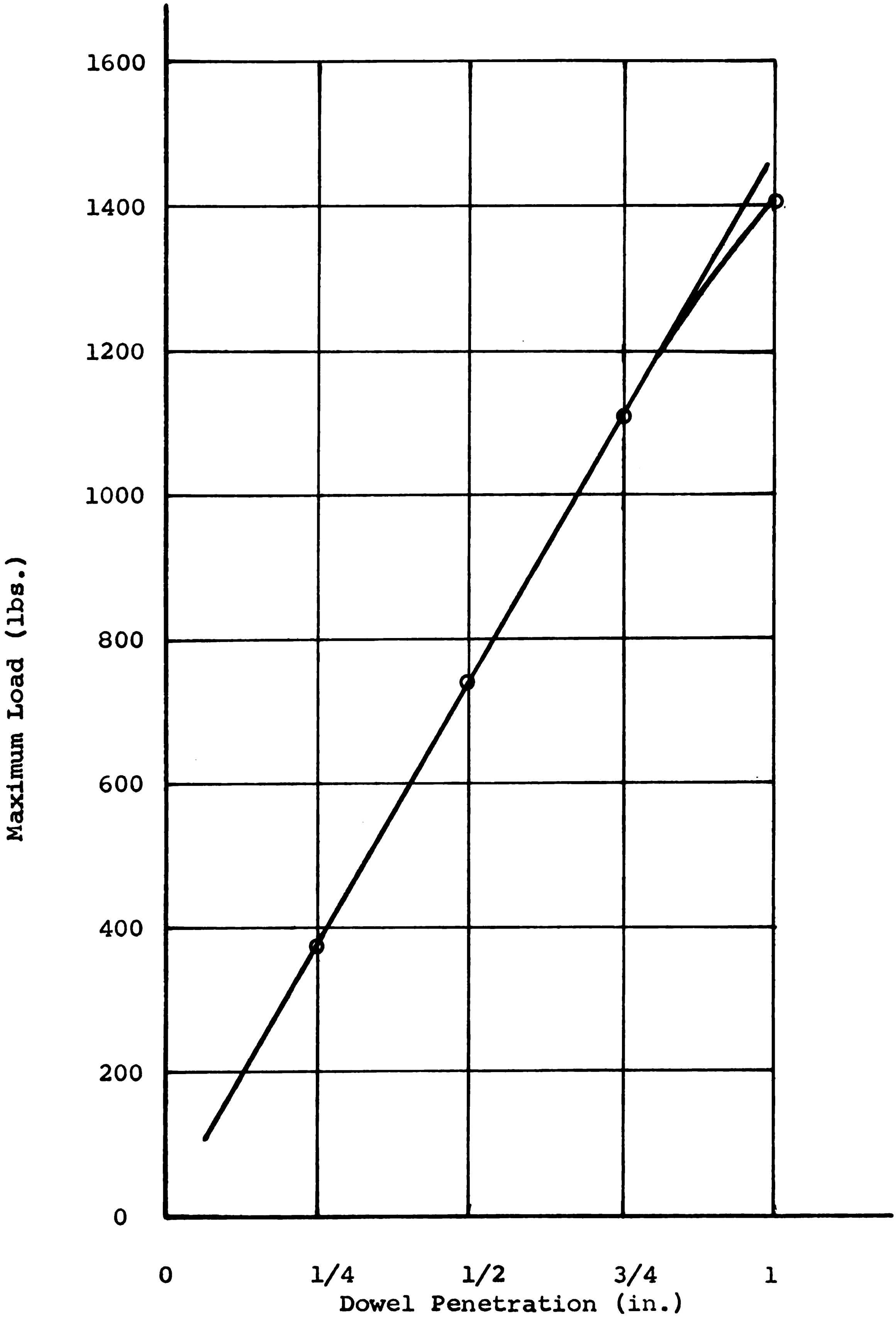


Fig. 18. Maximum load over dowel penetration for 3/8 inch diameter class.

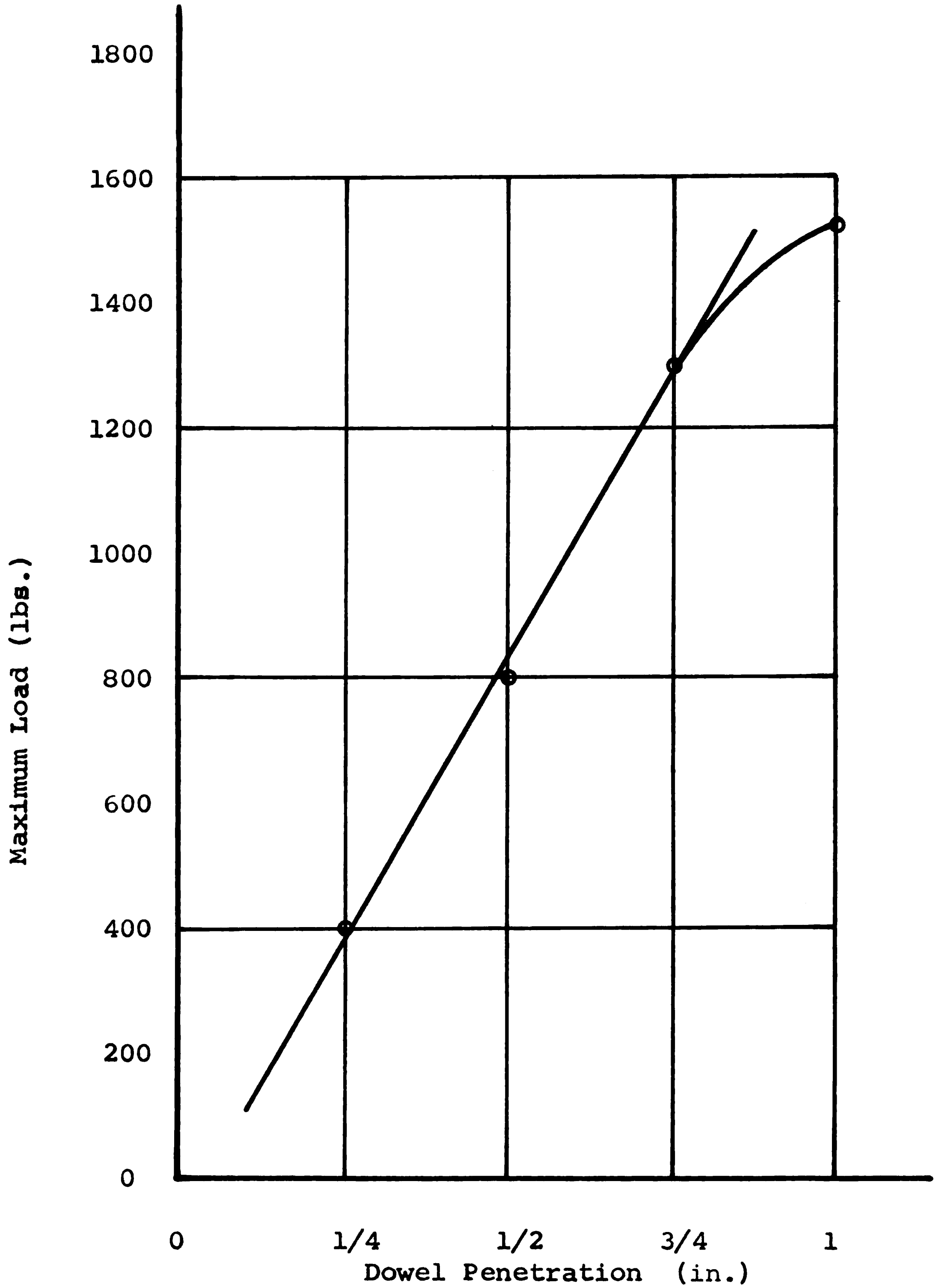


Fig. 19. Maximum load over dowel penetration for 7/16 inch diameter class.

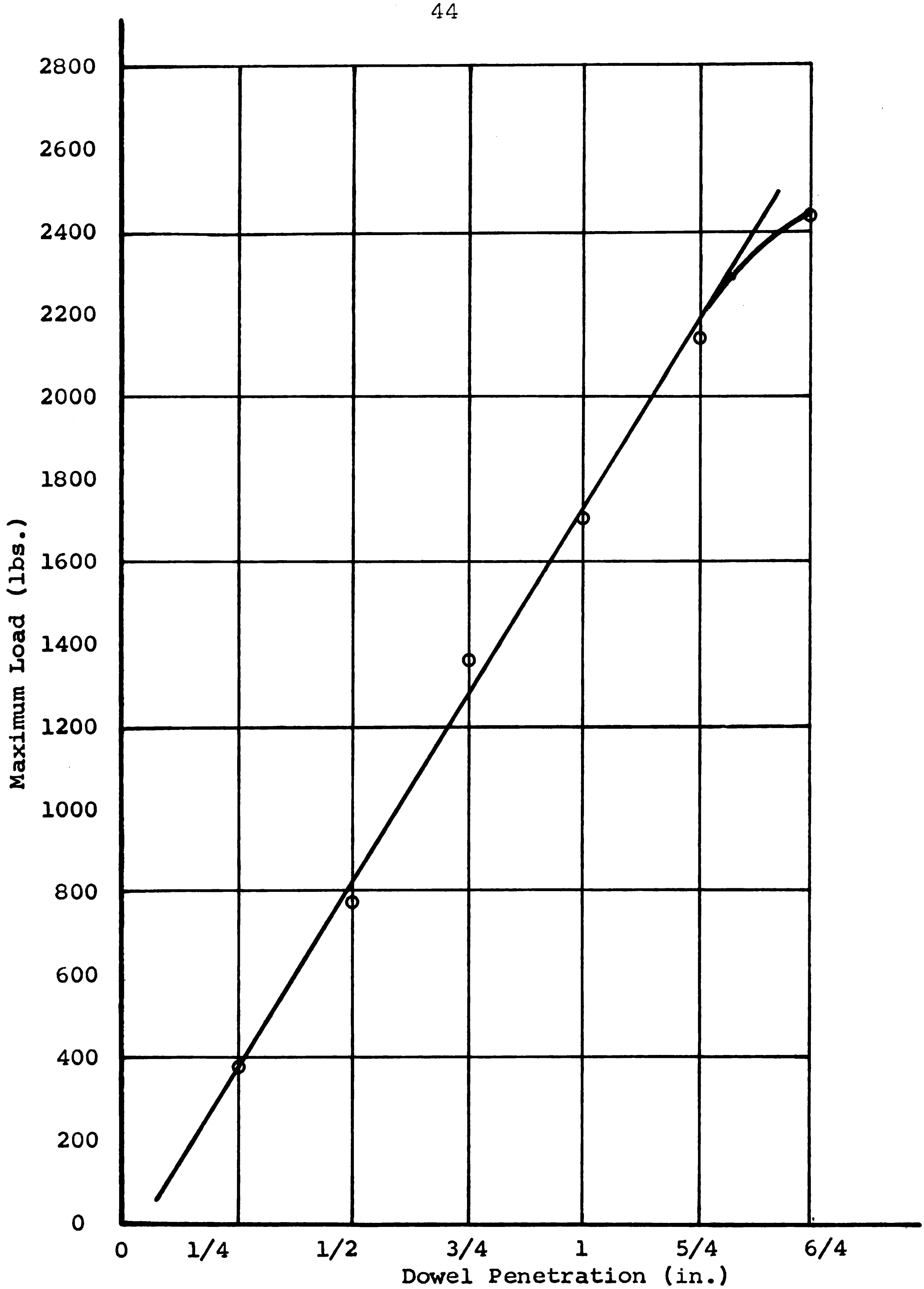


Fig. 20. Maximum load over dowel penetration for 1/2 inch diameter class.

Table 3. Analysis of variance of the 1/4 inch dowel diameter class for the withdrawal test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	622,356			
Between Classes	3	587,941	195,980	68.3**	5.95
Within Classes	12	34,415	2,868		

Table 4. Analysis of variance of the 5/16 inch dowel diameter class for the withdrawal test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	1,230,400			
Between Classes	3	1,209,388	403,129	230**	5.95
Within Classes	12	21,012	1,751		

** Indicates significance at 1% level.

Table 5. Analysis of variance of the 3/8 inch dowel diameter class for the withdrawal test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	2,531,719			
Between Classes	3	2,488,267	829,422	229**	5.95
Within Classes	12	43,452	3,621		

Table 6. Analysis of variance of the 7/16 inch dowel diameter class for the withdrawal test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	3,418,400			
Between Classes	3	3,327,863	1,109,288	147,023**	5.95
Within Classes	12	90,537	7,545		

** Indicates significance at 1% level.

Table 7. Analysis of variance of the 1/2 inch dowel diameter class for the withdrawal test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	23	12,992,924			
Within Classes	5	12,527,780	2,505,556	96,960**	5.09
Between Classes	18	465,144	25,841		

** Indicates signifance at 1% level.

Table 8. Results of studentized range test of maximum load averages of withdrawal specimens.

Dia. Class	Hole Depth Class (inches)	Hole Depth Class (inches) 5/4	1	3/4	1/2	1/4
	1	---	-	N.S.	*	*
1/4	3/4	---	-	---	*	*
	1/2	---	-	---	---	*
	1	---	-	N.S.	*	*
5/16	3/4	---	-	---	*	*
	1/2	---	-	---	---	*
	1	---	-	*	*	*
3/8	3/4	---	-	---	*	*
	1/2	---	-	---	---	*
	1	---	-	*	*	*
7/16	3/4	---	-	---	*	*
	1/2	---	-	---	---	*
	6/4	N.S.	*	*	*	*
	5/4	---	*	*	*	*
1/2	1	---	-	*	*	*
	3/4	---	-	---	*	*
	1/2	---	-	---	---	*

* Indicates a significant difference at 1% level between hole depth classes.

N.S. Indicates no significant difference.

Table 9. Analysis of variance test for linearity of the regression equation of maximum load over glue line area (withdrawal test).

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	67	18,410,804			
Regression	1	17,895,301	17,895,301	2,291**	7.04
Deviations from regression	66	515,503	7,810		

** Indicates regression is significant at 1% level.

Appendix B

Bending Test

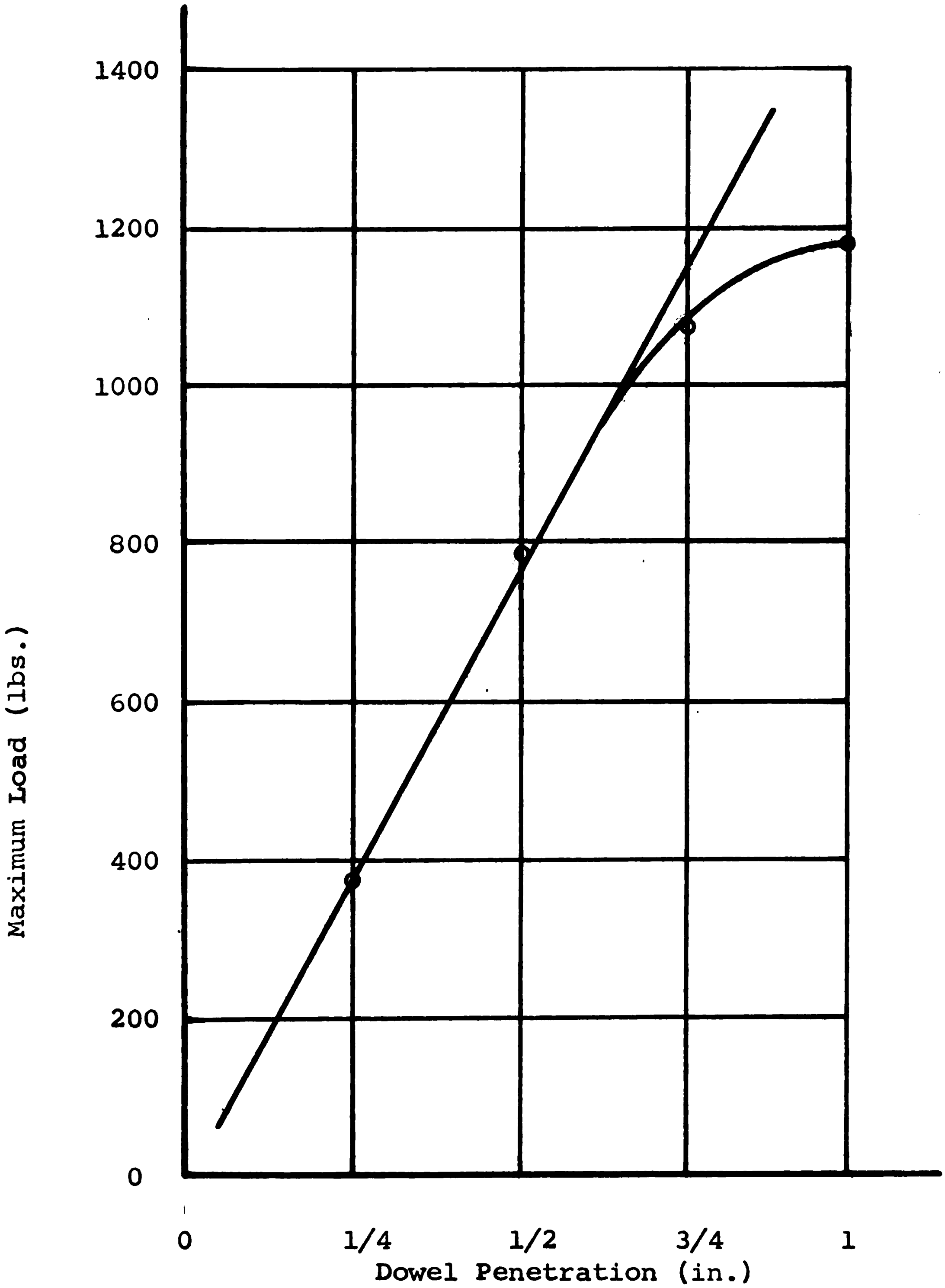


Fig. 21. Maximum load over dowel penetration for 1/4 inch diameter class.

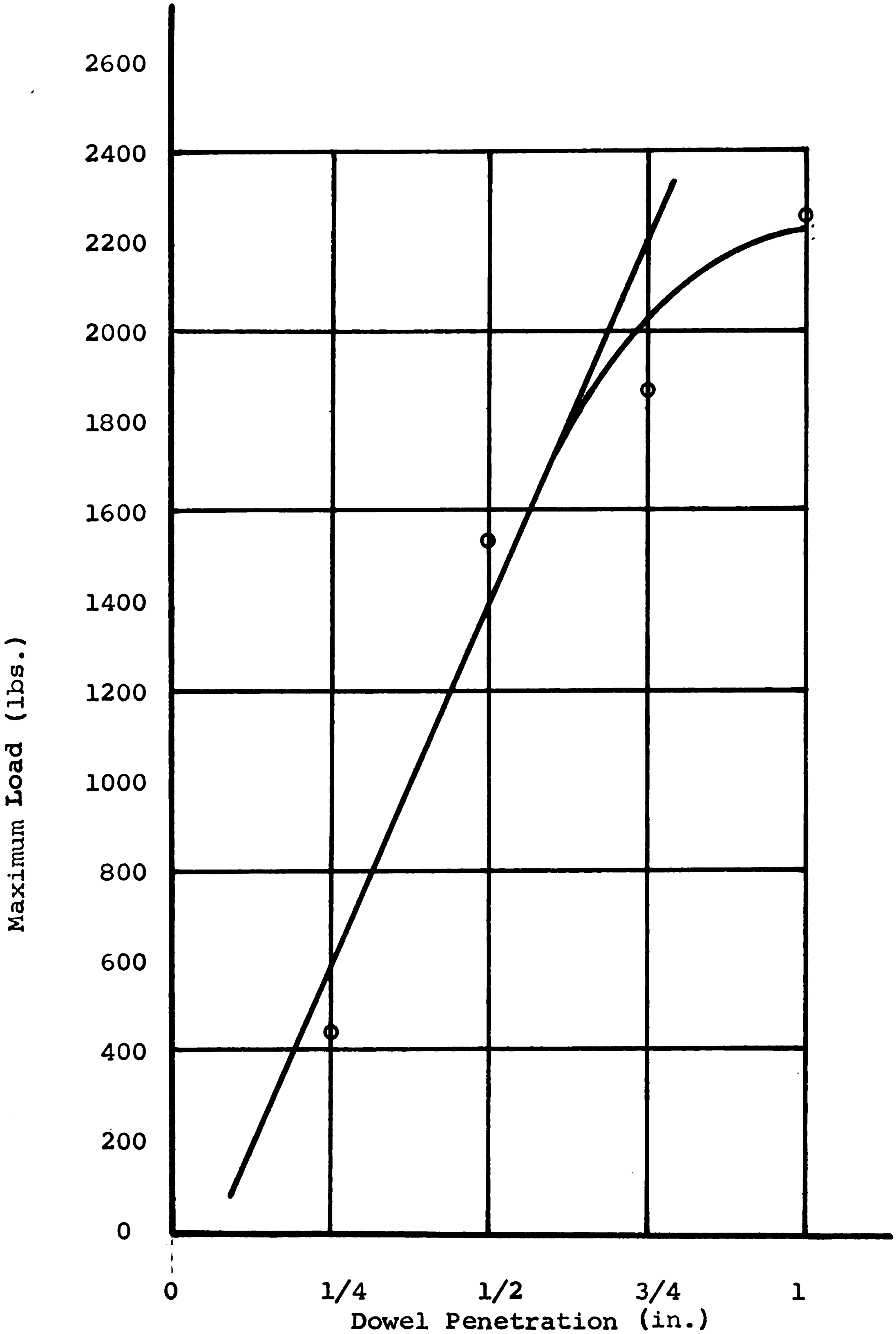


Fig. 22. Maximum load over dowel penetration for 5/16 inch diameter class.

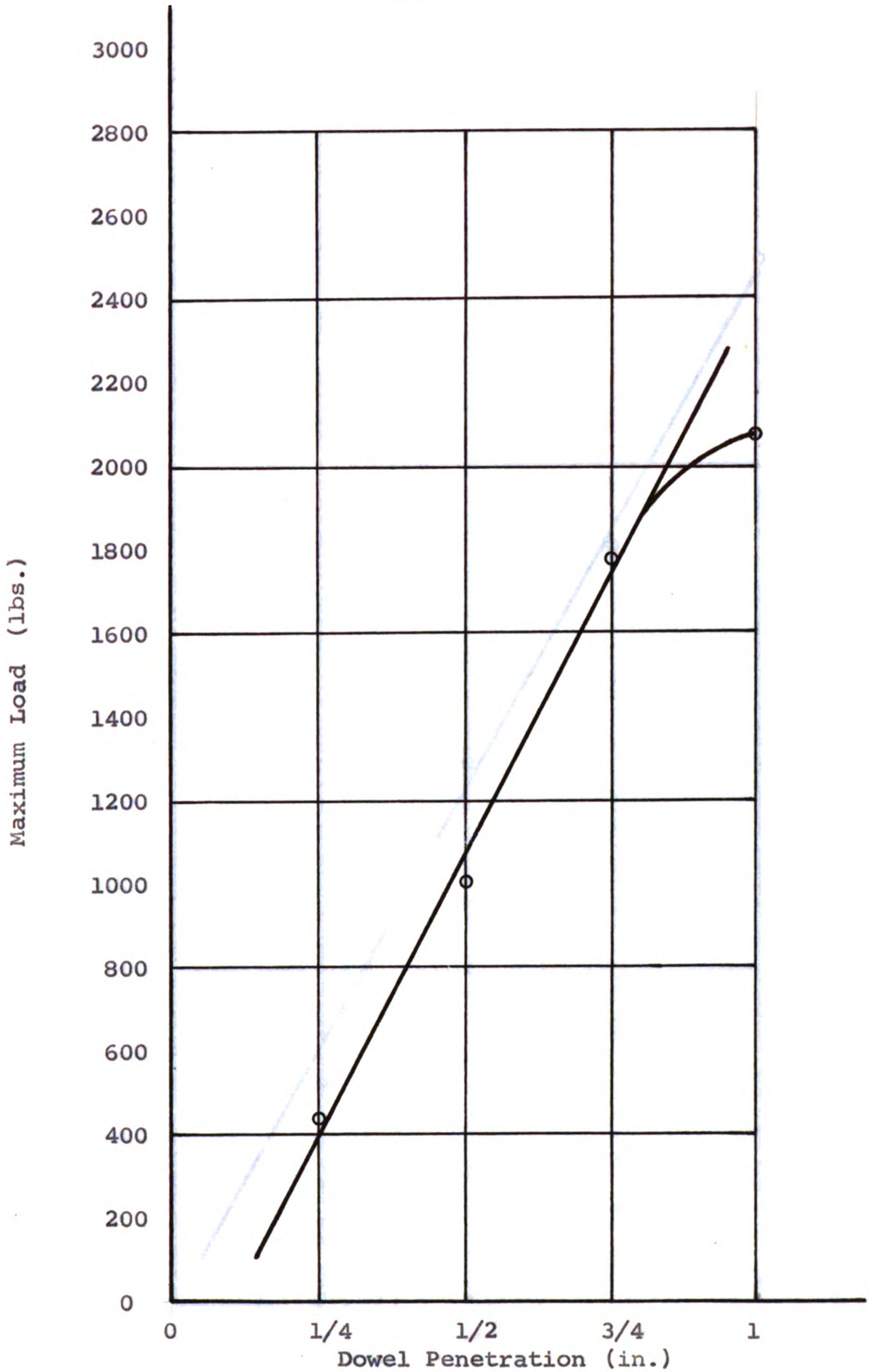


Fig. 23. Maximum load over dowel penetration for 3/8 inch diameter class.

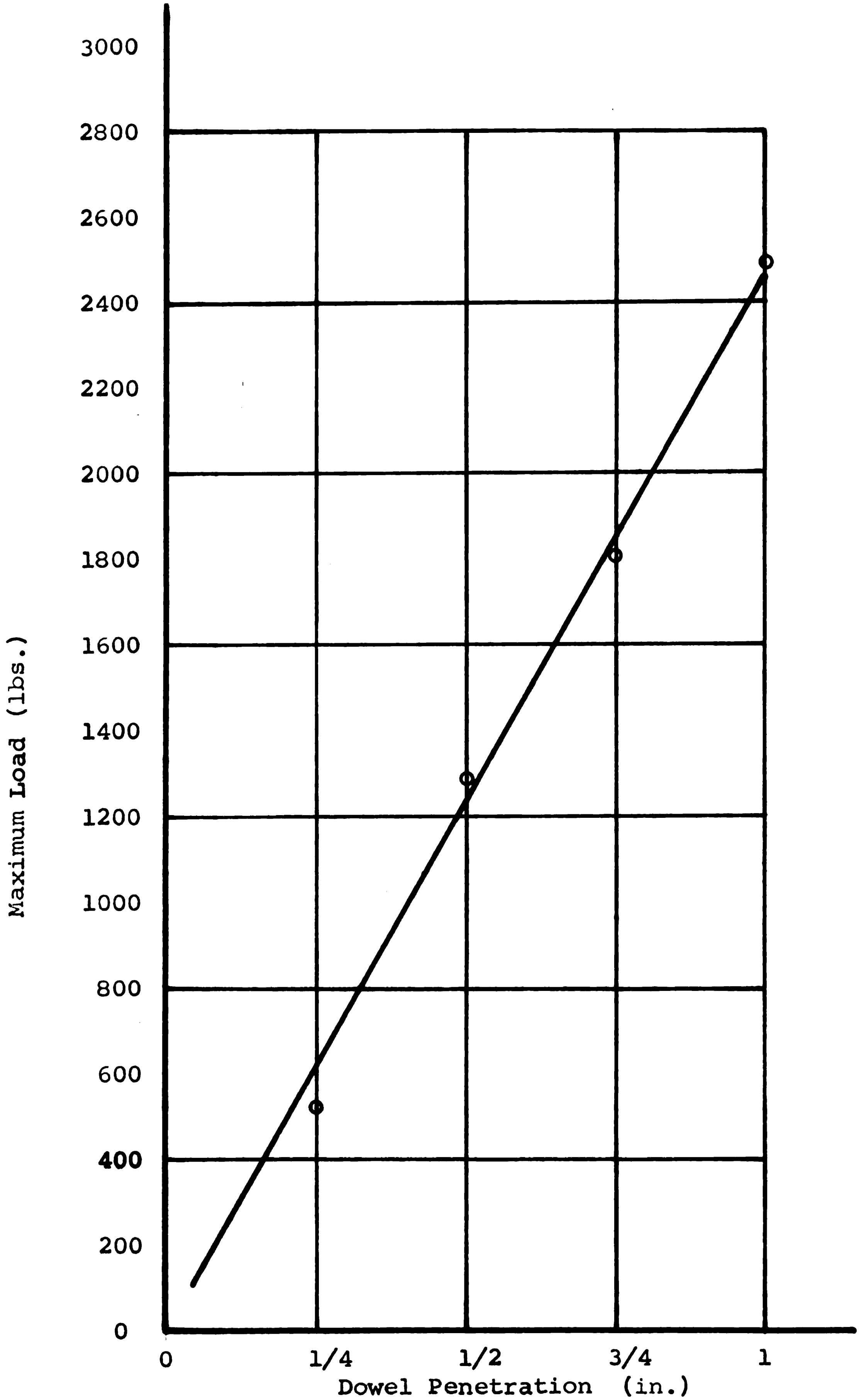


Fig. 24. Maximum load over dowel penetration for 7/16 inch diameter class.

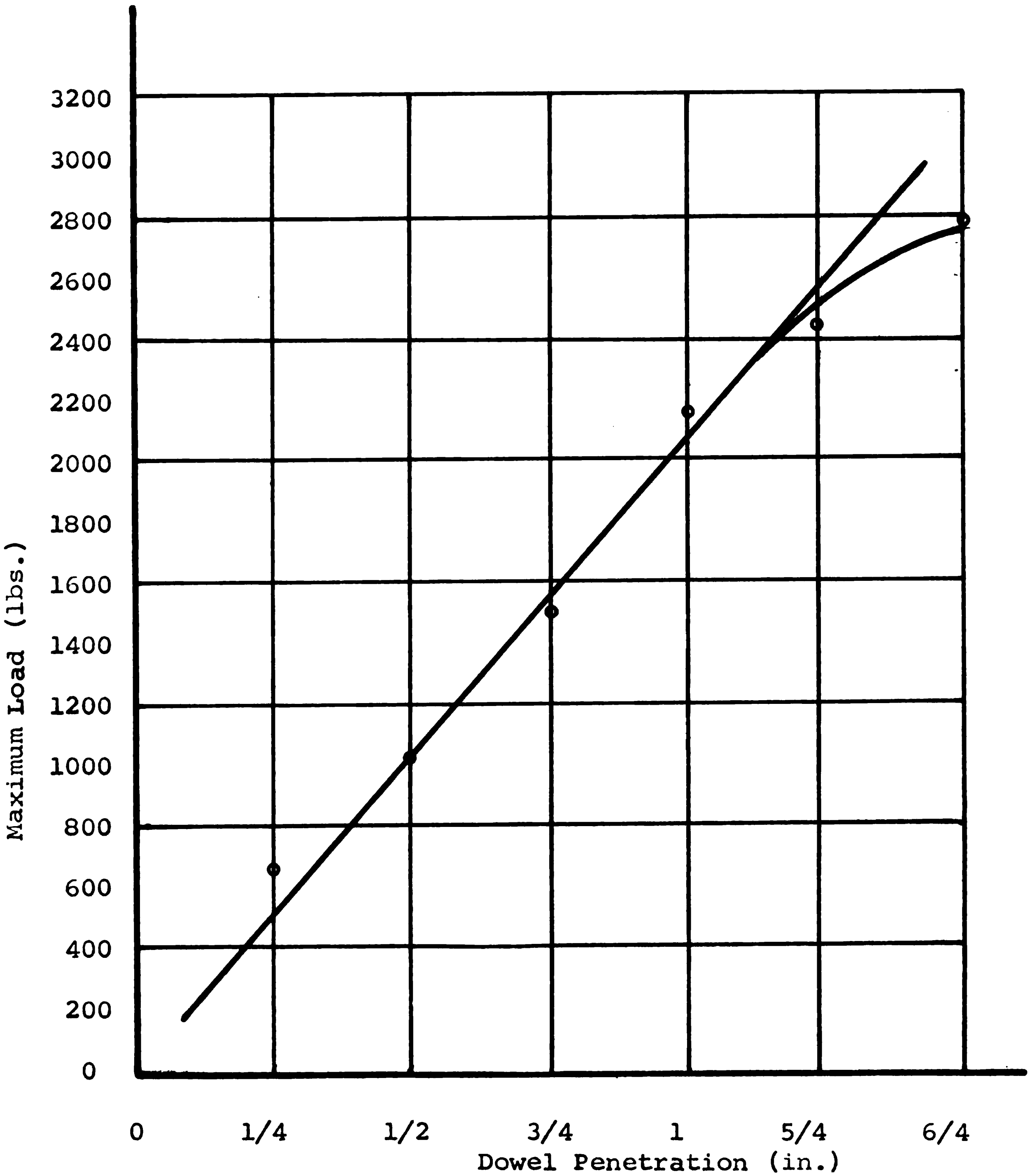


Fig. 25. Maximum load over dowel penetration for 1/2 inch diameter class.

Table 10. Analysis of variance of the 1/4 inch dowel diameter class for the bending test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	1,651,900			
Between Classes	3	1,621,325	540,442	212**	5.95
Within Classes	12	30,575	2,548		

Table 11. Analysis of variance of the 5/16 inch dowel diameter class for the bending test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	7,754,825			
Between Classes	3	7,250,463	2,416,821	58**	5.95
Within Classes	12	504,362	42,030		

** Indicates significance at 1% level.

Table 12. Analysis of variance of the 3/8 inch dowel diameter class for the bending test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	6,453,494			
Between Classes	3	6,406,419	2,135,473	544**	5.95
Within Classes	12	47,075	3,923		

Table 13. Analysis of variance of the 7/16 inch dowel diameter class for the bending test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	15	9,420,148			
Between Classes	3	8,585,154	2,861,718	41**	5.95
Within Classes	12	834,994	69,583		

** Indicates significance at 1% level.

Table 14. Analysis of variance of the 1/2 inch dowel diameter class for the bending test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	23	16,059,396			
Between Classes	5	15,341,909	3,068,387	77**	5.09
Within Classes	18	717,487	39,860		

** Indicates significance at 1% level.

Table 15. Results of studentized range test of maximum load averages of bending specimens.

Dia. Class	Hole Depth Class (inches)	Hole Depth Class (inches) 5/4	1	3/4	1/2	1/4
	1	---	-	N.S.	*	*
1/4	3/4	---	-	---	*	*
	1/2	---	-	---	---	*
	1	---	-	N.S.	*	*
5/16	3/4	---	-	---	N.S.	*
	1/2	---	-	---	---	*
	1	---	-	*	*	*
3/8	3/4	---	-	---	*	*
	1/2	---	-	---	---	*
	1	---	-	*	*	*
7/16	3/4	---	-	---	N.S.	*
	1/2	---	-	---	---	*
	6/4	N.S.	*	*	*	*
	5/4	---	N.S.	*	*	*
1/2	1	---	-	*	*	*
	3/4	---	-	---	*	*
	1/2	---	-	---	---	N.S.

* Indicates a significant difference between hole depth classes.

N.S. Indicates no significant difference.

Table 16. Analysis of variance test for linearity of the regression equation of maximum load over glue line area (bending test).

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	67	28,251,963			
Regression	1	21,471,491	21,471,491	209**	7.04
Deviations from regression	66	6,780,472	102,734		

** Indicates significance of regression at 1% level.

Appendix C

Specific Gravity and Correlation of Tests

Table 17. Analysis of variance of the specific gravity of the dowels in the two tests and in the five diameter classes.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	43	0.187,158			
Diameters	4	0.061,565	0.015,391	1.63	6.39
Tests	1	0.000,250	0.000,250	0.03	7.71
D x T	4	0.037,704	0.009,426	3.65*	2.65
Error	34	0.087,639	0.002,578		

* Indicates significance at 5% level.

Table 18. Analysis of variance test for linearity of the regression equation of bending test over withdrawal test.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$
Total	67	28,251,963			
Regression	1	21,923,523	21,923,523	229**	7.04
Deviations from regression	66	6,328,440	95,885		

** Indicates significance at 1% level.

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