

DOCTORAL DISSERTATION SERIES

Publication No. : 11,322

AUTHOR: Alan Ateo Marra, Ph. D., 1955
University of Michigan

TITLE: AN ANALYSIS OF A WOOD ADHESIVE
TEST METHOD USING A CROSS-LAP
SPECIMEN

University Microfilms, Ann Arbor, Michigan

AN ANALYSIS OF A WOOD ADHESIVE TEST METHOD
USING A CROSS-LAP SPECIMEN

by
Alan A. ^{T=0}Marra

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1954

Doctoral Committee:

Associate Professor Fred E. Dickinson, Chairman
Assistant Professor Wallace W. Gardner
Associate Professor Richard T. Liddicoat
Associate Professor Stephen B. Freston

AN ANALYSIS OF A WOOD ADHESIVE TEST METHOD USING A CROSS-LAP SPECIMEN

by Alan A. Marra

The cross-lap specimen, by virtue of its geometry and manner of stressing, appeared to possess important advantages for evaluating wood adhesives under conditions which reflect performance as well as strength. This research dealt with a study of the characteristics of the specimen with a view to its possible use in a test method. Its sensitivity was particularly investigated with regard to a number of factors which normally influence observed bond strengths, and these covered wood, specimen, adhesive, fabrication and testing variables. Several urea-formaldehyde adhesives were used with one wood, sugar maple. Eleven factors, observed in various combinations as part of six experiments, were analyzed statistically. A number of findings emerged which are pertinent to the adhesive-adherend system being considered.

Varying the rate of loading from 400 to 6000 pounds per minute did not increase the variation of the means beyond that of chance variation. The strength of the cross-lap specimen increased hyperbolically with increasing thickness but a decline in strength occurred beyond $2 \frac{1}{4}$ inches and this was attributed to the existence of internal stress caused by dispersal of glue water. When thickness variation was reduced to that normally occurring in a surfacing operations, it was found that the effect would be negligible. Similar considerations were implied with regard to small variations in width of the blocks. A specific gravity change superimposed upon the thickness change showed that specific gravity had an appreciable linear effect upon observed strength, and, that this effect was statistically the same for all thickness levels. This led to the belief that the effect of specific gravity was due mainly to

increased bond strength rather than to change in the elastic moduli of the wood. The variation due to specific gravity was calculated to be 232 pounds per 0.10 change in specific gravity.

Differing moisture content levels superimposed upon a thickness change showed a strong direct effect of moisture content upon strength below 9.4 percent, amounting to approximately 160 pounds per percent change in moisture content. Again it was shown that the major effect of moisture content was not due to changes in elastic moduli. The effect of moisture content upon bond strength was believed to be due to the interplay of rate of water loss with rate of cure. Confirming evidence for this view was obtained with a variation of rate of cure upon different moisture content levels. It was shown also that this interplay was operative at high moisture contents as well as low, although in an inverse manner.

In one experiment, flaws were introduced into the joint by means of grease and graphite, and into the adhesive by means of wheat flour. It was found that the cross-lap specimen responded to small additions of wheat flour but not in a proportionate manner. The response to joint flaws depended upon location of the flaw. Flaws located at external portions of the joint produced losses in strength which appeared to bear a more linear relationship with the length of the bond boundary than with the area of the bond. On the other hand, 80 percent of the central portion of the joint could be rendered unbonded without loss in observed strength. A rigid grip appeared to be slightly more sensitive to the presence of one-corner flaws than a self-aligning grip.

The use-factors of bonding pressure, assembly time and age of the adhesive were observed under interacting conditions and found to be non-effective in causing variation except as they reflect properties of the adhesive.

An estimate of the standard deviation existing in this method

was made on the basis of the pooled error variances from the different analyses of variance. It was calculated to be 156 pounds, which was approximately 10 percent of the mean strength. A randomized block method for reducing this error variation was proposed. Also proposed was a tentative experimental design intended to produce an "Intolerance Index" for the purpose of comparing wood adhesives on the basis of how they might perform under conditions of actual use where certain factors might vary combinatorially.

It was concluded that a test method involving the use of the cross-lap specimen holds promise for evaluating wood adhesives, particularly when it is desired to introduce many variables into an experiment.

ACKNOWLEDGEMENTS

This research was inspired by a desire to do something about the observation of adhesive properties with the view of attempting to facilitate the comparison of wood adhesives under conditions which reflect performance as well as strength. In the conduct of the work much is owed to many. The aid of William Kynoch, former chairman of the Wood Technology Department, L. A. Patronsky, Glenn P. Bruneau, and The National Association of Furniture Manufacturers, is gratefully acknowledged.

Thanks are due particularly, to Dr. Fred E. Dickinson and Dr. Stephen B. Freston of the Wood Technology Department for their helpful suggestions during the course of the research, and for their subsequent critical review of the manuscript. Professor R. T. Liddicoat, of the College of Engineering, contributed timely advice on the mechanical aspects involved, and by his patient and encouraging attitude, did much to confer confidence in the outcome of the work. The practical counsel of Dr. Wallace W. Gardner, of the School of Business Administration on statistical matters was greatly appreciated, especially in regard to the interpretation of data and the development of some applicable concepts.

In the typing of the manuscript, special thanks are due Miss Eleanor Marra, Miss Carol Frey and Mrs. Loraine Lunger for their care and endurance throughout the many revisions and alterations.

The execution of a research project of any magnitude inevitably depends heavily upon those who aid chiefly by understanding and suffering. Among these is Maxine, wife of the author, who provided a tranquil and flexible domestic climate which is so necessary for the activities of a researcher.

AAM

TABLE OF CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	vii
INTRODUCTION	1
STATEMENT OF THE PROBLEM	6
CONSIDERATIONS IN THE SELECTION OF THE SPECIMEN	8
EXPERIMENTAL APPROACH	23
EQUIPMENT, MATERIALS, AND PREPARATION OF STOCK	26
Testing Machines	
Woodworking Equipment	
Adhesives	
Lumber	
Preparation of Stock	
EXPERIMENTS AND DISCUSSION OF RESULTS	
EXPERIMENT I The Effect of Rate of Loading on the Observed Strength of the Cross-Lap Specimen	31
EXPERIMENT II The Effect of Block Thickness and Specific Gravity on Observed Strength	39
EXPERIMENT III The Effect of Moisture Content of the Wood upon Observed Strength	66
EXPERIMENT IV The Interaction of Rate of Cure with Wood Moisture Content	84
EXPERIMENT V Response of the Cross-Lap Specimen to Built-In Flaws.	94
(a) Response of the Cross-Lap Specimen to Quality of the Adhesive	
(b) Response of the Cross-Lap Specimen to Flaws in the Joint	
(c) Effect of the Method of Test, i. e. Grip Type, on the Observed Strength of the Cross-Lap Specimen	
(d) The Relationship of Adhesive Quality to Glue Line Flaws, The Quality X Flaw Interaction	
(e) The Relationship of Adhesive Quality to Method of Test, The Quality X Grip Interaction	

	Page
(f) The Relationship of Flaws to Method of Test, The Flaw X Grip Interaction	
(g) The Interaction of Quality, Flaws, and Grips	
EXPERIMENT VI Response of the Cross-Lap Specimen to Some Bonding Factors	133
WOOD FAILURE	150
STATISTICAL CONSIDERATIONS	155
Terminology	
Sensitivity	
Precision	
Improving Precision by Control of Factors	
Thickness	
Width	
Specific Gravity	
Wood Moisture Content	
Improving Precision by Experimental Design	
An "Intolerance Index"	
SUMMARY AND CONCLUSIONS	181
APPENDIX I DEVELOPMENT OF A TESTING MACHINE AND PROCEDURE USING THE CROSS-LAP SPECIMEN	188
APPENDIX II CALIBRATION OF TESTING MACHINES. . .	197
APPENDIX III COMPLETE ORIGINAL DATA	203
BIBLIOGRAPHY	211

LIST OF FIGURES

Figure		Page
1.	Wood adhesive test specimens	10
2.	The cube specimen	15
3.	Method of applying blocking agent to certain portions of a joint to localize the bond area in adhesive specimens	17
4.	The cross-lap specimen.	19
5.	Plot of observed strength of the cross-lap specimen as a function of the rate of loading.	37
6.	View of a portion of the various thickness specimens assembled in the jigs during cure of the adhesive . .	43
7.	Plot of the strength as a function of thickness of blocks for the cross-lap specimen averaged for all levels of specific gravity	47
8.	The cross-lap specimen showing (a) location of free-bodies, and illustrating the nature of internal stresses created (b) by redistribution of glue water, and (c) by imposition of the test load	52
9.	Plot of bending stress S_{x1} as a function of thickness of the cross-lap specimen, showing its relationship with internal stress S_{xi}	59
10.	Logarithmic plot of the ratio of strength to thickness as a function of thickness of the cross-lap specimen .	61
11.	Plot of strength of the cross-lap specimen as a function of specific gravity for each thickness level	64
12.	Plot of strength of the cross-lap specimen as a function of thickness for each moisture content	71
13.	Plot of strength of the cross-lap specimen for each thickness as a function of moisture content	72
14.	Logarithmic plot of the ratio of strength to thickness as a function of thickness for each level of moisture content	82
15.	Plot of strength of the cross-lap specimen as a function of moisture content for three levels of catalysis . . .	88
16.	Plot of strength of the cross-lap specimen as a function of parts catalyst for three levels of moisture content .	89
17.	Compression saddle used in the diaphragm machine to hold the cross-lap specimen during testing	97

Figure		Page
18.	Self-aligning grip used in the Dillon Tensile Tester and other machines	98
19.	Configuration of flaws placed in exterior locations of the glue line	101
20.	Effect on strength of the cross-lap specimen produced by by flaws located at exterior portions of the joint, plotted as a function of bond area	111
21.	Plot of strength as a function of the bond boundary in the cross-lap specimen	115
22.	Response of the cross-lap specimen to exterior changes in joint area depicted as curved functions	117
23.	Configuration of interior flaws placed in glue line	118
24.	Effect on strength of the cross-lap specimen produced by flaws located at interior portions of the joint, plotted as a function of bond area	119
25.	The diaphragm testing machine (NAFM Glue Tester) set up for making specimens	190
26.	The diaphragm testing machine (NAFM Glue Tester) set up for breaking specimens	191
27.	Jigs for assembling cross-lap specimens	192
28.	The diaphragm testing machine sensitized by means of SR-4 strain gauges and strain analyser	198
29.	Set-up for calibrating the strain gauge system, showing how the upper beam of the machine was reversed to simulate actual loading	199
30.	The Dillon Tensile Tester modified with SR-4 strain gauges and variable-speed motor	200
31.	Calibration plots for testing machines	202

LIST OF TABLES

Table		Page
1.	Effect of Rate of Loading on the Observed Strength of the Cross-Lap Specimen	35
2.	Analysis of Variance for Rate of Loading	36
3.	The Effect of Specific Gravity and Thickness upon the Observed Strength of the Cross-Lap Specimen	45
4.	Analysis of Variance Summary for Specific Gravity-Thickness Study	46
5.	Tabulation of Some Calculated Stresses Existing in the Cross-Lap Specimen at Rupture for Various Thicknesses	58
6.	Summary of Results Obtained by Varying Moisture Content and Thickness in the Cross-Lap Specimen.	69
7.	Analysis of Variance for Moisture Content and Thickness	70
8.	First Differences Between Paired Strength Values of Moisture Content and Thickness	79
9.	Pounds Strength Divided by Thickness for Each Level of Thickness and Moisture Content	81
10.	The Effect of Amount of Catalyst and Wood Moisture Content upon Observed Strength	87
11.	Analysis of Variance Summary for Amount of Catalyst and Moisture Content	87
12.	The Effect of Joint Flaws, Percent Wheat Flour, and Grip Type upon Observed Strength	104
13.	Average Percent Wood Failure for Flaw Study.	105
14.	Analysis of Variance Summary for the Flaw Study	106
15.	Average Accumulated Strength Values for Each Level of Adhesive Quality.	107
16.	Effect on Strength of Flaws Located at Exterior Portions of the Cross-Lap Joint Area	109
17.	Effect on Strength Produced by Flaws Located at Interior Portions of the Cross-Lap Joint Area.	118
18.	Analysis of Variance Summary for the Effect of Internally Located Flaws	118

Table		Page
19.	The Effect of Grip Type on the Observed Strength of the Cross-Lap Specimen	122
20.	The Interaction of Flaw with Quality	125
21.	The Interaction of Quality with Grips	126
22.	The Interaction of Flaws with Grips	129
23.	Results of Varying Assembly Time, Mix Age and Pressure with the Cross-Lap Specimen	141
24.	The Effect of Age of the Adhesive Mixture on the Observed Strength	142
25.	Analysis of Variance Summary for the Effect of Mix Age, Pressure, and Assembly Time	142
26.	Percent Wood Failure for Assembly Time, Mix Age, Pressure Study	143
27.	Summary of Results with Adhesive B under Variations of Assembly Time and Age of the Mixture	147
28.	Analysis of Variance Summary for Assembly Time and Age Variation on Adhesive B	147
29.	Calculated F Ratios for Several Variables and Interactions on the Cross-Lap Specimen	160
30.	Number of Specimens Required for Observing Given Differences between Means with 5 Percent and 1 Percent Significance	164
31.	Components of Variance for a Four-Factor Analysis of Variance	178

INTRODUCTION

During the past two decades the gluing of wood has become increasingly more important in the conversion of timber into marketable forest products. Although wood had been glued successfully for several thousand years, the art of gluing owes its present importance to comparatively recent developments. Two events have been largely responsible for the almost phenomenal rise of wood gluing: (1) the advent of synthetic resin adhesives which offered extremely durable bonds, producible under modern manufacturing methods, and (2) the depletion of choice timbers supplying the demand for high grade structural material. Among other contributing factors may be mentioned, such engineering advantages offered by glued constructions as, improvement in strength and dimensional properties of wood made possible by the selection, location and orientation of different members of a bonded assembly, the opportunity to utilize otherwise inferior species in noncritical parts of the construction, and the versatility in designing unlimited sizes and shapes.

Despite a high level of engineering that glued wood products and processes have attained, it is somewhat surprising that wood gluing remains more an art than a science. One of the reasons for this situation is that wood gluing crosses at least three major fields of knowledge, i. e., Chemistry, Engineering, and Wood Technology. The advances of the art have been made principally through the efforts, largely empirical, of chemists and engineers, while wood technologists have participated to a considerably lesser degree. It may be inferred

that the scientific status of wood gluing, and the speed of further progress are dependent as much upon increased information about wood, its surface characteristics and its interaction with the properties of the adhesive, as upon improvements in the chemical makeup of the adhesive or the mechanics of their application.

One of the reasons why the development of wood adhesives and bonding techniques have come about mainly along empirical lines is given by Staverman⁽¹⁾ who visualizes a grim outlook to the science of adhesion in general:

. . . the path which will ultimately lead to a complete understanding of the characteristics of adhesives from the properties of their molecules is very long and very thorny. Many sections of this road have not yet been cleared by science. Before any substantial progress can be expected, both our theoretical insight and our knowledge of quantitative data have to advance on many points and, in view of difficulties involved even in the estimation of a simple quantity like cohesion from molecular data, we have no warrant to expect early acquisition of sufficient knowledge to say with certainty, which measurable quantities describe the desired relations and how they are measured. In fact, the obstacles to a theoretical understanding sufficient to enable us to predict adhesive properties from molecular quantities are such as to make efforts in this direction well-nigh hopeless from the technologist's point of view. This means that, for the time being, significant improvements in the field of adhesives must be expected from direct trials by technologists, rather than from theoretical predictions by pure scientists.

One of the most common methods of developing a new adhesive, as Staverman points out, is to compare measurable properties of one adhesive with those of another previously found to give suitable performance. Many chemical and physical comparisons are made, such as viscosity, pH, particle size, solids content, polarity, and hardening properties. However, since present knowledge will not permit data obtained from this type of testing to be used with confidence in predicting the suitability of a wood adhesive, strength tests must also be made to

determine bond forming properties. The adequacy of the chemical and physical properties are always confirmed by strength data. For this purpose standard adhesive specimens are used. They are also used to evaluate handling properties such as rate of cure, storage, pot life, and spreader life; and to establish limits on assembly time, pressure requirements, amount of adhesive necessary, and other factors in the bonding process. The durability of the bond is also estimated by strength tests after subjecting specimens to appropriate exposure conditions. Finally the performance of an adhesive under actual use conditions involving different products, equipment, workmanship and service exposures are made, and this is often done with strength specimens cut from the product itself. Thus, strength tests of wood joints is a most important means of determining the adhesive properties of a formulation.

The use of test specimens to appraise the suitability of a wood adhesive in each of the areas mentioned, raises a number of problems, particularly in implementing experimental procedures and in interpreting results. The problems arise by virtue of the many factors which operate between the composition of an adhesive and the testing of a bond. These factors are complex, beginning with the conditions under which the tree grew and ending with the manner in which the specimen is held during loading.

G. Marra⁽²⁾ has classified the factors affecting bond formation as follows:

- Group 1 Those embodied in the adhesive formula, such as: type of resin, size of polymer, amount and kind of catalyst, amount and kind of fillers, and extenders, and chemicals added for specific properties.
- Group 2 Those involved in the application of the adhesive, such as: amount and manner of spreading, viscosity of mixture at time of spreading, relative humidity of

atmosphere, assembly time, amount of pressure application time, temperature and manner of generating heat.

Group 3 Those pertaining to the wood, such as: species of wood, heartwood or sapwood, springwood or summerwood, density, moisture content, quality and condition of the surface fibers, grain slopes, polarity of the surface molecules, and pH of the wood.

As far as the service-life of the bond is concerned, the foregoing factors are further superimposed upon two other groups;

Group 4 Conditions surrounding its use, such as: continuously dry or continuously wet, alternately dry and wet or various degrees thereof, and variations in temperature.

Group 5 Type of construction, such as: veneer or solid lumber, across-banded or parallel construction, and other variations in thickness of material and grain orientations of adjacent members.

The strength and durability of glued wood joints is an aggregate effect of various sub-groupings of these factors and their possible interactions with each other. Since many of these factors are known to have interactions with each other, the most conclusive method of studying their effect on adhesive action is to observe their operation under all reasonable combinations. Comprehensive investigations of this type, however, are very difficult, if not impossible, because of the prohibitively large number of specimens needed to cover the combinations and to circumvent the normally large variations associated with wood.

It follows from the above that the suitability of an adhesive cannot be properly evaluated by strength measurements obtained under a given set of conditions as is often done in specification testing. Adhesives are likely to differ greatly in their interaction with wood and process variables. Whether or not an adhesive forms a bond of prescribed strength is therefore of little consequence unless a number of variables are represented at various practical levels.

A test method which would permit the use of a minimum number of specimens incorporating a maximum number of gluing variables, and which could be closely controlled for specimen, wood, and processing variables, would appear to offer advantages for the observation of adhesive properties. If the method were at the same time simple to conduct with regard to the equipment and preparation of the specimens, it would find wide acceptance from adhesive manufacturer to adhesive user.

STATEMENT OF THE PROBLEM

The work reported here may be regarded as an approach to the general problem of obtaining significant adhesive data since it deals with a method of making observations in this field. It was initiated to devise a test procedure which would be easy to conduct and could be carried out on low cost, simple-to-construct equipment. It was hoped that the specimen used would be sensitive to adhesive and application variables and yet be controllable for observations of small differences among these variables.

A cross-lap specimen, later described, was selected on the basis of the ease with which it could be prepared and the properties it might possess by virtue of its geometry and manner of stressing. A simple machine was constructed for bonding and testing the specimen. The machine is described in Appendix I, together with an outline of a tentative testing procedure.

A specimen and a machine however do not make a test method. Much needs to be known regarding the specimen, its precision, and its sensitivity to the many factors which operate during the formation and testing of an adhesive bond. The purpose of this research was to develop information which would aid in determining the characteristics of the specimen and indicate its potentialities in a test method.

In studying the specimen, a number of factors were chosen as variables which were believed to influence the observed strength either through the wood, the specimen itself, the adhesive, the manner of using the adhesive or the manner of testing. The suitability of the

method was based upon how much the observed strength was affected by extraneous factors and how well these factors could be controlled. All of the factors were varied at several levels in combination with other factors such that possible interactions could also be revealed. The experimental work was carried out in six individual experiments and this then was drawn together under statistical considerations to provide a unified appraisal.

CONSIDERATIONS IN THE SELECTION OF THE SPECIMEN

One of the perennial problems in evaluating the quality of adhesive bonds is interpreting some strength figure in terms of a particular property. The strength of a bond as usually measured is invariably compounded with size of specimen, type of wood, moisture content and density of wood, grain direction, stress concentration-- and all these limited by the comparatively low strength of wood itself. Observation of strength of bond above that of wood appears to be out of the question. It can be reasonably argued, however, that when a bond equals the cohesive strength of wood, the ultimate has been attained provided no subsequent deterioration of the bond ensues.

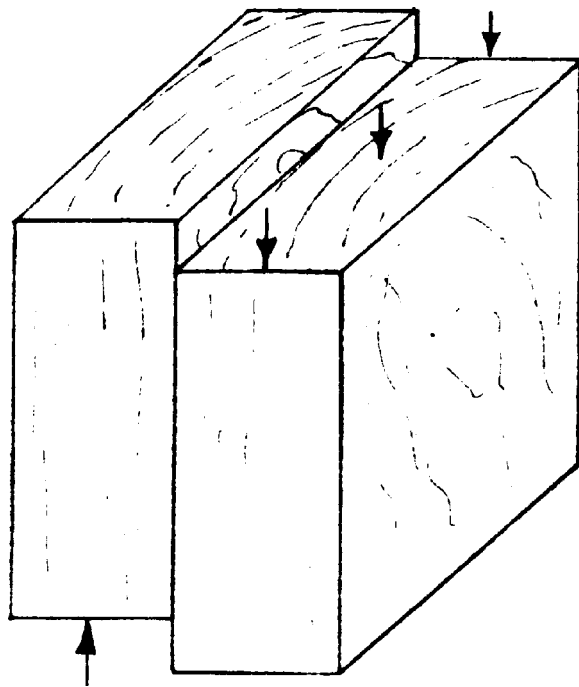
In considering any specimen which is intended to develop numerical values for the observation of some attribute of a material, assurance is needed that the same, or statistically identical values will always result from a given set of conditions. Otherwise there will arise speculation as to whether an observation reveals, instead, unaccountable changes in material quality, in conditions, or in the processing of the specimen. Present day methods in common use for measuring adhesive properties leave much room for this type of speculation. The interpretation of data thus often becomes hazardous except for broad generalities.

Another desirable consideration in a specimen is that the observed strength bear some consistent and, if possible, numerical relationship to the stress conditions encountered by glued constructions in service.

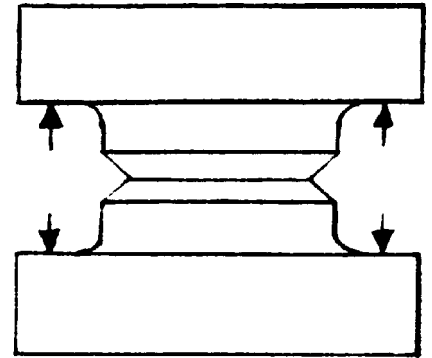
A major question arising from data of adhesive strength specimens concerns the distribution of the loading stress over the bonded area at rupture. It is generally recognized that the load is seldom distributed uniformly over an entire bond area. Experience shows that where there is abrupt change in cross section, there will be concentration of stress. Stress concentration varies, among other things, with the size and geometry of the specimen. Hence different values are obtained for strength of bond with different specimen dimensions. The expression of bond strength in terms of pounds per square inch therefore can be misleading. Moreover, the location of stress concentrations in certain parts of a specimen can influence greatly its sensitivity toward adhesive factors that may be under observation. Of further concern is the study of bonding variables, such as wood moisture content, which can conceivably alter stress concentration as well as bond quality.

An examination of the two currently popular specimens, the block shear and the plywood shear, Figure 1, (a) and (c), ASTM Methods D905-49 and D906-49⁽³⁾, shows that in both cases loading forces tend to create stresses excessively in the wood during testing; whereas stresses are concentrated at the bond in many constructions undergoing service exposures. It would seem that a more realistic, and also a more conservative, bond strength observation could be made if the specimen used would concentrate stress as much as possible in the bond, at the same time keeping the stresses from vulnerable edges of the wood members. Thus, the ultimate load would be more indicative of the actual strength of the bond, and wood failure would not be as likely to occur at relatively low loads.

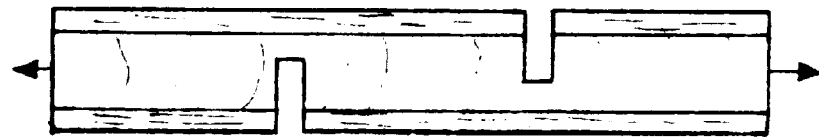
Many types of adhesive strength specimens have been proposed from time to time. Currently, the American Society for Testing Materials



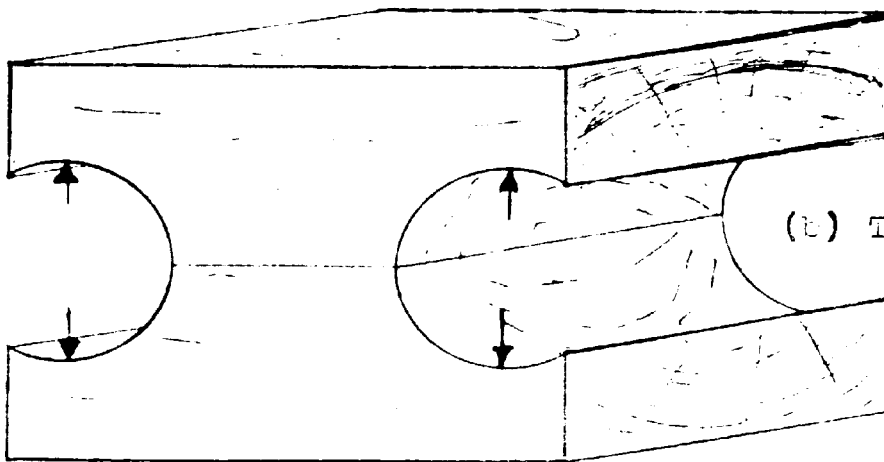
(a) Block shear specimen



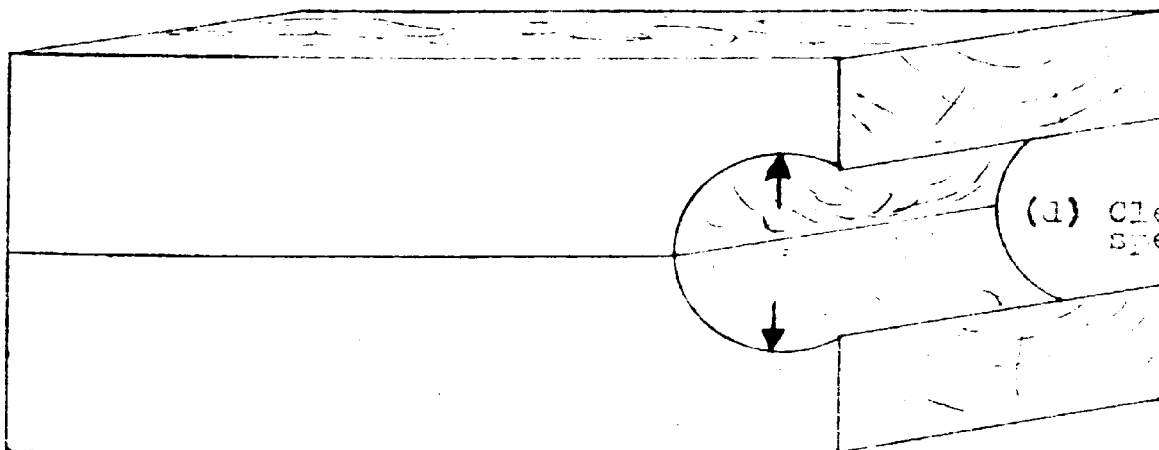
(e) Button specimen



(c) Plywood shear specimen



(b) Tensile specimen



(d) Cleavage specimen

Figure 1. Wood adhesive test specimens.

has adopted, or is in the process of standardizing, means for measuring such strength properties as shear strength by block, plywood and lap type specimens, tensile strength, cleavage strength, flexural strength, fatigue strength and impact strength.

Wood adhesives have traditionally been tested in shear and most of the knowledge on adhesive action has been accumulated with respect to this strength property. In selecting a specimen, it was reasoned that the most fruitful area for new knowledge would be in some other strength property. The growing belief that adhesive bonds are primarily stressed not in shear, but in tension, as the result of shrinking and swelling of the wood, provided the initial suggestion for an alternative stressing system. Debruyne⁽⁴⁾ and Dietz, Grinsfelder and Reisser⁽⁵⁾ have theorized, and more recently Blomquist⁽⁶⁾ has demonstrated, the existence of tensile forces at edges of joints. The theory is advanced that at the edges of bonded areas where bond failures usually originate, the individual particles of glue are under tension even though shearing forces are in operation on both sides. The author⁽⁷⁾ is in some sympathy with this view, having observed qualitatively the action of joints glued with a flexible adhesive. The adhesive film develops a stringy appearance across the bond which may be easily observed and which indicates the presence of tensile forces within the glue line itself.

Adhesive bonds are weaker in tension than they are in shear. As a general matter, it is appropriate to test a material in its weakest property rather than its strongest. In the case of wood adhesives, a further consideration is in order. Wood is stronger in shear along the grain than it is in tension across the grain. Greater forces thus come into play in a shear test of a side-grain-to-side-grain joint than in a tensile test. This is one reason for the use of the block shear specimen. Tensile tests of butt joints, that is, end-grain-to-end-grain, would of

course, provide even greater stresses on the bond because tension along the grain is the strongest property of wood. Such test joints, however, are not feasible because wood glues do not function well on these surfaces and maximum bonding power cannot be achieved. Moreover, butt joints are not used in wood constructions where high strength is necessary.

From the standpoints of the active tensile forces at edges of joints and the fact that joints are normally weaker in tension than they are in shear, it would appear that a tensile test of adhesive bonds might be a most revealing source of information. Since side-grain-to-side-grain is the usual joint condition, a tensile force normal to the joint would have to be imposed through the weakest direction of the wood. Such a tensile specimen could not register very high values before being limited by the strength of the wood. The so-called button specimen, ASTM Method D-897-49⁽³⁾, cleavage specimens (a special type of tensile test) and adaptations of the wood tensile test perpendicular to the grain, Figure 1, (b), (d) and (e), are all limited by the weakness of the wood in tension across the grain.

In spite of this contrary factor, it was felt that certain advantages resided in a tensile test by virtue of the direction of the forces involved, and that this warranted study to determine whether some means could be found to circumvent the limiting effect of low strength of the wood normal to the grain.

It was previously mentioned that stresses during loading are not evenly distributed over the bonded area of a specimen, and are likely to cause stress concentrations in the wood, depending upon the geometry of the specimen. This situation places the wood at a disadvantage with respect to the bond and is one cause of high wood failure and loss of significance. If the situation could be reversed

to produce greater stress concentration in the bond than appears in the wood bearing the load, it might be expected that rupture would reflect the actual bond condition more accurately.

A start in this direction is made by the button specimen when used on wood, Figure 1 (e). The cross section is necked down at the bond as shown. It may be observed that reducing the cross section in the vicinity of the bond does concentrate stress at the bond. However, this only assures that the break will occur at the center instead of at the shoulders if the bond is as strong, or stronger, than the wood. It does not alter appreciably the ratio of stress distribution between wood and glue because the wood adjacent to the bond approaches the same area as the bond itself. Yet, enough advantage is gained by the wood to reduce the amount of wood failure that would otherwise occur with a given test load.

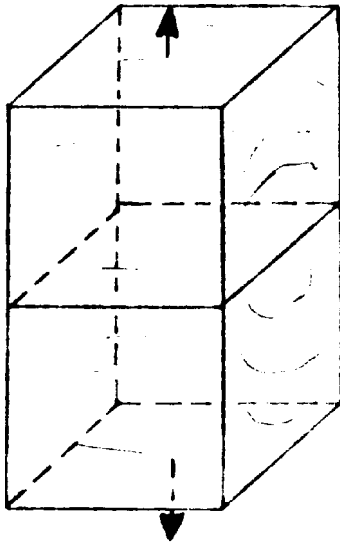
It is apparent that the sure way to alter the stress situation in favor of the wood is to reduce the bond area with respect to the joint area carrying load to the bond. A means of accomplishing this is shown in Figure 2. In (a), two cubes of wood one inch on an edge are glued together as shown, side-grain-to-side-grain. If a tensile force is applied, the load per unit area is the same in the wood as in the glue line. Hence, the weakness of the wood becomes the limiting factor in a strength measurement of a reasonably strong bond. In (b), the same size specimen is made having the same joint area. However, one fourth of the bond area is prevented from forming (by a blocking technique later discussed) at each end grain edge of the joint. Thus, there is twice as much joint area as bond area and consequently the stress, under tensile load, should be greater in the bond than in the wood, since the latter has more area under the same load.

Several desirable features are at once evident in the latter

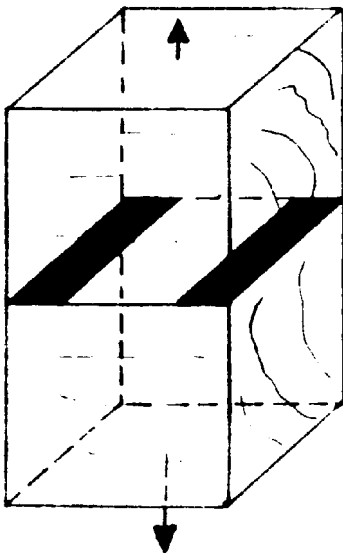
situation. (1) Since the wood area under load is greater than the bond area, higher bond strengths should be measurable before wood failure occurs. (2) The bond is removed from the vicinity of end grain which is most sensitive to tensile forces normal to the grain. Hence, wood failure must initiate as a tearing out action or as a break in the entire section. Either case should result in a higher unit strength reading for the bond. (3) Stress concentrations do occur. These, however, are located acutely at the bond and not in the wood. Thus, the bond should be able to register effects of a high order of strength at a comparatively low load imposed through the wood.

A number of preliminary experiments with this specimen, tested on a plywood testing machine with standard grips, gave values as high as 2000 pounds per square inch for the strength of a bond on hard maple without producing appreciable wood failure. Specimens could be made up in the same manner as block shear specimens, that is, using the same billets of wood, thus permitting close correlations between the two types of specimens. The procedure was to lay out the bond areas and the blocked areas on the face of one billet as in Figure 3 and then glue in the normal manner, applying the adhesive to the face of the other billet. It was found that these areas could be relocated after the glued billets were jointed, so that the specimens could be sawed in the correct places.

Graphite applied with a soft lead pencil was the blocking medium used in the preliminary experiments. A thin film of graphite prevents adhesion and at the same time does not interfere with the normal flow movements of the adhesive since it does not occupy appreciable space in the joint. Other blocking systems were also visualized such as petrolatum jelly, silicone grease, wax crayon or liquid wax applied with a brush.



(a) Joint area completely bonded



(b) Joint area half bonded. Graphite placed near end grain portion of joint.

Figure 2. The cube specimen.

This glue line blocking procedure is applicable to other specimens. It was tried on the standard wood tensile specimen normal to the grain (Figure 1 (b)). By judicious location of the blocked and unblocked areas, it was possible to drill the grip holes and cut out the specimen so that the bonded area occurred at the center of the joint area away from the end grain, (Figure 3). G. Marra⁽²⁾ used this procedure to investigate the sensitivity of standard glue specimens toward faults in the glue line. He found various plywood type shear specimens were remarkably insensitive to rather large unbonded areas.

While higher tensile strengths of the bond could be achieved with this blocking procedure, a number of disadvantages exist which appear to preclude its use as part of a simplified test method. (1) The introduction of a blocking agent into the procedure increases the possibility of surface contamination. (2) Variability of results are so great that deductions are not tenable except where wide differences exist. (3) The susceptibility to uncontrollable cleavage is high, making extremely sensitive self-aligning grips necessary. This was undoubtedly a contributing factor in the variability of results observed.

It was assumed that the two most desirable features of the graphite treated cube specimen just described, were the concentration of stress at the bond, and the removal of the bond from the vicinity of end grain. The high ratio of joint to bond area is a desirability consequent to the manner of loading.

Cursory analysis of the cross-lap specimen (Figure 4) indicates that the desirable features mentioned above reside in this specimen also. No blocking agent is necessary. Since load is applied to the specimen through the bearing edges provided by the overhang, that is, the ends of the cross, the joint area may be considered as extending beyond the bond area.

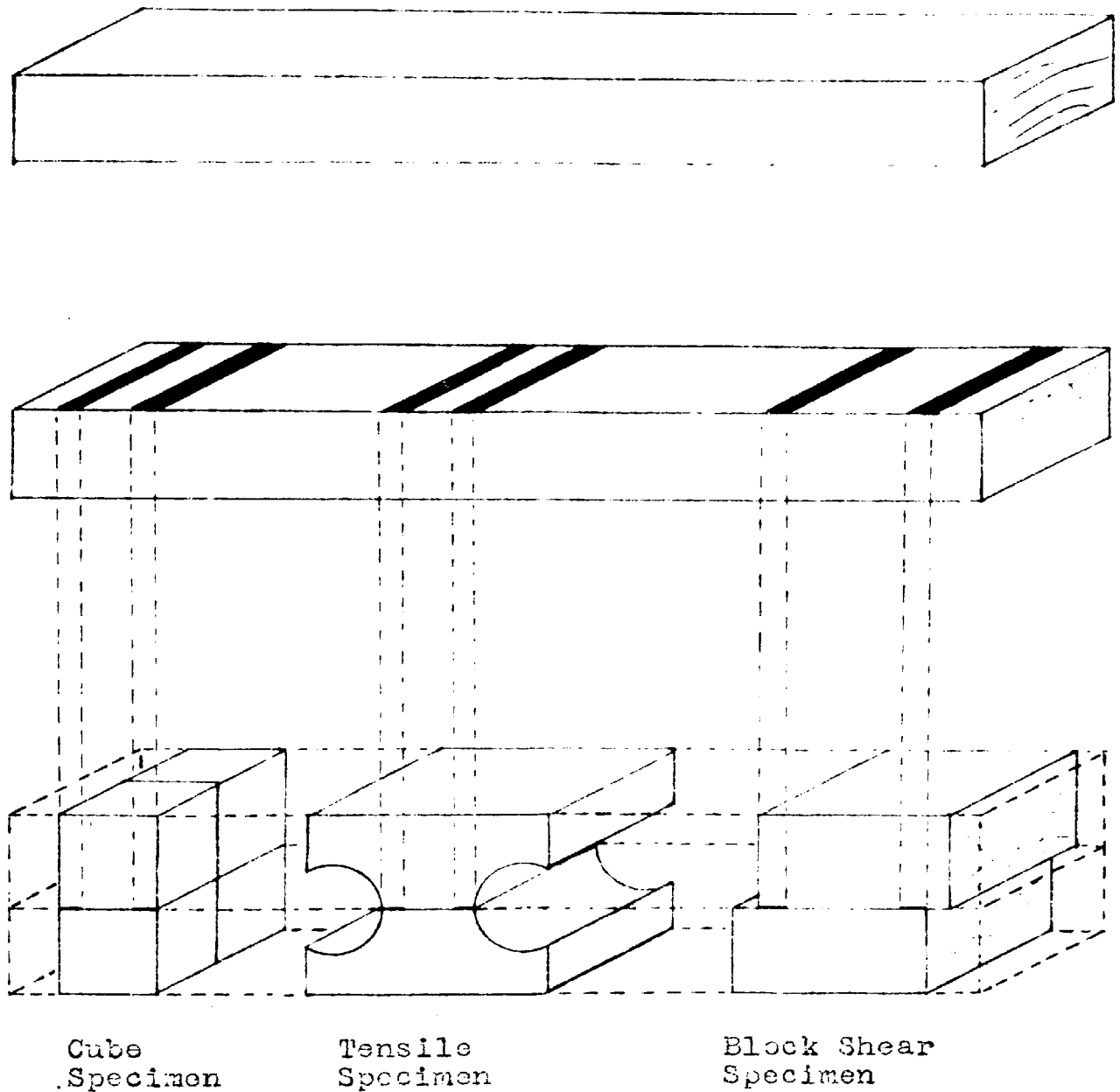


Figure 3. Method of applying blocking agent to certain portions of the joint to localize the bond area in adhesive specimens.

In addition, other features of interest may be listed: (1) Suitable jiggging permits preparation of specimens easily and in large numbers. (2) Specimens are glued individually in final form and thus require no machining after the glue hardens. (3) The wood blocks may be prepared in multiples from long strips and this promotes uniformity of machining large numbers of specimens. (4) Since specimens are glued individually, better randomization of wood variables should be possible. (5) Loads supplying bonding pressure, and testing stresses are not large and the necessary equipment need not be massive. (6) In producing joint surfaces in multiples while gluing singly, each specimen approaches more nearly a true fitting joint, and bonding pressure is not diverted uncontrollably to compressing high spots or overcoming warp. Thus, pressure should come under more positive control than is possible with other specimens glued in multiples. (7) Bearing edges for applying the test load are built into the specimen and these may be used either for compression or for tension loading. Other forms of loading such as torsion and impact are also visualized. (8) Since the grain of the wood is crossed, the maximum amount of shrinkage and swelling stresses may be imposed on the bond by moisture content changes. These are the most critical stresses a bond must withstand in service. (9) Specimen material may be prepared from one-inch lumber which is commonly available. Low grade lumber may be used since defects can be cut out in preparing the small blocks.

Several disadvantages are also evident: (1) Since there is no machining after gluing, there is no trimming, and edge effects during bond formation therefore remain in the specimen. (2) Excessive squeeze-out of the adhesive may affect the observed bond strength either by forming a fillet at the juncture of the two wood members, or by destroying the flatness of the bearing surfaces. (3) There is a pre-

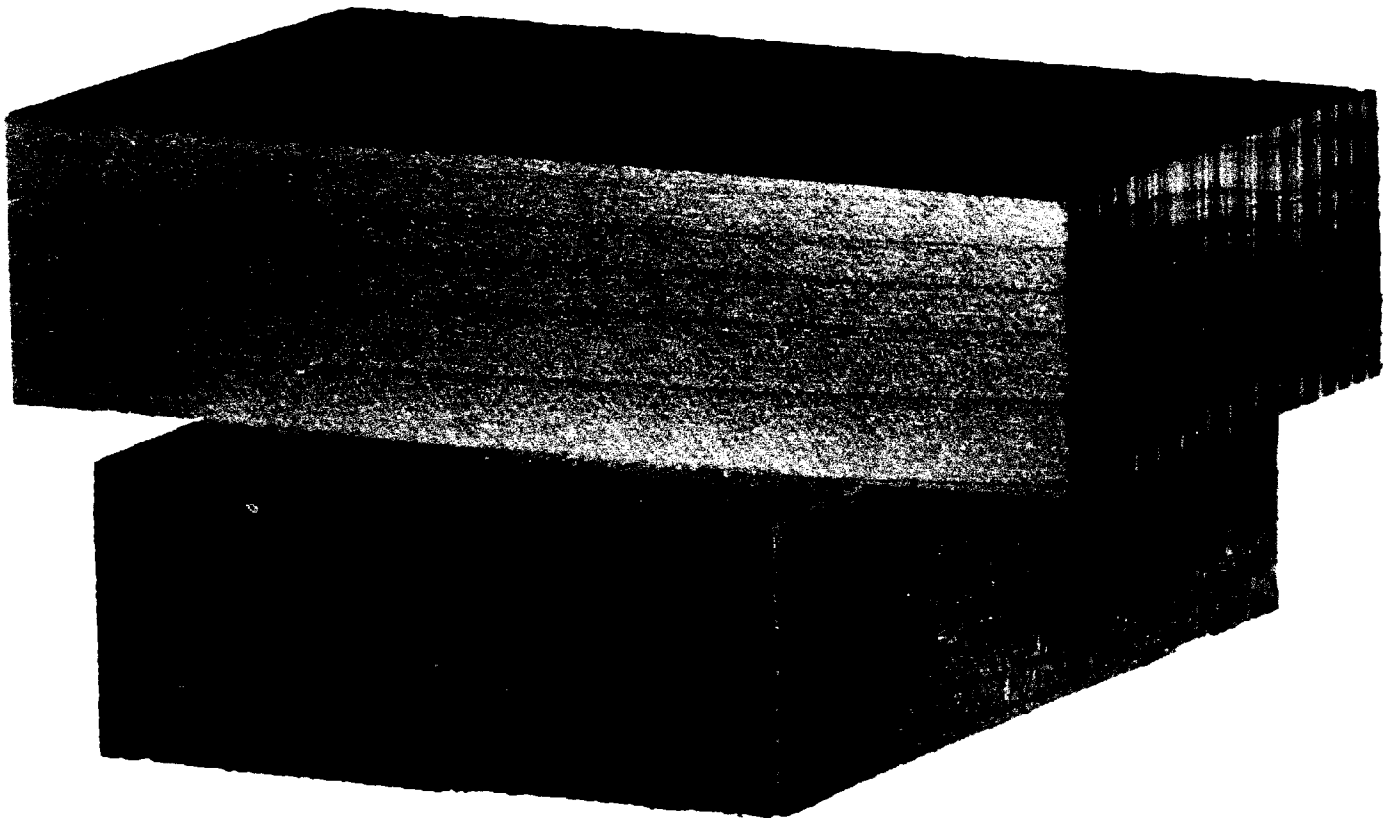


Figure 4. The cross-lap specimen

ponderence of end grain in the specimen and extreme care must be exercised to prevent moisture content changes during the course of an experiment unless this is one of the variables under observation.

(4) The possibility of cleavage exists. (5) Bending of the specimen under load may influence the observed strength. This might impose difficulties in studying factors which affect both the wood and the bond, e. g., moisture content.

A cross-lap specimen has been in use for many years for testing glass adhesives⁽⁸⁾. Its suitability for this purpose arises from the fact that grips which bite into the glass are not necessary. Recently a method using this specimen for testing glass adhesives was proposed to the American Society for Testing Materials. A cross-lap specimen is described by Kollman⁽⁹⁾ as used by Rudeloff and also by several Forest Products Laboratory publications^{(10), (11)}. An experiment involving a cross-lap wood specimen is reported by Rudkin⁽¹²⁾ of the Australian Forest Products Laboratory and by Pryor⁽¹³⁾ of the Royal Aircraft Establishment. Recently, Foreste⁽¹⁴⁾ attempted to compare results obtained with a cross-lap specimen with those obtained by the standard block shear specimen. His results were somewhat inconclusive due to wide variability in both methods. Hinken⁽¹⁵⁾ has worked with a modification of a cross-lap specimen in which he used circular shims to study gap-filling properties of adhesives. In these investigations, no unanimity of dimensions appear to exist.

The dimensions of the specimen in the present research were established largely on arbitrary grounds, tempered by feasibility both in laboratory and process control work. It was thought that the bond area should be some even multiple of one square inch in order to facilitate computation. Since the area of the bond is determined by the width of the wood blocks, the width of the blocks should also be as close as

possible to a whole number. One square inch area corresponding to one inch wide blocks was considered too small an area for good functioning of the adhesive. A four square inch bond area corresponding to two inch wide blocks was believed to be too large for easily generated testing loads. The decision, therefore, was between a two square inch area produced by 1.413 inch wide blocks, and a three square inch area produced by 1.731 inch wide blocks. The latter was considered most appropriate since a width of $1 \frac{3}{4}$ inches could be specified without serious effect on the total area.

Thickness of the wood blocks remained as an experimental variable, although for the benefit of a standardized procedure this dimension was fixed at $\frac{3}{4}$ inches. The chief determinate here was that a thickness of $\frac{3}{4}$ inches could be obtained from most lumber that might exist where gluing operations are being conducted. Greater thickness would result in less bending under load and consequently less stress concentration. A feature of this specimen, however, is the possibility of diverting stress concentrations to the bond and cause the failure to occur there instead of in the wood.

The length of the wood blocks was a matter of convenience. There appeared to be no point in having the ends of the blocks extend farther beyond the edge of the bond area than was necessary to provide a good bearing surface. It was evident that if the test load could be applied as close as possible to the edge of the bond, it would minimize the effect of bending in the wood. A half-inch overlap was considered sufficient.

The final dimensions of the wood blocks making up the cross-lap specimen, which are regarded in this paper as the standard, are thickness - $\frac{3}{4}$ inch, width - $1 \frac{3}{4}$ inches, and length - $2 \frac{3}{4}$ inches. These dimensions quite probably are not the most suitable from any

one point of view but represent a certain amount of compromise and expediency. Certainly, different dimensions would result in different amounts of stress concentrations and hence in different strength observations. Control of stress concentration was considered more important than its elimination in this type of specimen. Since it was felt that this normally unfavorable factor could be turned to good advantage in promoting responsiveness to the effects of other gluing factors. If the specimen reflects the bond situation with a good degree of reliability, its usefulness may subsequently be established through further experience.

EXPERIMENTAL APPROACH

In this study of a method, primary attention was directed to the specimen. Considerations of the apparatus were concerned mainly with the assurance that loads could be delivered in a controllable manner. Much of the latter is a mechanical problem and had previously been dealt with in the development of the testing machine. Many improvements will undoubtedly become evident as experience is gained. Such improvements, however, will be largely contingent upon whether it can be shown that the specimen is capable of providing useful information.

The approach taken was to incorporate into the specimen certain types of variables believed to affect bond quality, and noting by the subsequent strength observations, whether these were reflected in a statistically decisive manner. Some of these variables, such as moisture content and density, affect the wood of the specimen as well as the bond, and a means of isolating these effects was considered. Other variables such as rate of loading and type of grip can have important effects on the observed strength in a purely mechanical manner apart from the quality of the bond.

In all, eleven factors were studied. These may be classified as follows:

I. Mechanical Factors

- (a) Rate of loading
- (b) Type of grip and manner of loading
- (c) Configuration of bond area

II. Wood Factors

- (a) Thickness of the wood members
- (b) Specific gravity of the wood
- (c) Moisture content of the wood

III. Adhesive Factors

- (a) Flour extension
- (b) Rate of cure

IV. Application Factors

- (a) Assembly time
- (b) Age of the mixed adhesive
- (c) Bonding pressure

The above factors were used either singly or in combination in a number of experiments designed to show their direct or interaction effects. Each experiment is described and discussed as an entity in itself. It is believed that this type of presentation involving a number of studies with individual objectives is easier to follow. All factors are however, brought together in one summary with the conclusions which may be made.

The discussion of the results for each experiment is done mainly on the basis of the strength data obtained. Considerations of wood failure are made as a separate topic following the experiments. Finally, an analysis of the statistical behavior of the data is included as a means of appraising the suitability of the cross-lap specimen.

It should be noted that the philosophical approach to the problem of studying this test method may be regarded as horizontal rather than vertical. In other words, since the level of knowledge concerning the cross-lap specimen is low, it was felt that a wide coverage of the possible influential factors was needed in order to demonstrate the characteristics of the specimen. This then would form the groundwork for later experiments of a vertical nature which would seek to investigate rigorously and quantitatively the specific effects of various factors. A

consequence of a horizontal approach is that, while the operation of the factors studied are revealed positively or negatively, inevitably more questions are raised than are answered.

EQUIPMENT, MATERIALS, AND PREPARATION OF STOCK

Testing Machines

All gluing of the specimens was done in the diaphragm machine, Appendix I, using the assembly jigs and pressing fixtures. Thirty-six pressing jigs were available, permitting 180 specimens to be made at one time. The testing of the specimens was done either on the diaphragm machine, on a Dillon Tensile Tester, or on a Baldwin-Southworth hydraulic testing machine. Both the diaphragm machine and the Dillon Tensile Tester were modified to improve their sensitivity, Appendix II. For this purpose, SR-4 strain gauges were applied to parts of the machines undergoing strain and these were then calibrated with known loads. The testing loads were then read in micro-inches of strain and subsequently converted to pounds by use of the proper calibration factor.

The grips used to hold the specimen during testing were of two kinds, a self-aligning type, and a comparatively rigid type. The latter is the one used on the diaphragm machine and the former is used on the other machines. These grips were believed to possess peculiar properties and are the subject of study in Experiment V where they are further described.

Woodworking Equipment

The woodworking equipment used is indicated under Preparation of stock.

Adhesives

The same basic type of synthetic resin adhesive, urea formaldehyde, was used for all experiments. It was selected partly because of its widespread use, and partly because its properties can be easily varied. In the majority of the experiments, a catalyst-incorporated powdered adhesive was used in order to minimize mixing variables. A number of brands were used, but no particular significance is attached to the differences between brands. Most of the relationships investigated would apply to any adhesive capable of forming a strong bond under the conditions of the experiments. In some cases, notably in those involving the application factors of assembly time, pressure and age of the adhesive mixture, it is conceivable that different brands would respond differently. Evidence of this is shown in Experiment VI where Adhesive A can be compared with Adhesive B.

Following is a list of the adhesives used. They will be referred to later only by the designated code.

- Adhesive A - Plaskon 250-2, a powdered resin with catalyst and filler incorporated. It is mixed by adding 60 parts of water to 100 parts of glue base. When so mixed it has a working life of approximately 160 minutes at 75° F.
- Adhesive B - Lauxite 77A, a powdered resin with catalyst and filler incorporated. It is also mixed by adding 60 parts water to 100 parts of glue base. When mixed it has a working life of approximately 200 minutes at 75° F.
- Adhesive C - Plaskon 211, a powdered resin with filler incorporated but with catalyst separate. It is mixed by adding 60 parts water to 100 parts glue base. Catalyst additions of 1, 2, and 3 parts per 100 parts glue base give working lives of approximately 2, 4, and 5 hours respectively at 75° F.

Adhesive D - Urac 185, a liquid resin modified to give gap-filling properties. Catalyst and filler are blended together as a separate additive. The glue is mixed by adding different quantities of the catalyst blend. In this case varying the catalyst changes the consistency of the mixture but not its working life or its rate of cure. It was mixed with 13 parts catalyst to 100 parts of liquid resin base, giving a working life of approximately 2 hours at 75° F.

Lumber

The lumber used for all the experiments was kiln dried hard maple, (Acer Saccharum Marsh). It was carefully selected to eliminate defects such as knots, mineral streaks, wild and diagonal grain and any discolorations indicative of decay and heartwood insofar as possible. Specific gravity and moisture content were controlled as part of the experimental procedure. The wood was free from casehardening at the time of use.

Preparation of Stock

Approximately 1200 board feet of 5/4 inch lumber, random in length and width, was sorted for the best boards. These were then cut to approximately 50-inch lengths and ripped to two-inch widths. In this form, wood for about 6000 specimens was stored in each of three constant temperature-humidity rooms. The strips of wood were stickered to allow free circulation of air. They remained in the rooms for two years and it was assumed that they were at a uniform equilibrium moisture when used.

The constant temperature-humidity rooms were labeled and maintained as follows:

Equilibrium			
Room	Moisture Content	Temperature	Relative Humidity
1	5%	75	25%
2	9%	75	50%
3	16%	75	80%

Equilibrium moisture contents of 5, 9, and 16 percent were selected to give the maximum practical range that wood adhesives encounter.

At the start of the experimental phase, the strips were further reduced to small billets 23.5 inches long. These were jointed one side and one edge on a 12-inch jointer and planed down to a uniform thickness of approximately 0.88 inches. They were then ripped on a band saw to a width of 1.8 inches. The final width of 1.75 inches was obtained by passing the billets through a planer on edge. These billets were thus reduced to final width, a convenient length, and a thickness which would permit two light cuts for final surfacing. In this condition they were returned to their respective conditioning rooms. A sample of ten of the uniformly dimensioned billets in each room was measured to the nearest thousandth in width and thickness and to the nearest hundredth of an inch in length. This gave an average volume for the billets which was used to estimate the specific gravity. The billets were then weighed and divided into ten gram weight classes. At the same time, the billets were inspected and culled to eliminate all visible defects.

For a given experiment, a number of billets were taken at random from the selected weight class, estimating an average yield of six blocks per billet. These were passed through the planer, and a cut of 1/32 inch was removed. At this point each billet was inspected to determine on what side and in what direction the last pass through the planer was to be made. The last pass generated the joint surface and

this surface was thenceforth protected from contact with metal surfaces or other sources of contamination. A face side and a back side was thus identified and made distinct by a wavy pencil line drawn the length of the back. The pencil line was drawn in such a manner that the two end blocks could later be identified for possible culling due to clipping in the planer.

The billets were then cut, face up, into $2 \frac{3}{4}$ inch lengths for the gluing blocks, which had final dimensions of $\frac{3}{4} \times 1 \frac{3}{4} \times 2 \frac{3}{4}$ inches. Cutting to length was done on a band saw using a fence set to the right length, and a square to feed the billets through perpendicular to the blade.

Selection of the glue blocks* into sample groups was done randomly by drawing them blindly from a box. Before placing them in the box, the blocks were given a final inspection to eliminate those showing chipped grain or other surface defects created by the planer. Low-angle incident light was used to accentuate surface irregularities during inspection.

It may be said that the surfaces of the glue blocks were exceedingly smooth and true. Often in lifting one block from a stack of blocks, another could be picked up by the attractive forces operating between the two surfaces.

The final surfacing and cutting of the glue blocks was done immediately before the specimens were glued. The blocks were kept in the proper humidity rooms until a few minutes before gluing. Curing and conditioning of the specimens was also done in the humidity rooms.

* At this point the material is referred to as glue blocks. After they are glued together they are called specimens. In other words, the wood does not become a specimen until after gluing.

EXPERIMENTS AND DISCUSSION OF RESULTS

EXPERIMENT I

The Effect of Rate of Loading on the Observed Strength of the Cross-Lap Specimen

The rate of loading is known to have a measurable effect on the strength of materials in general. An increase in the rate of loading usually results in an increase in the apparent strength. When testing a composite construction such as the cross-lap specimen in which a relatively plastic material, wood, is bonded (with its grain at right angles), by means of a brittle adhesive, it is difficult to predict what a change in rate of loading might do to the observed strength of the bond. This is because each component behaves differently to the rate change and either component can influence the strength. Furthermore, while each component individually may conform to the general rule of increased strength with increased rate, the possibility exists that their combination may cause a reverse effect due to stress concentrations which would be set up between the two materials by virtue of their different moduli of elasticity.

Testing machines are of two broad types, those having a constant rate of travel of the cross head, and those delivering a constant rate of loading. The former produce a constant rate of deformation of the test specimen. In this case the rate of loading depends upon the modulus of elasticity of the material and will be constant within the proportional limit, but not beyond. The latter

give a constant rate of load throughout the test and the rate of deflection or deformation will again depend upon the modulus of elasticity.

Which of these two variables, rate of deformation or rate of loading, is the most desirable to control, is one of the debatable questions in testing. When testing uniform materials with standard specimen sizes, specifying a particular rate for one will normally also limit the other. In the case of composite constructions where different combinations of adherends and adherents having different moduli and different dimensions are being tested, controlling one loading factor leaves the other to operate according to the existing resistive situation. For example, in a later experiment, it is desired to determine what effect thickness of the wood blocks has on the observed strength. If specimens are tested under conditions of constant deflection, the rate of loading will be different for the different thicknesses. Should rate of loading be a factor in influencing observed strength, it would be difficult to determine the exact effect of thickness.

In the present experiment, rate of loading was studied to determine whether, within practical limits, an effect could be observed on the cross-lap specimen. No attempt was made to examine this factor in detail over the complete range of possibility. The purpose was to show whether any differences in results could be anticipated as a consequence of this factor between different types of specimens and testing machines to be used in later experiments.

Design of Experiment

- (1) Twelve jigs of five specimens each.
- (2) One adhesive - Adhesive D.
- (3) Specimens numbered 1 - 60 beginning with first specimen of first jig and continuing through last specimen of last jig.

- (4) Twelve groups of five specimens each, selected by use of table of random numbers.
- (5) Each group of five tested at 12 different rates of loading from 400 pounds to 6000 pounds per minute with increasing intervals as indicated in Table I.

Procedure

For the rate of loading experiment, 60 identical specimens were made as indicated below. This permitted segregation into 12 groups of five specimens each. The lower range of the Baldwin Southworth testing machine covered rates of loading from 0 to 6000 pounds per minute. Twelve points were selected to span these speeds, with smaller intervals between points at the slower rates since this region was believed to be the most critical.

In producing 60 identical specimens involving a gluing operation, there is always present a conjecture as to whether the first one glued is actually identical to the last one. Due to the thickening that occurs in catalized synthetic resin adhesives with elapse of time, it is impossible to assure a homogenous population of specimens when gluing requires more than one hour's time. By proper statistical design and treatment, however, this source of variation was taken into account. Each specimen was numbered consecutively and identified with its time of assembly. A table of random numbers was then used to select the sample which was to represent each of the loading speeds. Each specimen therefore had an equal chance of being chosen for a given speed. By maintaining its identity with time, the effect of this factor could also be extracted from the data.

No attempt was made to select the wood blocks prior to assembly in the jigs other than to discard those with obvious defects such as heartwood, mineral streaks, knots, nicks, etc. Blocks were chosen at

random from a well-mixed box. The glue was applied to one surface only of the joint in all cases. After a ten-minute assembly time, a pressure of 100 pounds per square inch was applied for five minutes. Thumb-nuts were then applied to the top plates on the jigs, and the stack of specimens set aside for the glue to harden. Excess glue squeezing out of the joint was removed before hardening. While the glue was hardening, the specimens were maintained for a period of nine days at the same conditions with which the wood was previously in equilibrium. At the end of the conditioning period, the specimens were tested on a Baldwin-Southworth machine using the lower capacity range, 0-6000 pounds. The grips used are designated as self-aligning grips. (See Experiment V)

Results

Table I presents average strengths obtained with the various speeds indicated. The data are plotted by averages in Figure 5. The dotted horizontal line indicates the grand mean of all the observed strengths.

Discussion

As can be observed from the plot of the results, the mean strengths obtained for each rate of loading fall about the horizontal line representing the grand mean. That the distribution of the sample means about the grand mean is due to chance is supported by an analysis of variance, Table II. The variance of the means is but slightly greater than the variance of individuals, indicating that no additional variation was introduced by varying the rate of loading.

It should be noted that in view of the large error variance, a relationship between rate of loading and observed strength could in fact

TABLE 1

Effect of Rate of Loading on the Observed Strength
of the Cross-Lap Specimen

Rate of Loading Pounds Per Minute	Strength Pounds
400	1440*
600	1500
800	1355
1000	1410
1250	1405
1500	1320
1750	1275
2000	1330
3000	1365
4000	1435
5000	1350
6000	1300
Average	1370

* Each value is the average of five observations.

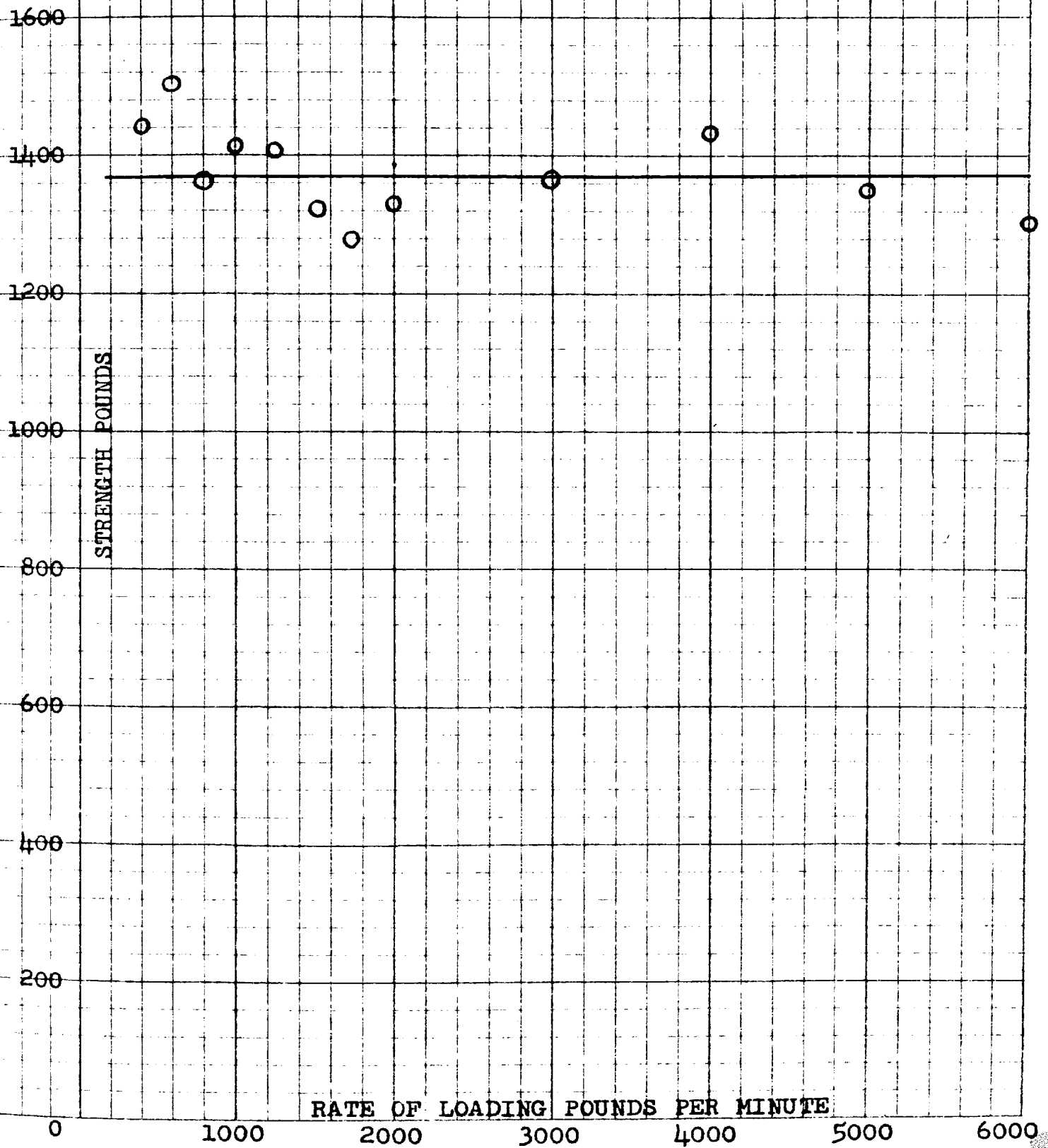
TABLE 2
Analysis of Variance for Rate of Loading

Source	N(SS)*	DF	N(MS)	F	P
Total	81,028,400	59			
Rates	15,346,400	11	1,395,127	1.02	>.30 NS
Error	65,682,000	48	1,368,375		

* In this and subsequent analysis of variance tables,

- N = total number of observations
- SS = sum of squares
- DF = degrees of freedom
- MS = mean squares
- F = ratio of factor variance to error variance
- P = probability that F can be exceeded by chance, expressed as a decimal part of a hundred
- > = greater than
- < = less than
- NS = not significant, i.e. the factor is not likely to be a cause of variation.

Figure 5. Plot of observed strength of the cross-lap specimen as a function of the rate of loading.



exist, without being measurable. However since an effect is not detectable over the wide range covered in this study it does not seem probable that the small range actually anticipated in the following experiments will cause undue error.

EXPERIMENT II

The Effect of Block Thickness and Specific Gravity on Observed Strength

The thickness of the blocks to be glued into specimens had been more or less arbitrarily set at 3/4 inch, primarily because this thickness could be readily obtained in mill-run stock with sufficient allowance to make a clean surfacing cut in a planer. It was recognized that the thickness of the member plays an important role in the observed strength of the joint due to the bending which occurs during testing. The amount of bending which develops between the bearing points and the edge of the joint produces stress concentrations and these in turn subtract from the maximum load otherwise attainable. However, since thickness can be controlled to close tolerances, it was believed that this factor would not be a source of variation. Furthermore, in experiments involving comparative analysis of data, the level of the observations as influenced by a constant thickness factor, should not have a bearing on the interpretation of the results. It was also felt, as previously stated, that such bending as would occur, might possibly improve the specimen's sensitivity to adhesive factors.

For the purposes of a standardized procedure, fixing the block thickness at a prescribed point would settle the matter. Nevertheless, aside from academic interest, there is reason to investigate the effect of this factor. Thickness affects bending, which affects stress concentration, which in turn affects observed strength. Specific gravity and moisture content of the wood also affect bending. When it is desired to

observe the effect of the latter two factors on the quality of the bond, some means of dissociating these interactions must be devised. By superimposing a moisture content change or a specific gravity change upon a thickness change, it was reasoned that the effect of bending on strength could be asymptotically eliminated. Thus residual differences in strength could be related to the precise effect of moisture content or specific gravity upon bond quality.

The effect of block thickness does not appear to have been investigated by other researchers, though it was indirectly considered. Rudkin⁽¹²⁾ worked with specimens 3/16-inch thick and compared the results with specimens made of 3/8-inch thick material, (mountain ash, masonite, asbestos sheet). His main interest was in noting that the coefficient of variation was statistically the same in both cases, and therefore observations on gluing procedures for these materials could be compared at either thickness. His data, however, shows that the strength at 3/8-inch thickness was 1.2 to 3.1 times greater than at 3/16-inch thickness. In two cases the results were slightly greater at 3/16 than at 3/8-inch thickness. The latter is unexplained, but it would appear that the "shackle" or grip used may have been responsible. Means for reducing the bending of the specimen during loading were provided, and this consisted of a system of wedges which could be driven between the back of each wing of the specimen and the throat of the "shackle". Varying placement of the wedges could cause appreciable variation in the observed strength.

Moser⁽⁸⁾ in working with glass adherends used the thickness of the glass available, although thicknesses of at least 1/2-inch were mainly used. He did not compare strengths of one thickness against another. Rudeloff⁽⁹⁾ appears to have recognized both a bending action and the inherent low tensile strength of wood across the grain. His cross-lap

specimen was made up of blocks 125 mm wide by 50 mm thick by 185 mm long. However, since he speaks of sizing the end grain before gluing, it is inferred that the blocks were cross and butt joined. No data are given.

The present experiment was conducted to characterize the influence of the thickness factor on the observed strength of the cross-lap specimen. It was set up as a two-variate design involving different levels of thickness and specific gravity. The results however, showed the operation of additional factors which were not anticipated, and hence were not allowed sufficient scope to register decisively. Although the main effect of thickness was therefore not completely brought under observation, its general behavior can be traced. The design of the experiment also provided a means of observing the direct effect of specific gravity and its possible interaction with thickness.

In a preliminary study it was shown that strength values of 855, 1300, and 1515 pounds resulted from thicknesses of 3/8, 3/4 and 6/4-inch respectively. It was deduced that the strength would become asymptotic at some maximum value as the thickness increased beyond the point where no bending occurred. The strength asymptote would thus represent a value where factors which influence strength by virtue of bending are not operative. A plot of the above results indicated that the asymptote might be closely approached by one more doubling of the thickness to three inches.

Design of the Experiment

- (1) Five thicknesses - 3/8, 3/4, 1 1/2, 2 1/4, 3 inches.
- (2) Four specific gravity variations of 0.63, 0.68, 0.72 and 0.75.
- (3) Four replications.

- (4) One adhesive - Adhesive A.
- (5) One moisture content - 9.4 percent.
- (6) Total of 80 specimens.

Procedure

The specimens were assembled in the jigs as shown in Figure 6. By combining the various thicknesses or by using filler blocks, it was possible to fill each jig completely. The thickness classes were exact multiples of the standard 3/4-inch block. The different thicknesses were therefore made up by laminating additional blocks onto the two comprising the test joint. The laminating was done at the same time as the test joint since it involved only the orientation of the blocks in a given jig load. Specimens in the 3/8-inch class were assembled as 3/4-inch specimens. The thickness was reduced to 3/8-inch by sawing off 3/8-inch prior to testing. It was found that this could be readily done on a band saw using a wide blade and a ripping fence.

Gluing of the specimens was done on the diaphragm machine using a pressure of 100 pounds per square inch of glue line, an assembly time of ten minutes, and a time in the press of five minutes. At the end of five minutes in the press, thumb nuts were tightened snug by hand, and the jig full of specimens was placed in the same constant temperature humidity room in which the wood had been conditioned. The next day the specimens were removed from the jigs and allowed to condition in the same atmosphere for six additional days before testing.

The adhesive was applied by brush to one side only of the joint. It was spread as uniformly and as rapidly as possible. Small irregularities in quantity and distribution were assumed to be equalized when pressure was later applied since some squeeze-out always occurred. This squeeze-out was removed before the adhesive hardened.

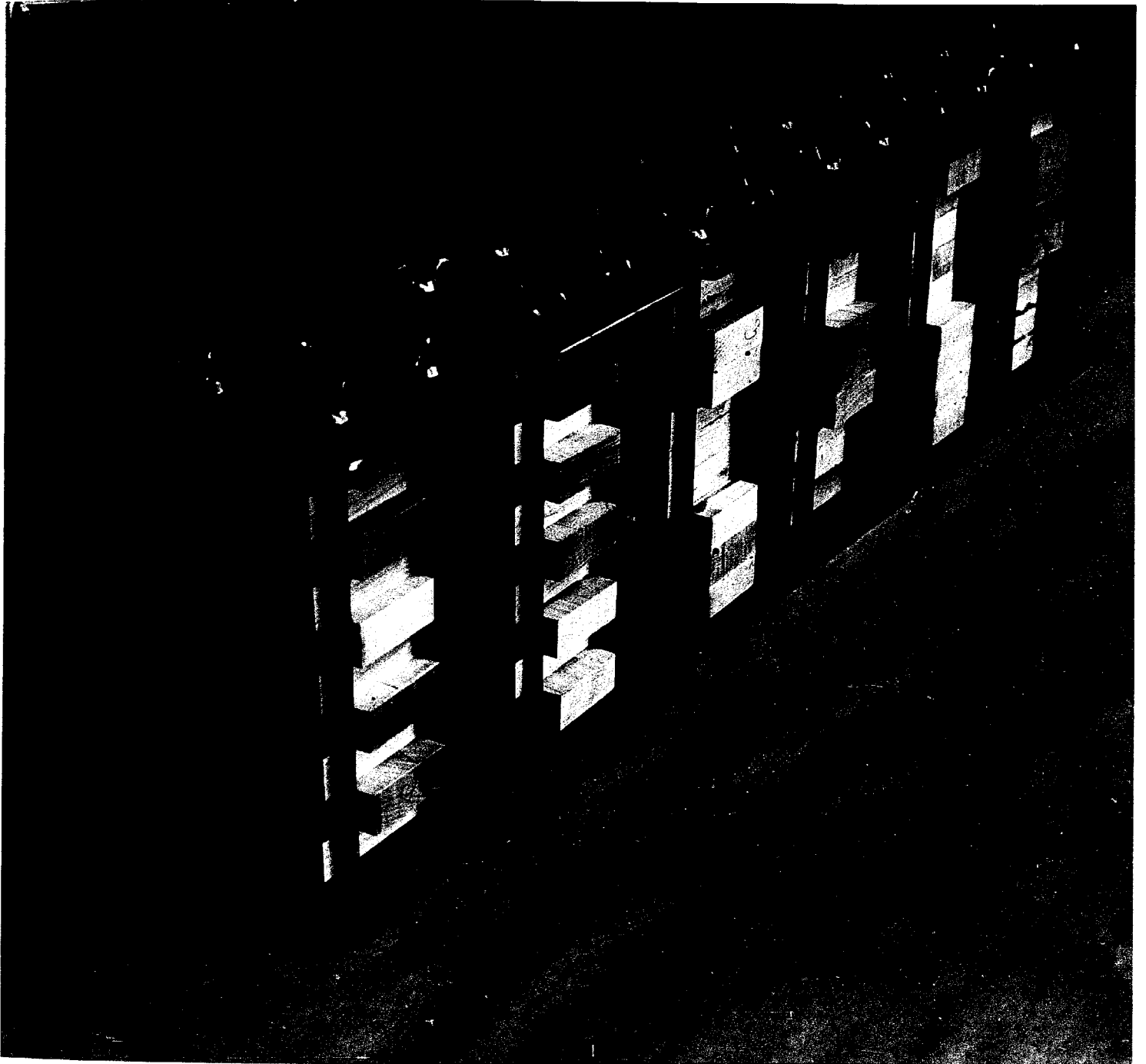


Figure 6. View of a portion of the various thickness specimens assembled in the jigs during cure of the adhesive

Specimens were assembled at random in order to balance out possible effects of age of the mix. (A later experiment however showed that such randomization was unnecessary with the adhesive used.)

Testing of the specimens was done in the modified Dillon Tensile Tester using the self-aligning grips. The rate of separation of the grips was 0.110 inch per minute as observed by direct measurement. Rate of loading was dependent on the thickness of the specimen since the amount of bending varied for a given load with the different thicknesses. For specimens over 3/4-inch in thickness, the rate of loading was observed to be approximately 1500 pounds per minute.

Results

The results were initially recorded in micro-inches of deflection as read on the strain analyser. They were later converted to pounds strength by multiplying by the calibration constant, 1.509 pounds per micro-inch. Wood failure was also observed. The complete data is summarized below in Table 3 by averages. A plot of the data showing strength as a function of thickness is given in Figure 7, using the combined averages for all specific gravity classes in each thickness interval.

The results show a definite effect of specific gravity upon observed joint strength, suggesting, in fact, a linear relationship normally existing between strength and specific gravity. The effect of block thickness is very marked as previously found but the expected asymptote did not materialize.

It would appear from the plot of Figure 7 that the prior presumption of an asymptote for strength is somewhat dubious. A "t" test based on the error term of the analysis of variance shows the strength value for the 3-inch thickness to be significantly different (at the 1% level) from that of the 2 1/4-inch thickness. Likewise the value of the 1 1/2-

TABLE 3

The Effect of Specific Gravity and Thickness upon the
Observed Strength of the Cross-Lap Specimen

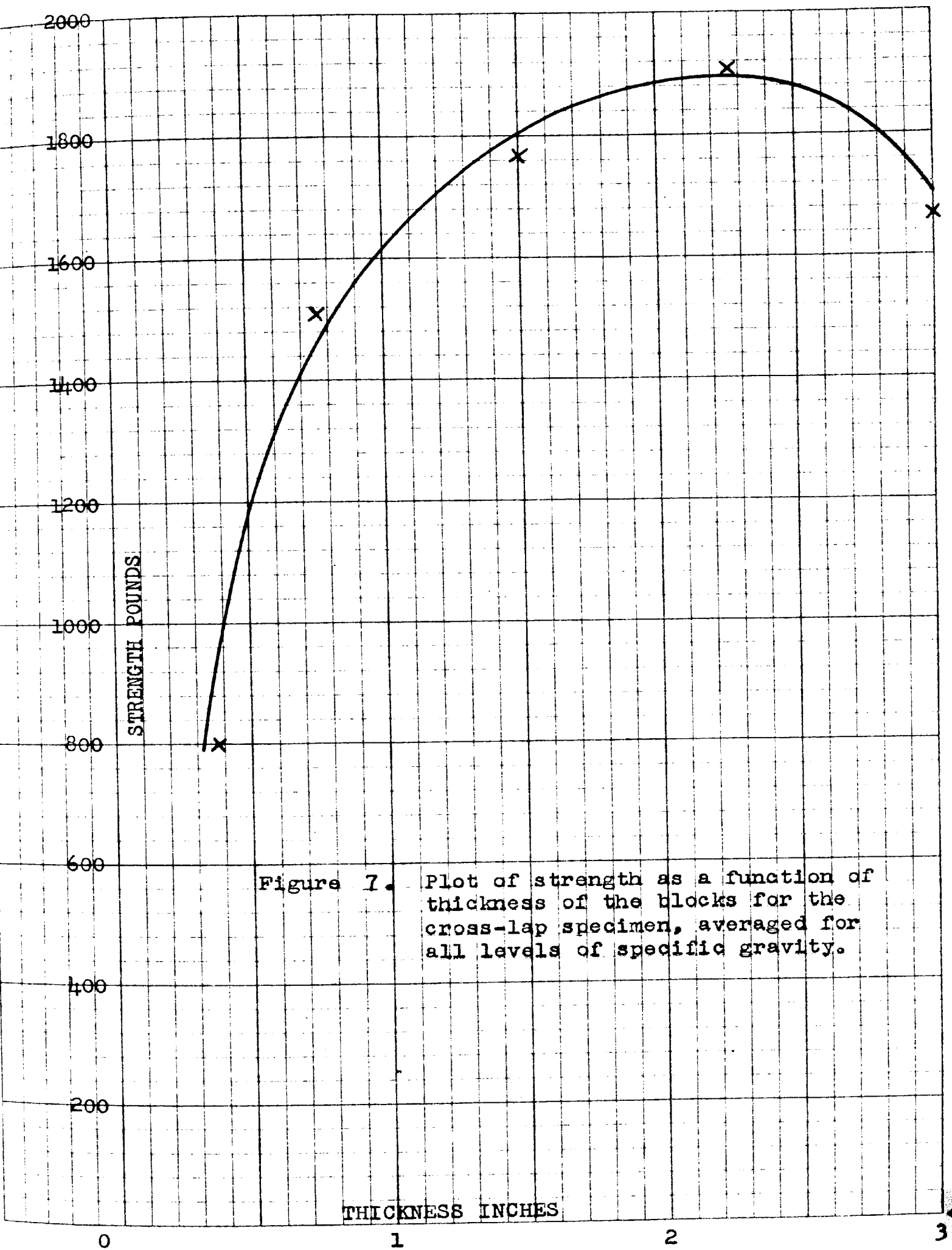
Thickness Inches	Strength - Pounds				
	Specific Gravity				
	0.63	0.68	0.72	0.75	Average
3/8	750*	846	821	992	802
3/4	1360	1508	1667	1486	1505
1 1/2	1676	1641	1777	1967	1766
2 1/4	1740	1895	1950	2068	1904
3	1582	1631	1811	1640	1666
Average	1382	1497	1605	1631	1529
Percent Wood Failure					
3/8	28	30	26	24	27
3/4	41	27	36	21	30
1 1/2	51	15	27	31	31
2 1/4	54	25	34	63	44
3	50	15	25	15	26
Average	43	22	29	31	32

* Each figure is the average of four observations.

TABLE 4

Analysis of Variance Summary for Specific Gravity
Thickness Study

Source	N(SS)	DF	N(MS)	F	P
Total	1,080,916,631	79			
Replicate sums	936,613,611	19			
Thickness	862,471,246	4	215,617,812	89.65	<.0005
Specific Gravity	45,512,691	3	15,170,897	6.31	<.001
Specific Gravity X Thickness	28,629,674	12	2,385,806	.99	NS
Error	144,303,020	60	2,405,050		



inch thickness is also significantly different between the 2% and the 5% level. The evidence therefore is that a maximum strength is indicated at or near the 2 1/4-inch thickness and that a reduction in observed strength occurs with further increases in thickness. This evidence adds new facets to the study, for it signifies the presence of other factors operating in conjunction with bending to affect the strength.

Discussion

Before discussing the results with respect to the original object, it may be well to speculate upon the possible causes for the down-turn of strength. In order to analyze the situation as it appeared to exist in this experiment, it is necessary to study more fundamentally the interplay of forces at the glue line.

If the assumption is made that a bond equal in strength to that of the wood can be produced, a number of causes for low observed values may be cited. When the bond strength is equal to the wood strength, the theoretical observed strength of the joint should be equal to the force necessary to rupture three square inches of wood in tension perpendicular to the grain. As a basis for discussion, it may be assumed that the tensile strength of maple perpendicular to the grain is 1000 pounds per square inch. For three square inches the joint strength should therefore be 3000 pounds.

Among the reasons why the cross-lap specimen may fail to support 3000 pounds are:

- (1) Stress concentration due to change of section, i. e., from one member to the other.
- (2) Stress concentration due to bending of the blocks between the bearing point and the edge of the joint.
- (3) Low tensile strength normal to the grain of the particular blocks under test.

- (4) Low quality of the bond caused by adhesive and application factors.
- (5) Low specific gravity which affects bending, tensile strength, and quality of the bond.
- (6) High angle of the grain which affects bending and tensile strength.
- (7) Moisture content of wood which affects bending tensile strength and quality of the bond.
- (8) Moisture content change or redistribution of moisture after the adhesive has set. These cause internal stress on the joint.
- (9) Shrinkage of the adhesive upon curing, also a cause of internal stress.

The above nine factors affecting observed bond strength were either controlled variables, constants, or were randomized in this experiment. However, the possibility of unpredicted interactions exist in addition to those mentioned. One of these may stem from factors (8) and (9) which cause internal stress. Reinhart⁽¹⁷⁾ has indicated how internal stresses may either increase or decrease the observed value of the strength depending upon the nature of the stresses, the geometry of the specimen and the nature of the imposed load.

One source of internal stresses is moisture change. In making the cross-lap specimens for this experiment special emphasis was placed on the fact that the wood was at complete equilibrium prior to gluing and that the specimens were conditioned back to the original moisture content prior to testing. It was therefore assumed that the specimens were stress-free at the time of test. However, the adhesive is applied in water solution, and this water apparently must be reckoned with in the cross-lap specimen. Equilibrium in the specimen may not mean that a stress-free condition existed. The water is absorbed by the wood while the adhesive hardens. The wood in the vicinity of the joint consequently will swell in accord with the amount of water present and

what frictional resistance is offered by the opposing lamina on the other side of the uncured glue line. After the adhesive hardens and the wood returns to its original moisture equilibrium, some shrinkage must occur. This shrinkage, however, is now restrained because of the bond to wood of opposite grain. Hence, a stress pattern is set up in which each block is under tension across the grain and under compression along the grain. A stress gradient perhaps also exists from the bond interface to the opposite side of the block.

In addition to the stresses set up by redistribution of glue water, the bond itself also tends to shrink as it cures. This shrinkage compounds that produced by moisture change. Thus the specimens arrive at the testing machine in a prestressed condition, the stresses being in the plane of the glue line, and for a free-body at a corner, may be considered as acting as shown in Diagram (b), Figure 8.

In Figure 8, M and N have been taken as free-bodies from opposite sides of a glue line at a corner of the specimen. This is a logical point of study. It is shown in a later experiment that the corners of the specimen are responsible for the greatest proportion of the strength. As they reside in the specimen, these two free-bodies exert stress on each other under moisture change since they are bonded together with their grain at right angles. The shrinkage of one body across the grain is always restrained by the bond to perpendicular grain of the other body. Body N tends to shrink in a horizontal direction parallel to the plane of the paper and in so doing places a compressive stress S_{xi} on M. In restraining this action, M creates an internal tensile stress S_{zi} on N. By a converse action, stress S_{zi} is induced on M and S_{xi} is induced on N in a direction perpendicular to the plane of the paper.

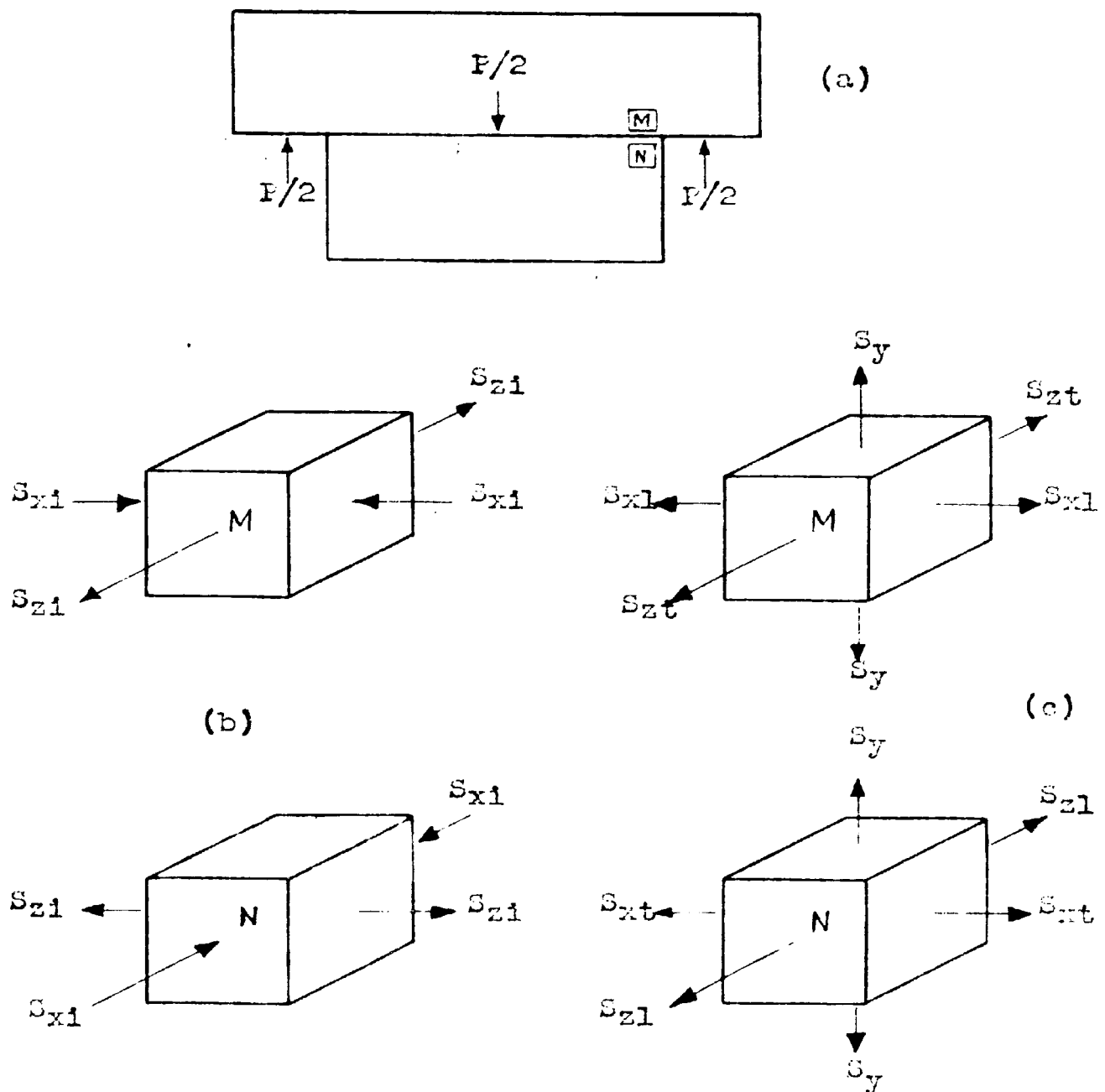
S_{xi} and S_{zi} are equal in magnitude although they are associated

with different moduli of elasticity, i. e. , longitudinal and transverse, and have undergone the same movement. This is because the stress arises from deformation of the element having the lower modulus of elasticity, and this element has partially strained internally in conformance to Young's law.

Considering now the stresses imposed on these two free-bodies by the test load, it is seen in Diagram (c), Figure 8, that they are likewise variously oriented. The test load produces stress on the free body in two forms: (1) as tension normal to the glue line expressible as $S_y = P/A$ in which P is some portion of the total load and A the area involved, and (2) as tension parallel to the grain defined by $S_x = \frac{MC}{I}$ in which M is the moment at the edge of the joint calculated from the point of application of the load, $C = h/2$, the distance from the joint surface to the vertical center of the block, and I the moment of inertia about the center of the block.

The bending moment not only produces stress along the grain in the block in which the bending occurs, but also across the grain in the other block. The latter, however, is considerably less than the former because it is induced by a longitudinal strain upon a transverse section of lower modulus. Thus stresses S_{xl} , S_{xt} , S_{zl} and S_{zt} arise from the bending of the specimen acting as a cantilever beam with load applied at the bearing points 0.20 inches from the edge of the joint. The upward thrust induces stress in both bodies, as does the downward thrust. The stresses are not equal but may be related by strain relationships.

S_{xl} is the maximum stress at extreme fiber due to bending. It is a tensile stress parallel to the grain in body M, i. e. , in a horizontal plane. S_{xt} is the stress induced across the grain in body N by the strain accompanying S_{xl} . Conversely, S_{zl} is the tensile stress along the grain in body N due to bending of the lower block under downward thrust, and



- M - Free body in upper member
 N - Free body in lower member
 $\frac{P}{2}$ - Thrust of the load-bearing edges
 S_{xi} - Internal compressive stress due to restraining the shrinkage of adjacent block
 S_{zi} - Internal tensile stress due to restraint of shrinkage within block
 $S_y = \frac{P}{A}$ - Stress normal to glue line
 $S_{zi} = S_{xi}$ - Extreme fiber stress along grain at interface produced by bending moment
 $S_{zt} = S_{xt}$ - Fiber stress across grain produced in one block by bending strain of other block

Figure 8. The cross-lap specimen showing (a) location of free bodies, and illustrating the nature of internal stresses created (b) by redistribution of glue water and (c) by imposition of the test load.

S_{zt} the portion of this stress transmitted across the glue line to body M across the grain.

S_{xl} and S_{zl} are equal and can be represented by the expression

$S = \frac{MC}{I} = \frac{6Fl}{bh^2}$. S_{xt} and S_{zt} are also equal. S_{xl} and S_{zl} may be related to S_{xt} and S_{zt} by the moduli of elasticity and strain relationships. Since the relative strains are the same:

$$\frac{S_{xl}}{E_{\text{longitudinal}}} = \frac{S_{xt}}{E_{\text{transverse}}}$$

similarly

$$\frac{S_{zl}}{E_{\text{longitudinal}}} = \frac{S_{zt}}{E_{\text{transverse}}}$$

The internal and external stresses may now be simplified and combined. Since free-body N has the same stresses acting upon it as free-body M except for a 90° horizontal transformation, only M need be analyzed further. It can be seen in Figure 8, for free-body M, that external stress S_{xl} opposes internal stress S_{xi} ; likewise, that external stress S_{zt} is in the same direction as internal stress S_{zi} . S_{xi} may therefore be considered as subtracting from the value of S_{xl} , while S_{zt} is additive to S_{zi} . S_y acts independently of other stresses.

During loading of the specimen three mutually perpendicular stresses are thus in operation, viz. S_y , $(S_{xl} - S_{xi})$, and $(S_{zt} + S_{zi})$. These stresses are not fully known. Furthermore the resultant of these stresses is not only unknown, but varies as the magnitude of the individual stresses vary. S_{xi} and S_{zi} may be considered as constants of the bond. S_y varies only with the load, and S_{xl} and S_{xt} vary not only with the load but also with the thickness of the specimen since they arise through bending of the wood blocks.

In summary of the above, the stresses operating in the cross-lap

specimen during loading are defined by the following equations:

$$S_y = \frac{P}{A} \quad (1)$$

$$S_{xl} = \frac{MC}{I} = \frac{6Pl}{bh^2} \quad (2)$$

$$S_{xt} = S_{xl} \frac{E_t}{E_l} \quad (3)$$

$$S_{xi} = S_{zi} \quad (4)$$

$$S_{xl} = S_{zl} \quad (5)$$

The data of this experiment provide a clue as to how these stresses may be further related. Assuming that a maximum strength will be observed under conditions of minimum internal stress, one condition of minimum internal stress would be such as to make $S_{xl} = S_{xi}$ and thereby exactly cancel each other. The data indicate that maximum strength is reached when the thickness of the blocks is approximately 2 1/4 inches. At this point, if the tensile stress S_{xl} induced by the bending of the blocks under load, is equal to the internal compressive stress, S_{xi} , along the grain due to shrinkage of the opposing block, then

$$S_{xl} = S_{xi} = S_{zi} = \frac{MC}{I} = \frac{6Pl}{bh^2}$$

where P = the load at rupture = 1900 pounds

l = 0.20 inches = the length of the cantilever beam, i. e., the distance from the bearing point to the edge of the bond.

b = the width of the block = 1.75 inches

h = the thickness of the blocks = 2.25 inches at the point of maximum strength

substituting

$$S_{xl} = S_{xi} = S_{zi} \frac{6 \times 1900 \times 0.20}{1.75 \times 2.25^2}$$

from which

$$S_{xl} = S_{xi} = S_{zi} = 258 \text{ pounds per square inch}$$

and since

$$S_{xt} = S_{xl} \frac{E_t}{E_l}$$

$$S_{xt} = S_{xl} (0.065)^* = 16.7 \text{ pounds per square inch}$$

On the basis of this reasoning, it may be said that internal stress in the joint of the cross-lap specimen when bonded in the manner described, is of the order of 260 pounds per square inch, being a compressive stress along the grain and a tensile stress across the grain. Expressed as a percent of the average maximum strength, the internal stress is calculated to be approximately 13.5 percent of the total strength of the bond.

It is interesting to compare this figure with the results obtained by Lewis et al⁽¹¹⁾ and Fryor⁽¹³⁾ who observed an effect of internal stress attributed to the equalization of glue water. They showed that an increase in strength resulted when cross-lap specimens were tested at moisture contents slightly higher than at fabrication, and reasoned that the swelling which occurred with the increased moisture was compensating the shrinkage stresses which were present. It was noted that an increase in moisture content of 4 - 5 percent resulted in an increase in observed strength of approximately 15.5 percent.

* The ratio of E_t/E_l is approximated after the values of the ANC Handbook (18) and taken as the average of $\frac{E_{\text{tangential}}}{E_{\text{longitudinal}}}$ and $\frac{E_{\text{radial}}}{E_{\text{longitudinal}}}$ since the specimens used contained mixtures of variously oriented ring structure.

Lewis noted further that the same increase in strength was not shown in a similarly made joint tested in compression shear under the same conditions. No reason was advanced for this divergence of results. It may be inferred however, that prestressing of the joint by equalization of glue water, affects the strength more when tested in tension than in shear because of differences in stress distribution between the two methods of test.

It may be postulated that if the increase in strength observed after increasing the moisture content is due to a reduction in internal stress, the maxima presently observed with changes in thickness should disappear with a slight increase in moisture content. Thus the strength-thickness curve should rise to a true asymptote. Experimental confirmation of such a situation would show whether Lewis and Pryor's results are due to stress relief or to changes in elastic properties of the wood.

The development of the internal stress, S_{xi} , raises a question as to whether the strength of the cross-lap specimen might not be strongly related to the time interval between curing of the adhesive and testing the joint. During the early stages of curing, the adhesive gains strength, and the wood swells with the imbibition of glue water. This should result in a peak strength when the curing reaction has produced strength equal to that of the wood, and the wood itself is still in a swollen condition. Shrinkage stresses due to subsequent contraction of the film and the wood then come progressively into prominence, and these gradually detract from the apparent strength of the joint. A plot of strength as a function of time may therefore show the same relationship as strength and thickness, rising from the origin to a blunt peak and then declining slowly to some asymptotic value.

Returning to the present experiment, it may be further reasoned

that at thicknesses less than 2 1/4 inches the internal compressive stress is canceled and superseded by the bending-induced stress, while the internal tensile stress is increased by addition of the across-the-grain-stress S_{xt} . At thicknesses greater than 2 1/4 inches, bending stresses are not sufficient to cancel the internal compressive stress. The observed strength therefore decreases. How far the strength would continue to fall with increasing thickness remains a question. Some estimate of the thickness beyond which the strength might become constant may be deduced by an extension of the relationship of S_{xl} to S_{xi} at other thicknesses.

Figure 9 is a plot of S_{xl} (bending stress) against the thickness of the blocks using the average data of Table 3 in formula (2), Table 5. It is evident that the bending stress, S_{xl} , is rather considerable at a thickness of 3/8 inches, being of the order of 3900 psi. This reduces sharply to 540 psi at 1 1/2 inches and levels off gradually toward zero beyond 3 inches. From this it would appear that the observed strength should rise to a maximum and then gradually decrease toward some constant value at a thickness of about six inches.

With regard to the usefulness of the cross-lap specimen for revealing bond condition, it would appear that the lower end of the thickness scale should be of greater interest. It is seen in Figure 9 that the bending stress increases rapidly as the thickness decreases toward 3/8-inch. This poses the possibility of a critical thickness which might create the most potent or sensitive combination of stresses to operate upon a bond. It leads to the thought that perhaps a thinner rather than a thicker specimen would better reflect changes in bond quality.

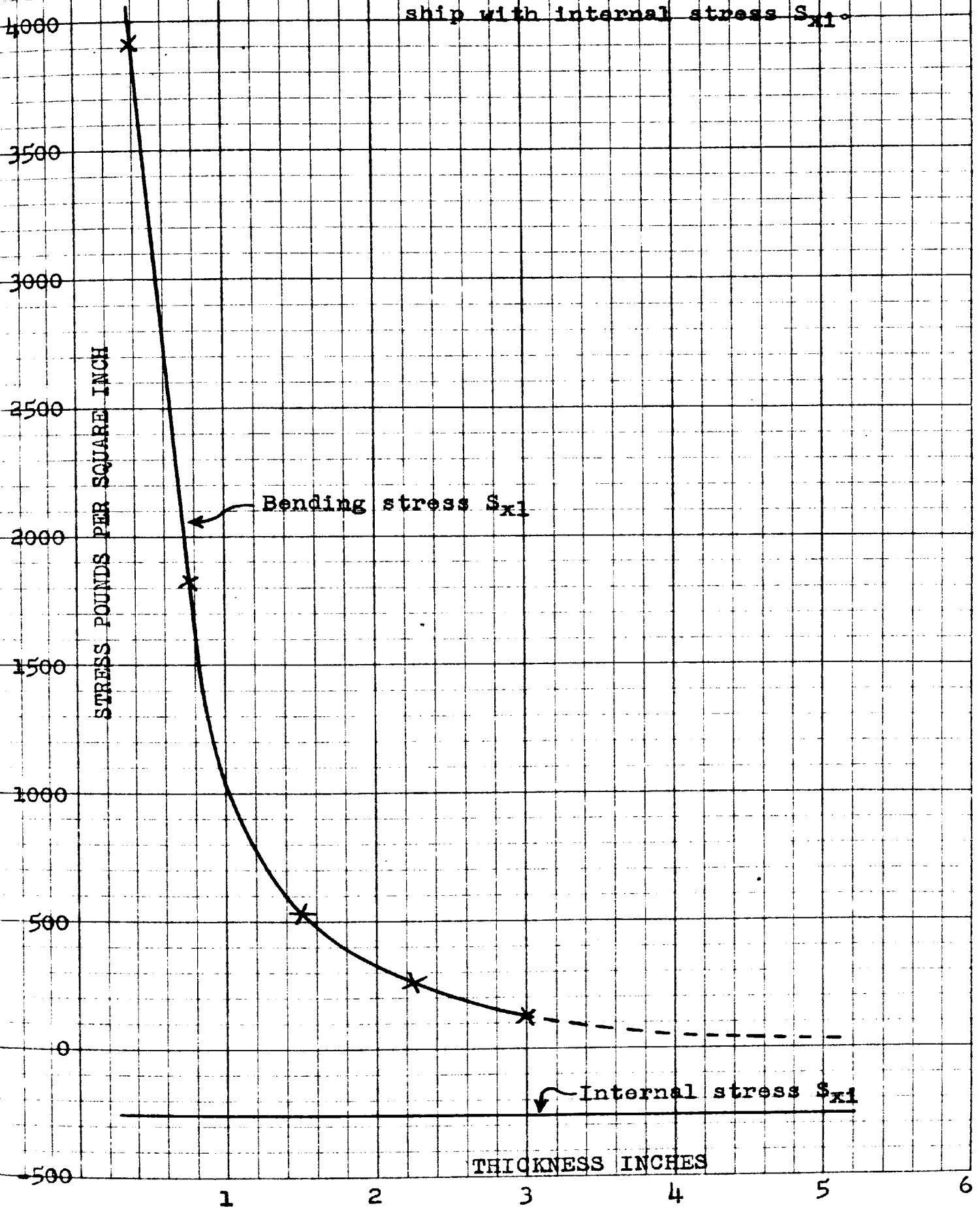
The preceding discussion implies that one of the original objectives of this experiment cannot be completely achieved. It is shown that the thickness does have a drastic effect, but since varying stress

TABLE 5

Tabulation of Some Calculated Stresses Existing in the Cross-Lap Specimen at Rupture for Various Thicknesses

(1) Thickness Inches	(2) Joint Strength Pounds	(3) Bending Stress S_{x1} PSI	(4) Internal Stress S_{x1} PSI	(5) Bending Stress S_{zt} PSI	(6) Internal Stress S_{zi} PSI	(7) Net Stress Along Grain Col. (3) + (4) PSI	(8) Net Stress Across Grain Col. (5) + (6) PSI
3/8	802	3910	-258	360	258	3652	618
3/4	1505	1830	-258	168	258	1572	426
1 1/2	1766	538	-258	50	258	280	308
2 1/4	1904	258	-258	24	258	0	282
3	1666	127	-258	12	258	-131	270

Figure 9. Plot of bending stress S_{x1} as a function of thickness of the cross-lap specimen, showing its relationship with internal stress S_{x1} .



situations exist, it may not be possible with the present data to characterize this effect by means of a simple equation which can be solved for maximum values. Several transformations of the data were made in order to determine whether the effect of thickness obeyed any mathematical laws which might aid in the interpretation of the results. One of the straight-line relationships which appeared promising was a logarithmic plot of the ratio of strength to thickness as a function of thickness, Figure 10. The data falls on a fairly good line. This would indicate an equation of the type:

$$\begin{aligned} \text{Log } Y/X &= a - bx \\ \text{or } Y/X &= 10^{(a - bx)} \\ \text{and } Y &= 10^a \left(\frac{X}{10^{bx}} \right) \end{aligned}$$

The data for the .68 specific gravity series of Table 3 were fitted to this equation by the method of least squares. Evaluation of the constants yielded the equation below:

$$Y = 10^{3.4661} \frac{X}{10^{0.3432X}}$$

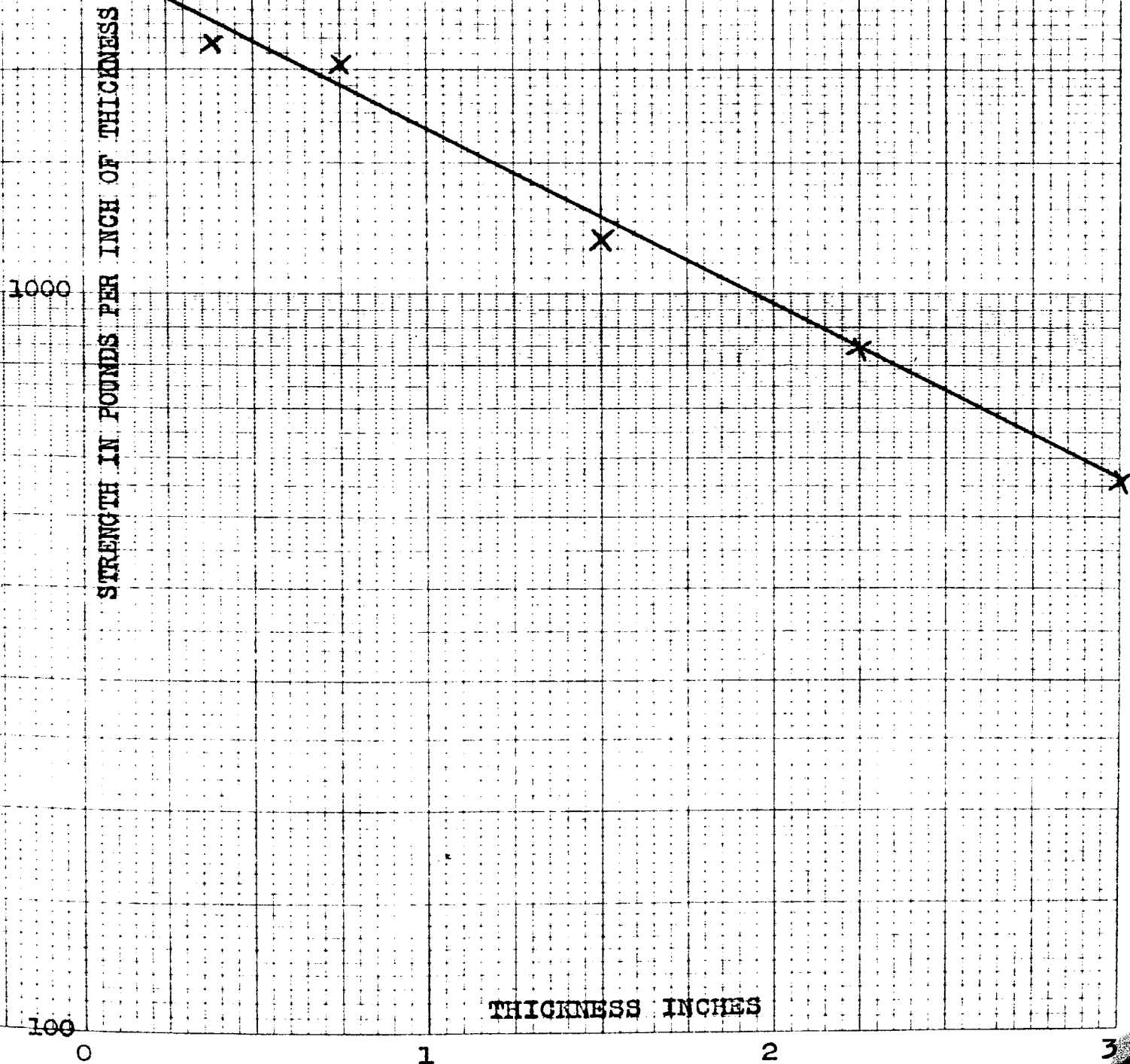
However, introducing various values of X (the thickness) into this equation showed strength values which were in general too low, with a peak at approximately 1 1/2-inches thickness rather than at 2 1/4-inches. The drop-off from the peak was more rapid than the data indicated should be the case, and reduced toward zero rather than toward a fixed value. For these reasons this could not be used as anticipated. Within the limits of the data however, a relationship is shown which enables the estimation of the effect of different increments of thickness.

As a matter of future investigation, when more points can be plotted, it would appear fruitful to attempt an equation of the form

$$Y = ax^b c^x$$

10,000

Figure 10. Logarithmic plot of ratio of strength to thickness as a function of thickness of the cross-lap specimen.



in which the constants are all positive numbers with c being less than 1. According to Running (25), this equation describes a curve which rises to a maximum and then recedes toward a constant value.

Since the equation of the line in Figure 10 did not completely represent the data as far as effect of maximum thickness of the blocks was concerned, it did not provide means of extrapolation to reveal the isolated effects of different specific gravity levels on the bond strength. Statistical evidence of the role of specific gravity is, however, available and this is discussed below.

The analysis of variance, Table 4, showed that specific gravity was the cause of significant variation about the grand mean, the significance being of the level which implies that the variation could be due to chance only one time in a thousand. The analysis furthermore indicates that there is no interaction between specific gravity and thickness, that is, that the effect of specific gravity is the same for all thicknesses. It therefore appeared valid to pool the strength values of each thickness level for the four specific gravity intervals and thus improve the weight of each average. A plot of the pooled averages is given in Figure 11 (dash line), from which a straight line relationship is strongly indicated. By inspection of this line, the following general equation for the effect of specific gravity on strength of the cross-lap specimen may be approximated:

$$Y_1 - Y_0 = b(X_0 - X_1)$$

$$\text{or } Y_1 = Y_0 + b(X_0 - X_1)$$

from the graph, $b = \frac{580}{.250} = 2320$

$$\text{hence } Y_1 = Y_0 + 2320 (\text{SpG}_0 - \text{SpG}_1) \quad (\text{A})$$

$$\text{where } Y_1 = \text{the strength at any specific gravity } (\text{SpG}_1)$$

$$Y_0 = \text{the strength observed at a specific gravity of } \text{SpG}_0 \text{ for a given thickness.}$$

The validity of equation (A) for expressing the relationship of specific gravity to strength at any thickness of blocks is confirmed in Figure 11 by the family of lines representing the thickness classes. It can be seen that the slopes are approximately the same. The slope at a thickness of 2 1/4 inches is particularly well defined by the experimental points while the other thicknesses show various irregularities. A constant slope between thickness classes is further evidence that no appreciable interaction exists between specific gravity and thickness. It should be noted however, that the effect of specific gravity upon bending is minute in comparison with the effect of thickness, and could well be lost in experimental variation.

The equation $Y_1 = Y_0 + 2320 (SpG_0 - SpG_1)$ may be considered as describing or accounting for the total effect of specific gravity upon the observed bond strength. As was noted earlier, a question exists regarding the precise function of specific gravity in affecting the strength. Does specific gravity affect the quality of the bond by affecting the porosity of the wood and the amount of wood substance available for bonding, or does specific gravity affect the way the specimen deforms under load, thus varying the stress concentration factor? In view of the lack of interaction with thickness, it may be inferred from the data obtained, that the quality of the bond is mainly affected by specific gravity change and that its effect upon bending is relatively minor. Further evidence for this inference may be deduced from the indication that the line representing averages in Figure 11 would pass through the origin if extended at the same scale. Straight lines representing the relationship of specific gravity to most strength properties of wood usually intercept the specific gravity axis at approximately 0.1. It would thus appear that the quality of a bond in the cross-lap specimen depends more upon the availability of bonding surface than upon the

The validity of equation (A) for expressing the relationship of specific gravity to strength at any thickness of blocks is confirmed in Figure 11 by the family of lines representing the thickness classes. It can be seen that the slopes are approximately the same. The slope at a thickness of 2 1/4 inches is particularly well defined by the experimental points while the other thicknesses show various irregularities. A constant slope between thickness classes is further evidence that no appreciable interaction exists between specific gravity and thickness. It should be noted however, that the effect of specific gravity upon bending is minute in comparison with the effect of thickness, and could well be lost in experimental variation.

The equation $Y_1 = Y_0 + 2320 (SpG_0 - SpG_1)$ may be considered as describing or accounting for the total effect of specific gravity upon the observed bond strength. As was noted earlier, a question exists regarding the precise function of specific gravity in affecting the strength. Does specific gravity affect the quality of the bond by affecting the porosity of the wood and the amount of wood substance available for bonding, or does specific gravity affect the way the specimen deforms under load, thus varying the stress concentration factor? In view of the lack of interaction with thickness, it may be inferred from the data obtained, that the quality of the bond is mainly affected by specific gravity change and that its effect upon bending is relatively minor. Further evidence for this inference may be deduced from the indication that the line representing averages in Figure 11 would pass through the origin if extended at the same scale. Straight lines representing the relationship of specific gravity to most strength properties of wood usually intercept the specific gravity axis at approximately 0.1. It would thus appear that the quality of a bond in the cross-lap specimen depends more upon the availability of bonding surface than upon the

Figure 11. Plot of strength of the cross-lap specimen as a function of specific gravity for each thickness level.

Δ - 3/8-inch thickness

O - 3/4 " "

$\triangle$ - 1 1/2" "

$\square$ - 2 1/4" "

$\square$ - 3 " "

X - Average all thicknesses

2400

2100

1800

1500

1200

900

600

300

STRENGTH POUNDS

SPECIFIC GRAVITY

0

.600

.650

.700

.750

.800

>>

strength properties of the adherend.

It is evident from the foregoing discussion that the evaluation of the cross-lap specimen with respect to thickness is not a simple matter, and that an intensive amount of experimental data is needed to reveal the ramifications of this factor. In summary: The effect of thickness of the wood blocks is very marked, particularly at the lower levels, and appears to exhibit an optimum in the vicinity of 2 1/4 inches. At the higher thicknesses, the operation of other factors become more pronounced. A possible explanation for the peculiar behavior of thickness is made on the basis of internal stress caused by swelling and shrinking of the wood due to dispersal of glue water, and its neutralization by bending of the specimen under load. Specific gravity was found to affect strength linearly but independently of thickness.

The use of a thickness variation as a second independent variable in the observation of factors which affect both the wood and the bond appears to offer a means of partially eliminating a source of confounding.

EXPERIMENT III

The Effect of Moisture Content of the Wood upon the Observed Strength

A study of the effect of wood moisture content upon bond strength is beset with the same factors mentioned in the previous experiment. In the present instance, the moisture content of the wood was expected to affect not only the behavior of the specimen under load, but also the behavior of the adhesive during the time when the bond was being formed. It would therefore be difficult to assess the specific effect of moisture content upon bond strength. The object of this experiment is to observe whether some separation of effects might be accomplished by means of a superimposed independent variable which should permit the operation and hence the accounting of the side effects.

The additional independent variable is thickness of the blocks comprising the specimen. As in the case of specific gravity, moisture content should affect the observed strength. Thickness of the specimen affects bending strength to a greater degree than moisture content. Moisture content, moreover, operates in an opposite manner to thickness in affecting bending strength. This is contrary to the previous situation where specific gravity and thickness operated in the same direction to increase the strength. In either case however, a thickness level should be reached where bending stresses no longer occur and the joint strength should attain a maximum value commensurate with the quality of the bond or the tensile strength of the wood normal to the grain.

Based upon its relation to the strength of the wood, high specific gravity wood was expected to yield a higher joint strength than low specific gravity wood. This was confirmed in the preceding experiment. Following the same reasoning, it would be anticipated that high moisture content wood should yield lower joint strengths than low moisture content wood since strength decreases with increasing moisture content. This would hold if there were no interaction of moisture content with the adhesive.

To ascertain these hypotheses this study was conducted in a manner identical to Experiment II, except that moisture content at three levels was substituted for the specific gravity variable. The moisture contents were chosen on the basis of practicality, being the normal operating equilibrium moisture contents given by the rooms in which the lumber was conditioned. It is noted that they include the optimum generally recommended, and the upper and lower extremes.

Design of Experiment

- (1) Three moisture contents, 5.4, 9.4 and 15.0 percent.
- (2) Five thickness levels of $3/8$, $3/4$, $1-1/2$, $2-1/4$, and 3 inches.
- (3) Four replications.
- (4) One adhesive - adhesive A.
- (5) Total number of specimens, 60.

Procedure

The procedure used in making and breaking the specimens, and recording the results was identical to that of Experiment II. The wood blocks were kept at equilibrium moisture conditions until time for gluing, after which they were returned to their respective conditioning

rooms for the seven day aging period before testing. Specific gravity was held constant for each moisture content level; that is, billets were selected from each conditioning room which were in the same specific gravity class.

Results

As before, the results were recorded as micro-inches of dynamometer deflection and were converted to pounds by the calibration constant, 1.509 pounds per micro-inch. Wood failure again was recorded for each specimen after rupture. The results are summarized by averages in Tables 6 and 7 below. Plots of the results are given in Figures 12 and 13.

The data show the characteristic rise to a maximum strength and subsequent decline with increasing thickness as occurred in the previous experiment. Also evident is a marked increase of strength with increasing moisture content particularly between the interval of 5.4 and 9.4 percent. This result is contrary to expectation on the basis of wood strength at the three moisture contents and indicates the operation of some other predominate factor. The data also indicates that whereas specific gravity seemed to affect all thickness levels equally, as shown by absence of interaction, the same is not true of moisture content. Here a significant interaction, occurring by chance less than 2.5 times in a hundred according to the analysis of variance (Table 7), appears to be in operation.

Discussion

The data of this experiment adds further confirmation to the decline in strength after a certain thickness has been reached. Since this situation was discussed previously, it need not be considered again,

TABLE 6

Summary of Results Obtained by Varying Moisture Content and Thickness in the Cross-Lap Specimen

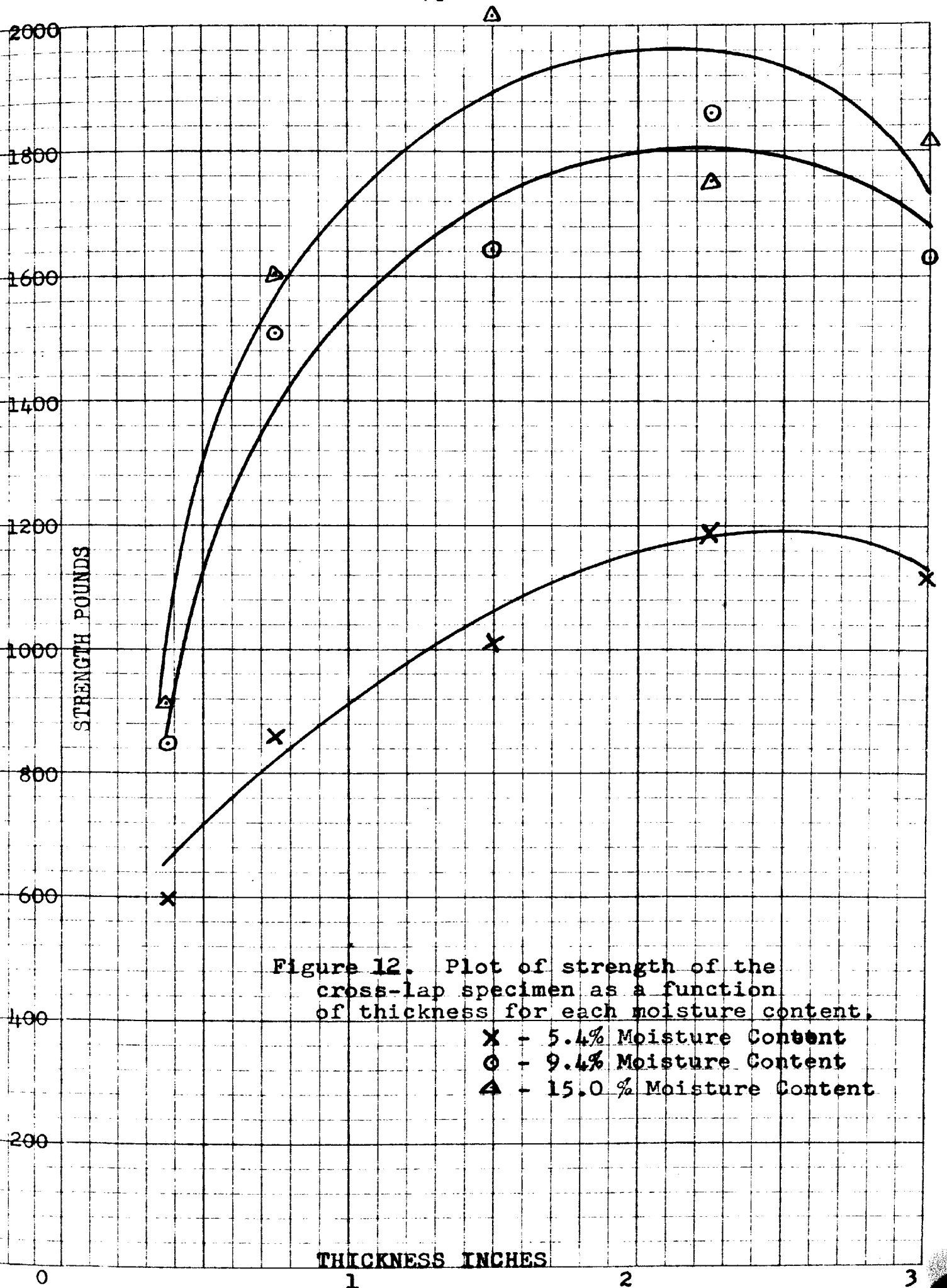
Thickness Inches	Strength - Pounds			
	Moisture Content			
	5.4%	9.4%	15.0%	Avg.
3/8	598*	846	911	785
3/4	859	1508	1605	1324
1 1/2	1012	1641	2016	1556
2 1/4	1187	1859	1753	1600
3	1116	1631	1815	1521
Average	954	1497	1620	1357
Percent Wood Failure				
3/8	8	30	40	26
3/4	3	29	25	19
1 1/2	5	16	35	19
2 1/4	8	25	21	18
3	8	15	42	21
Average	6	23	33	21

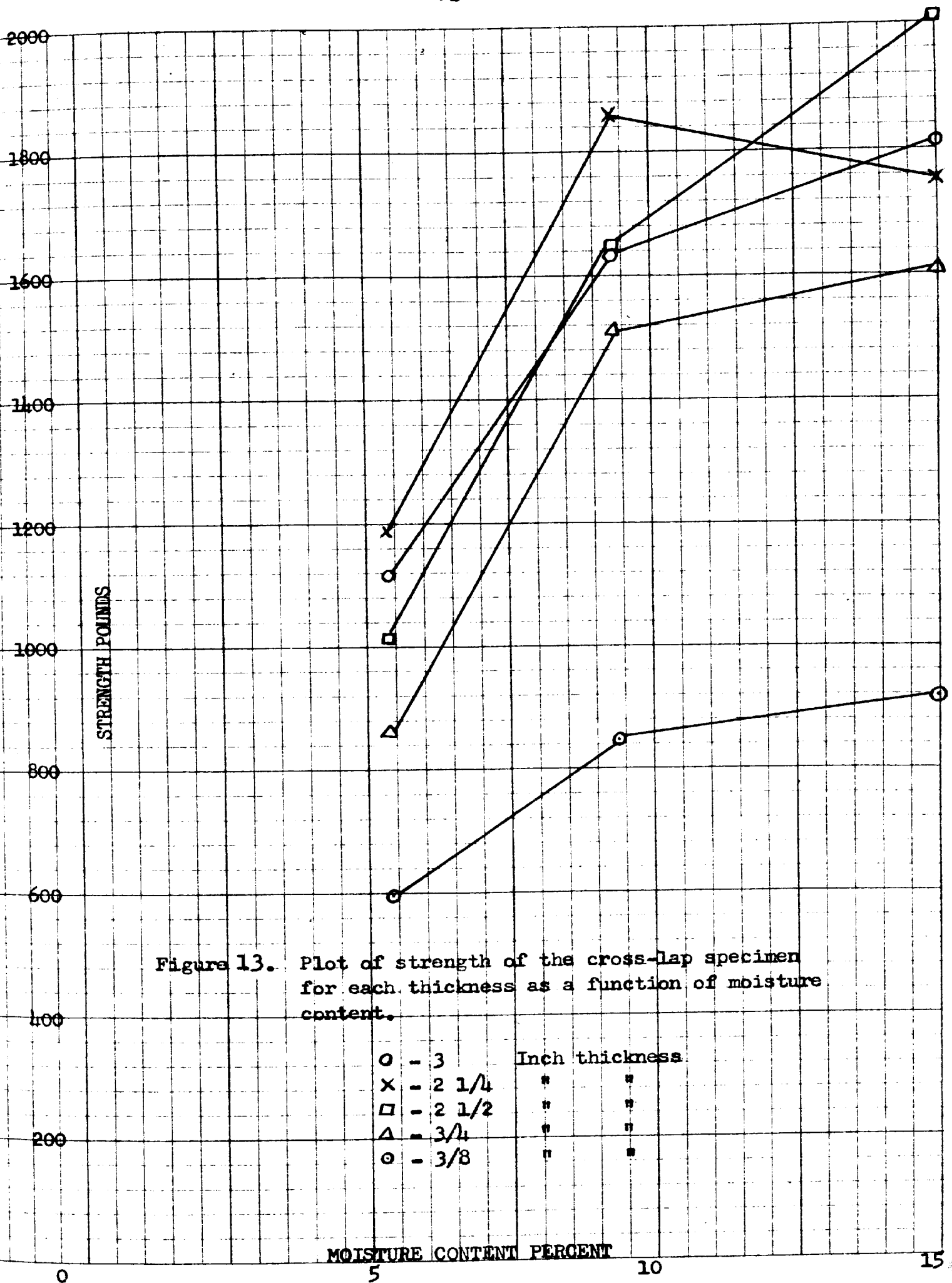
* Each figure is the average of four observations.

TABLE 7

Analysis of Variance for Moisture Content and Thickness

Source	N(SS)	DF	N(MS)	F	P
Total	756,114,299	59			
Sub-totals	667,969,454	14			
Thickness	326,535,134	4	81,633,784	41.68	< .0005
Moisture Content	301,216,184	2	150,608,092	76.89	< .0005
Interaction T x M	40,218,136	8	5,027,267	2.57	< .025
Error	88,144,845	45	1,958,774		





except to inquire whether the interaction observed had any effect upon the location or magnitude of the decline.

The major phenomena which requires attention is that the effect of moisture content on observed bond strength does not accord with the relationship of strength of wood to moisture content. Since higher strengths are expected of wood with low moisture content, it may be presumed that specimens of low moisture content should give the highest strength. The reverse being the case, two inferences may be made, one, that an effect has been produced on the quality of the bond, and two, that a stress concentration factor is caused to vary with the change in moisture content.

In support of the theory that the quality of the bond is reduced on low moisture content wood, are considerations of the mechanism by which resin adhesives cure from a liquid state to a solid mass. Urea adhesives, such as the one used in this experiment, are condensation products of urea and formaldehyde. When manufactured, they are condensed to a molecular size which is a compromise among such factors as water solubility, storage life, speed of curing, and consistency. Curing of the adhesive to form a bond between two wood surfaces, involves a means of reactivating the condensation reaction which has been arrested for the benefit of longer storage life. The reactivation of the reaction is done by lowering the pH of the mixture with suitable catalysts, or by increasing the temperature of the glue line. In either case, the result is progressive increase in molecular size toward an insoluble gel and subsequent cross-linking to produce a strong, hard, rigid, brittle mass.

The traditional conception of the development of strength by the so-called natural adhesives is that loss of water to the wood causes the adhesive to harden. Such is not the case with synthetic resins. The hardening action takes place in a water medium. Water, in some optimum

amount, is necessary during curing to facilitate molecular orientation, and thus promote the maximum number of intermolecular bonds, which in the last analysis, determine how strong the adhesive film will be. It is conceivable that when a cold-setting urea resin adhesive is applied to wood which is too dry, the wood is capable of absorbing water from the adhesive mixture faster than is good for the chemical action of curing. A weakness within the bond thus develops.

Weakness on the outside of the adhesive film, that is, at the interface between wood and adhesive, also can be visualized. The rapid loss of water from the adhesive mixture in contact with the wood surface, causes an increase in the consistency of the glue. In consequence, the adhesive is retarded in its penetrability into the wood and a shallow bond results.

This reasoning would lead to the belief that the higher the moisture content of the wood, the stronger might be the cured adhesive film. There appear to be limitations also on the upper limit of moisture content and a number of factors may be responsible, such as over-penetrability, diffusion of catalyst, and dilution at the interface. The present data was not intended to show a maximum moisture content and further speculation in this regard is not warranted.

The main point is that at low moisture content, 5.4 percent, the joint strength is definitely low, being of the order of 40 percent less than that at 15 percent moisture content. A plot of strength as a function of moisture content, Figure 13, using the values from Table 6 indicates that the curves joining the points plunge rather sharply toward the zero axis and suggests that further reductions in moisture content would produce drastic reductions in strength of the joint. This situation further supports the inference that a decrease in bond quality produces the major effect at the lower moisture contents rather than an increase in

stress concentration. The latter factor alone would not reduce the strength to zero as the moisture content approached zero, but might more probably create an asymptotic value below which the strength would not fall. It is somewhat easier to visualize the bond quality reducing toward zero as the moisture approached zero since the wood becomes increasingly more absorptive and hence more powerful in removing water from the adhesive before curing can be completed.

A final observation in this regard was provided by the chisel and the file used in removing glue squeeze-out from the edges of the blocks. A small wood chisel was used to scrape away as much glue as possible immediately after the assembly jigs had been secured. Just prior to testing, occasional small particles of hardened glue were found on the bearing surfaces of the blocks, or had been overlooked at the joined edges. These were then removed with a few light strokes of a file. The glue that was removed with a chisel was always of a rubbery texture when removed from high moisture content wood, and always crumbly when removed from low moisture content wood. Later, in using a file on this squeezed-out glue, it was hard and firm as glass on high moisture content wood, and friable as cinders on low moisture content wood. It was apparent that the latter represented an unfavorable condition for the hardening of the adhesive.

The interaction between moisture content and thickness is not easily explained. From Figure 12 it is evident that one source of interaction is related to the slope of the curves for the three moisture contents. The curve for the 5.4 percent moisture content wood is considerably flatter than the other two. In other terms, the increase in strength with increase in block thickness is not as pronounced at 5.4 percent moisture content as it is at the higher moisture contents. For example, increasing the block thickness from $3/8$ to $3/4$ inches causes

an increase of 261 pounds (44 percent) at 5.4 percent moisture content, an increase of 662 pounds (79 percent) at 9.4 percent moisture content, and an increase of 694 pounds (77 percent) at 15.0 percent moisture content.

One reason for such behavior might be considered as additional substantiation of the previous argument, i. e., that the bond strength is in fact low on the lower moisture content wood. The low strength of the bond makes it incapable of realizing full advantage from increasing block thickness.

A shift in location of the maximum strength with respect to thickness of the blocks also appears to exist. This occurs at the 2-1/4 inch thickness for 5.4 percent and 9.4 percent moisture content, and at 1-1/2 inch thickness for 15 percent moisture content blocks. On the basis of the reasoning developed in the previous experiment this would indicate a condition of greater internal stress, being in the order of 600 psi, for the specimens glued at 15 percent moisture content. It is difficult however, to see how the internal stress could be greater at high moisture contents than at low. Actually, for the same amount of water pickup at higher moisture contents, there should be less stress created since a lower Young's modulus also exists.

A possible explanation may reside in a difference in rate of hardening* on the different moisture content woods and this in turn could conceivably cause a difference in the amount of swelling which could occur with the imbibition of glue water. The rate of hardening is much faster on low moisture content wood than on high because the drying action complements the curing reaction. As a consequence, the maximum amount of swelling may not occur, (for the given amount

* Note that the term hardening is used in contrast to curing since the latter implies the chemical reaction, and this rate is not affected.

of glue water), before the adhesive is hard enough to restrain the swelling. With less swelling before hardening, there will be less shrinkage afterward.

The reconciliation of this situation requires intensive experimentation with this specific objective in view. It appears increasingly evident that factors affecting the mode of failure of bonded wood joints are in operation. Further information is needed regarding the question of whether a stress limit or a strain limit is in existence and whether factors operate to make either limit effective in a given instance. The situation with regard to the preceding paragraph may indicate that equalization of strain is occurring due to the bending action rather than equalization of stress, since greater deformations under load are involved at the higher moisture contents.

That changes in stress distribution also may have a bearing on the observed strength differences between moisture contents can be deduced from the continued increase in strength above 9 percent moisture content. Data showing development of better bond strength at moisture contents above 12 percent than at 8 - 9 percent is not reported in the literature. It is frequently noted however, that bonds tested in the dry condition are lower in strength than those tested after some soaking. This is usually attributed to the greater plasticity of the wood at higher moisture contents and the consequent greater ability to disperse stress concentrations. Whether or not such action can be attributed to the cross-lap specimen is debatable. However, if it can be assumed that bonds made at 15 percent moisture content are in reality equal to those made at 9 percent, the increase in observed bond strength might be associated with a more favorable stress situation.

Pryor (19) in working with specimens of the cross-lap type, suggested that differences in moisture content of the wood had little effect

upon the observed strength. In later work (13) wherein the moisture content of the wood was increased slightly after the adhesive had hardened, an increase in strength was noted and the conclusion was drawn that equalization of the stress caused by dispersal of glue water had occurred. The author feels that while action of the latter type exists, the effect of changes in moduli of elasticity should not be discounted.

The existence of an interaction between moisture content and thickness implies that the bending properties of the specimen may have an influence upon the strength observed at the different moisture contents. It can be seen from Table 8, a tabulation of the first differences between vertical and horizontal pairs of observations from Table 6, that the differences between moisture contents, Table 8 (A), vary greatly at the different levels of thickness. Of particular note is the trend toward less difference as the thickness of the blocks decreases. It is conceivable that further reductions in block thickness could wipe out a large percentage of the differences observed between moisture content. Conversely, it appears that an optimum thickness exists for maximizing the differences. Likewise the differences between thickness levels are shown in Table 8 (B) to vary with the moisture content.

One of the objectives of this experiment was to determine whether the effect of moisture content upon observed strength could be separated into two distinct effects, i. e., that of the bond quality and that of the physical properties of the wood. Following the reasoning in the previous experiment, it should be possible to achieve an isolation of the effects. The effects of moisture content upon bending should gradually disappear with increasing thickness, leaving a residual difference which may be ascribed to the quality of the bond. In view of

TABLE 8

First Differences Between Paired Strength Values
of Moisture Content and Thickness

(A) Differences between Moisture Content Levels

Thickness Inches	Pounds Strength Differences Between Moisture Content Levels		
	5.4% and 9.4%	9.4% and 15%	Average
3/8	248	65	157
3/4	649	97	373
1 1/2	629	375	502
2 1/4	672	-106	281
3	515	184	345
Average	543	164	354

(B) Differences between Thickness Levels

Percent Moisture Content	Pounds Strength Difference between Thicknesses Levels				Average
	3/8 and 3/4	3/4 and 1 1/2	1 1/2 and 2 1/4	2 1/4 and 3	
5.4	261	253	175	-71	155
9.4	662	133	218	-228	196
15.0	694	411	-263	62	226
Average	539	266	130	-237	286

the statistical interaction between moisture content and thickness, it would appear that a differential effect has occurred with these two factors and this precludes generalizing upon the effect of either.

The interaction between moisture content and thickness appears, however, to have definite limitations and this leads to further inquiry into the nature of the relationship of these two factors. A similarity of response between moisture content and thickness may be deduced from Figure 14. Figure 14 is a logarithmic graph of the strength per unit of thickness plotted as a function of the thickness for each moisture content (Table 9). The expression of strength in terms of unit thickness represents a rate of strength change with thickness change. The logarithmic linearity of the plotted points indicates that the rate of strength change is exponentially and inversely proportional to the thickness within the limits of the data. The linear relationship holds true for each level of moisture content. Moreover, the parallelism of the lines for each moisture content, suggests that the rate of change of strength with thickness is dependent upon the level of strength. If this is the case, a corollary condition must also exist, i. e., that the interaction was not due to differential effect of moisture content upon the wood at the different thicknesses; a condition which, as in the case of specific gravity, could have been due to the small magnitude of the moisture effect in comparison to the effect of thickness.

It appears therefore that the curves of Figures 12 and 13 may be regarded as similar in character and reflect the same general relationships for the two independent variables, moisture content and thickness. An inversion of strength with different combinations of moisture content and thickness is not indicated. A statement of the situation with regard to these factors may be made, viz: that moisture content and thickness both affect strength independently of the other but

TABLE 9

Pounds Strength Divided by Thickness for Each Level
of Thickness and Moisture Content

Thickness Inches	Pounds Strength Per Inch of Thickness		
	Percent Moisture Content		
	5.4	9.4	15.0
3/8	1600	2250	2420
3/4	1145	2010	2240
1 1/2	675	1095	1350
2 1/4	525	825	780
3	372	545	605

10,000

Figure 14] Logarithmic plot of the ratio of strength to thickness as a function of thickness for each level of moisture content.

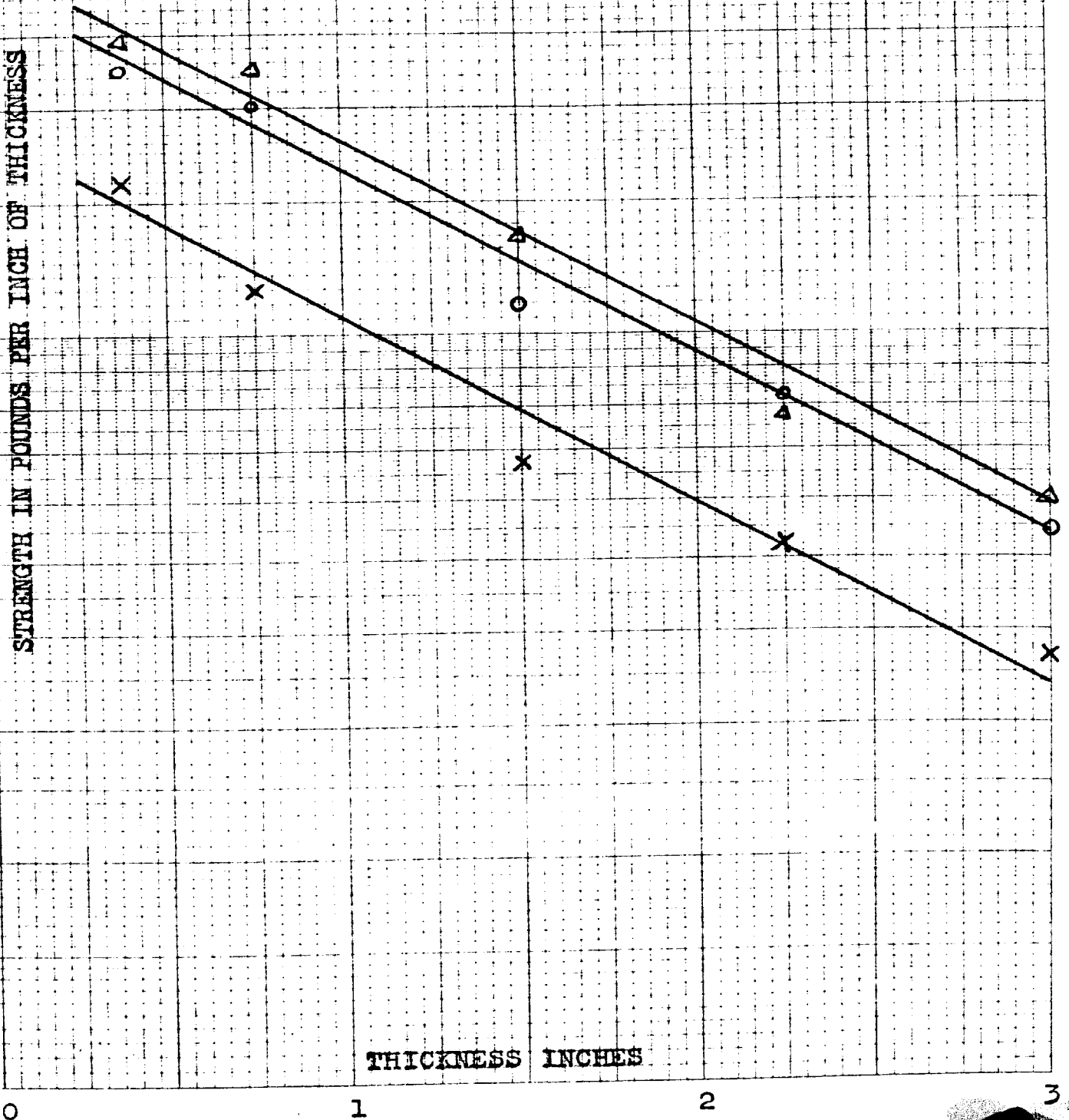
x - 5.4% moisture Content
 o - 9.4% " "
 Δ - 15.0% " "

STRENGTH IN POUNDS PER INCH OF THICKNESS

THICKNESS INCHES

1000

100



the magnitude of the effect of one is dependent upon the level of the other.

In summary, it may be said that moisture content has a marked effect upon the observed bond strength of the cross-lap specimen and that the measurement of this effect is dependent upon the thickness of the specimens. Thus, a statement as to the effect of moisture content upon bond strength must be conditioned by a reference to the thickness of the blocks comprising the specimen. While the effect of moisture content appears to be largely one of bond quality, the effect upon the physical properties of the specimen also must be taken into consideration. Further research into this matter should include adhesives whose bond strengths are independent of moisture content.

EXPERIMENT IV

The Interaction of Rate of Cure with Wood Moisture Content

In the previous experiment, a question was raised as to whether an effect upon strength might exist due to differential rates of hardening on the various moisture content woods. It was postulated that different rates of hardening could occur with the same adhesive on different moisture content wood due to differing absorptive power. It was also shown that a different quality of adhesive hardness likewise occurred at the different moisture contents. Thus, moisture content influenced both the rate of hardening and the quality of the bond. Observation of these two effects is the subject of this experiment.

As was mentioned earlier, the curing of a urea resin is a chemical reaction, regulated by the presence of acid catalysts. The pH of the adhesive mixture largely controls the rate at which the reaction proceeds. Thus the rate of cure may be varied by varying the amount of catalyst in the mixture. The adhesive used in the previous experiments was one in which a fixed amount of catalyst had been incorporated by the manufacturer. The amount normally incorporated is such as to provide a useable mixture for a period of three to four hours at 70 degrees Fahrenheit. Such a mixture requires clamping times of four hours to overnight and is considered to meet the average requirements in this respect. Often however, mixtures may be desired which are faster or slower curing. In this case the manufacturer may supply the resin without catalyst incorporated and the user then adds the amount he feels

necessary. A urea resin, similar to Adhesive A but with the catalyst separate, was obtained for this experiment. It is designated as Adhesive C.

By adding one, two, and three parts of catalyst per 100 parts of resin the rate of curing could be varied to two, four, and five hours at 75 degrees Fahrenheit. These three rates of curing were imposed upon the three moisture contents at a single thickness level, 3/4 inches, for the purpose of observing the independent effect of the rate of curing factor, the rate of hardening by water loss being constant within moisture content intervals.

Design of Experiment

- (1) Three moisture contents of the wood, 5.4, 9.4 and 15.0 percent.
- (2) Three levels of catalysis, 1 part, 2 parts and 3 parts per 100 parts of resin corresponding to 2 hours, 4 hours and 5 hours curing time.
- (3) Five replications per combination making a total of 45 specimens.

Procedure

The wood blocks were prepared and selected in a manner identical to the earlier experiments. They were also assembled into specimens in the same manner. Specimens of the different moisture contents representing a level of catalysis were glued with the same adhesive mixture. The total time lapse between applying the adhesive to the first specimen and the last specimen was 15 minutes. Thus the element of age of the adhesive for each moisture content level was considered negligible.

After assembling, the specimens were placed in their respective controlled atmospheres to condition for seven days. At the

end of this time they were tested on the Dillon Tester as in the preceding experiment.

Results

The results, transformed from micro-inches to pounds, are summarized in Table 10. A summary of an analysis of variance is given in Table 11. Figures 15 and 16 are plots of the strength observed as a function of moisture content and as a function of amount of catalyst used, respectively.

The results indicate that while moisture content of the wood maintains an overpowering effect on the observed strength, the amount of catalyst, or in reality, the rate of cure of the adhesive, does not appear to have a strong direct effect. The analysis of variance shows that the effect due to the amount of catalyst could have occurred by chance between 5 and 10 times in a hundred experiments. Such a large opportunity for chance results is usually regarded as grounds for disregarding the influence of a causal factor. In this case, however, the presence of a prominent interaction shows that the effect of catalyst depends upon the moisture content of the wood. This fact tends to minimize the statistical confirmation of the direct action of catalyst because the comparisons are made on averages which combine all moisture contents in each catalyst level.

Discussion

Considering the effect of catalyst on each moisture content, it is seen that an effect is present, but is different for each moisture content. The effect at low moisture contents is direct, that is, increasing catalyst increases the strength. At high moisture content the effect is inverse; increasing catalyst reduces the strength. On the

TABLE 10

The Effect of Amount of Catalyst and Wood Moisture Content upon Observed Strength

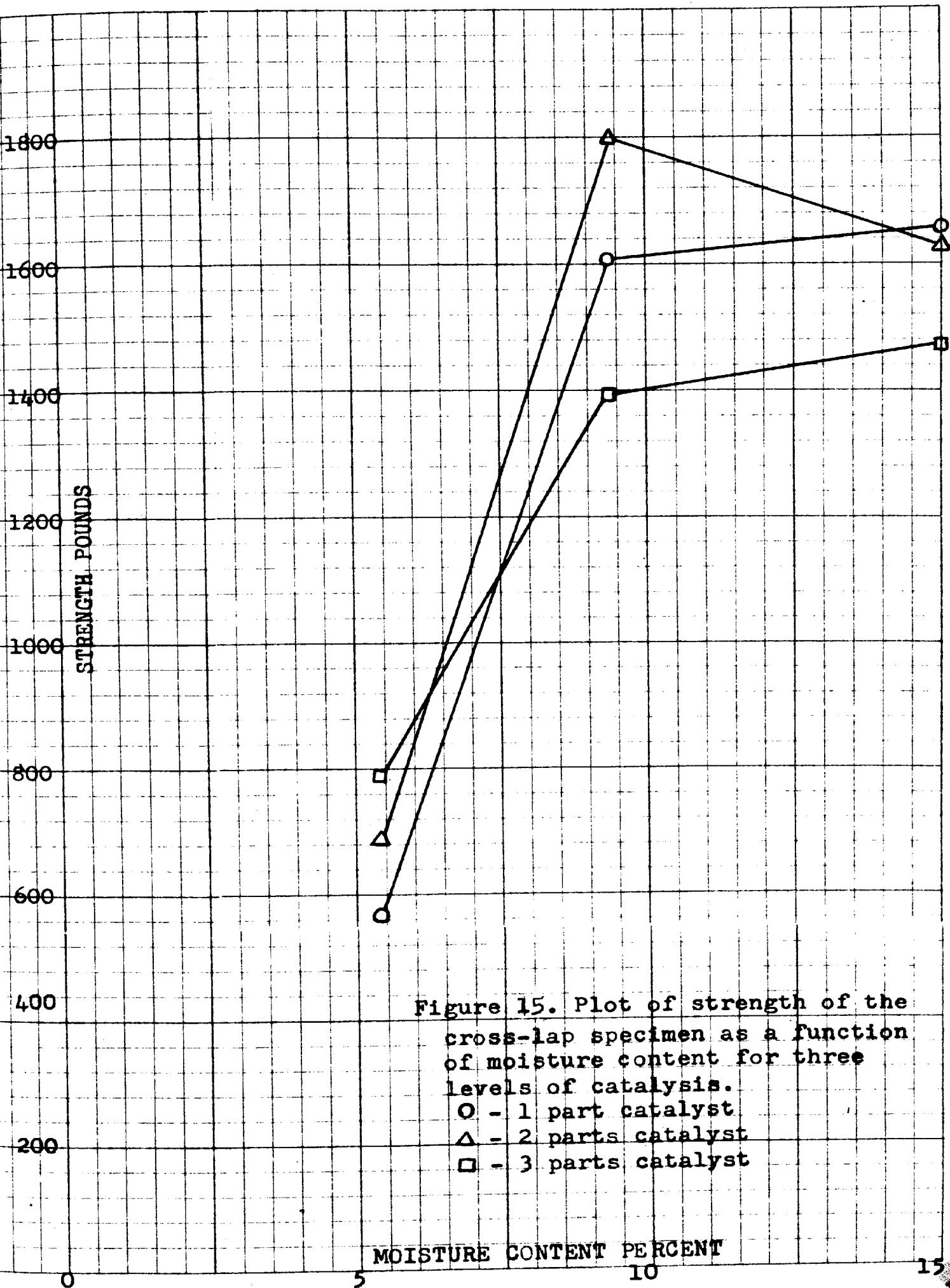
Parts Catalyst	Strength - Pounds			
	Percent Wood Moisture Content			
	5.4	9.4	15.0	Average
1	566*	1610	1650	1276
2	686	1795	1623	1368
3	783	1395	1471	1216
Average	674	1600	1581	1286
Percent Wood Failure				
1	0	25	17	14
2	0	49	17	22
3	0	24	28	18
Average	0	33	21	18

* Each figure is the average of five observations.

TABLE 11

Analysis of Variance Summary for Amount of Catalyst and Moisture Content

Source	N(SS)	DF	N(MS)	F	P
Total	446,837,264	44			
Sub-totals	402,158,402	8			
Catalyst	7,859,666	2	3,929,833	3.17	>.05, <.10
Moisture Content	374,626,406	2	187,313,203	150.93	<.0005
Interaction	19,672,330	4	4,918,082	3.96	<.01
Error	44,678,862	36	1,241,080		



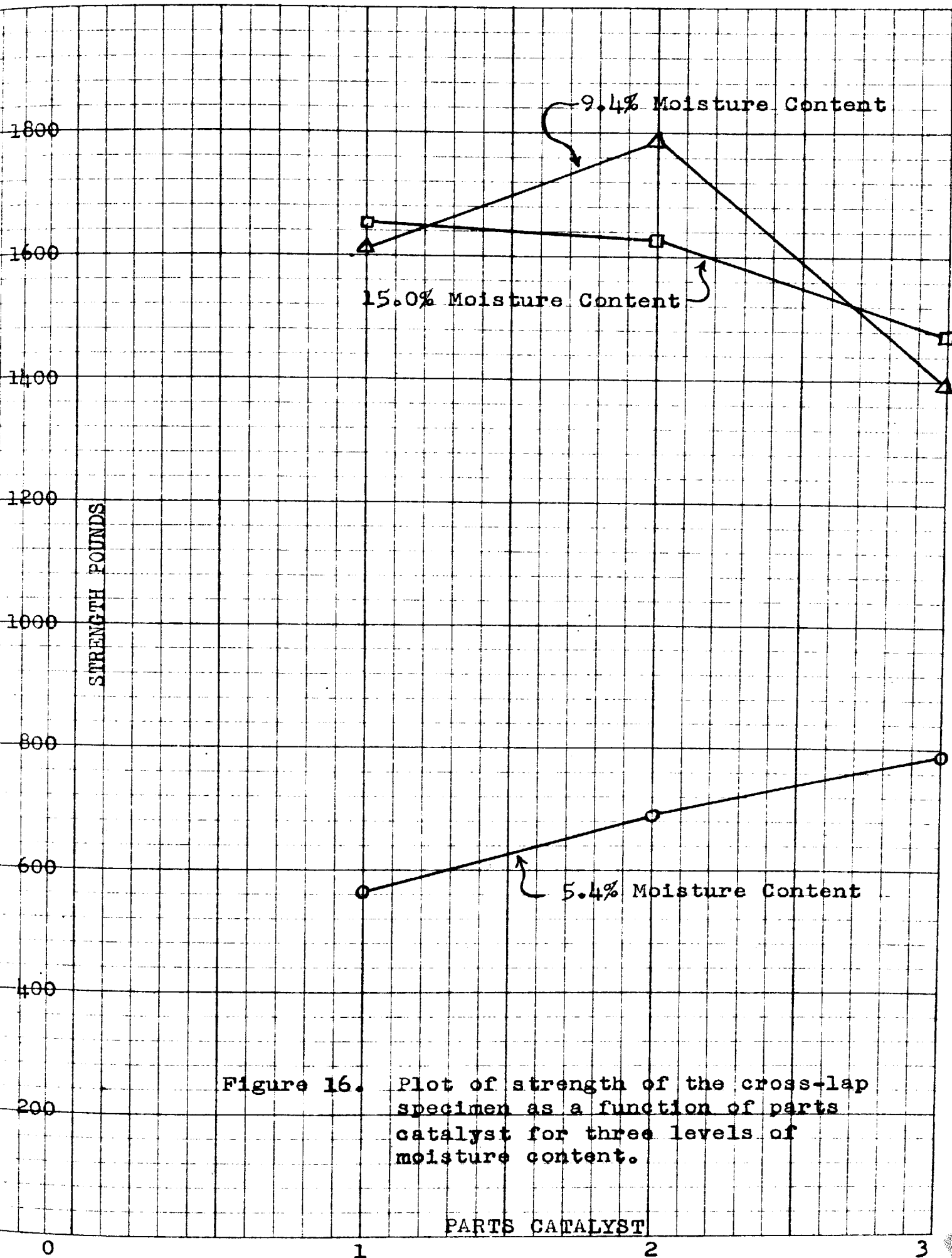


Figure 16. Plot of strength of the cross-lap specimen as a function of parts catalyst for three levels of moisture content.

other hand, an optimum amount of catalyst is strongly indicated at the intermediate moisture content.

Results of this nature suggest that a number of factors are in operation during the formation of an adhesive bond to wood. While these factors are not specifically the subject of this study, and therefore not experimentally substantiated, they would have a bearing on the planning of fuller investigations and some discussion of them is in order.

Three situations may be visualized as occurring during bond formation which may be affected by the rate of cure of the adhesive and the moisture content of the wood. These are:

- (1) The balance between rate of water loss from the adhesive and the rate of curing which affects the molecular orientation both at interfaces and within the adhesive film.
- (2) The amount of penetration of the adhesive into the wood which is affected both by the rate of water loss into the wood, and by the rate of curing. The effect is produced through a change in mobility of the adhesive.
- (3) The amount of water retained by the adhesive after curing which is affected by the same factors as in (2). In this case the effect operates through the strength of the adhesive film and the possible shrinkage which it can subsequently undergo.

Introducing these situations into Table 10 and Figures 15 and 16, several interesting deductions may be drawn. At low moisture contents, increasing the rate of cure by increasing the amount of catalyst tends to increase the strength of the joint. The action is evidently one where more water is present in the adhesive and in its immediate vicinity during cure and this improves the molecular activity. The presence of more water during cure is a consequence only of the faster curing. Despite the rapid absorption by the wood, a greater proportion of water is present at particular stages of cure, the early stages perhaps being the most critical.

Would this increase in strength at low moisture contents continue with further increases in catalyst? A limit to the improvement of strength by adding catalyst is postulated on the basis of situation (2). The penetration of the adhesive into the wood would be progressively reduced by the compounding effect of decreased mobility due to loss of water and due to the increased rate of cure. Thus the bond would be anchored more and more to surface fibers if anchored at all. A limit exists also in the bounds of practicality. Further increases in catalyst would produce mixtures having extremely short working lives and hence would be difficult to handle.

Of interest in this connection is one commercial practice which attempts to avoid the latter difficulty. When extremely rapid curing is desired, a concentrated liquid solution of the catalyst is sometimes applied to one side of the joint and the uncatalized resin adhesive is applied to the other side. When the two parts are brought together, the catalyst diffuses into the resin and brings about the cure. This system achieves a fast cure with a resin mixture which has an indefinite working life. It may be noted, however, that the side of the joint carrying the catalyst is disposed to insufficient penetration because the high concentration of catalyst quickly immobilizes the adhesive. Situation (3) also applies here in that too much water may be occluded by the fast curing resin and this will later lead to shrinkage stresses and crazing of the adhesive film. Finally it may be said in caution that the high concentration of acid catalyst in contact with wood is a potential cause of degradation and ultimate failure of the joint.

Returning to the question of increased strength with increasing catalyst on low moisture content wood, the inference may be drawn that further improvement in strength would accrue until overcome by the lack of penetration. Where this point might be, is not shown by the

data. It can only be deduced, from Figure 16, that more than three parts of catalyst would be needed to reach maximum strength.

At the intermediate moisture content, where the level of strength is much greater, it appears that the balance between penetration, rate of curing, and rate of water loss to the wood has occurred within the range of catalysts used. A distinct optimum is shown by the data at two parts catalyst. Following the above reasoning, this would indicate that with one part catalyst, the rate of curing is too slow in comparison with the rate of water loss. At three parts catalyst, the rate of water loss has combined with the increased rate of cure to reduce the amount of penetration and hence the strength.

The results on the high moisture content wood further demonstrate, although not as clearly, the dependency of bond strength upon a proper balance between rate of curing and rate of water loss. While the slope of the curve for 15 percent moisture content in Figure 16 is upward toward the left, it is obvious that it must soon reverse toward the origin since as the catalyst reduces toward zero the degree, as well as the rate of cure will eventually be affected. Hence it may be inferred that the optimum amount of catalyst for this moisture condition lies between zero and one part, and quite probably is close to one.

It has been theorized that the rate of water loss should be in balance with the rate of cure in order to obtain maximum strength of the bond. The data appears to support the theory in the case where the rate of water loss is too great in comparison with the rate of cure. That the reverse may also be true is indicated by the decline in strength with increasing catalyst on high moisture content wood. Although considerably more experimental confirmation is needed, a theoretical basis for such an occurrence may be found in the gel structure of the adhesive film. As was mentioned earlier, it is possible for resin adhesives, such

as used in this study, to cure to a rigid solid while contained in an impervious receptacle. This means that all of the water with which the resin was originally mixed, approximately 40 percent of the total weight, has been occluded, that is, retained within the gel structure of the resin. The retention of most of this water however is only temporary. As further curing occurs, much of this water is expressed from the structure with concomitant shrinkage of the resin bulk. As curing progresses, additional water is liberated as water of condensation, a by-product of the curing reaction.

The amount of water contained in the cured adhesive can conceivably influence the strength of the film, as well as the state of stress which may be generated. Whether or not such changes can actually be reflected in the strength of a bond is not completely answered. It appears that the element of time would have to be introduced into the situation in order to observe the effect of this factor because the amount of water in the film, and hence the strength, would vary with time. In this experiment, it was assumed that complete cure took place within seven days. In view of the lower strengths observed, this may have produced an error in the case of the high moisture content wood.

In summary, cross-lap specimens assembled at three different moisture contents with an adhesive catalyzed at three different levels were observed. Strength values indicate that the effect of catalyst is largely dependent upon the moisture content, being direct at low moisture content, inverse at high moisture content, and showing an optimum at intermediate moisture content. Some reasons for this behavior were discussed and these attempted to relate the rate of curing and the rate of moisture loss with the bond strength.

EXPERIMENT V

Response of the Cross-Lap Specimen to Built-In Flaws

The evaluation of an adhesive by means of a strength specimen presupposes accuracy in the fabrication of the specimen, in the loading mechanisms used to make and break the specimen, and in the grips used to hold the specimen during loading. In such an idealized system the strength observed would be uniform for a given adhesive, and would bear some consistent relationship with its inherent properties. Unfortunately, glued wood specimens cannot be assumed to be perfect due to the non-homogeneity of the wood, due to inaccuracies in the machining of the wood surfaces, and due to varying gluing conditions. Insofar as these irregularities constitute weaknesses in the joint quite apart from the quality of the adhesive, and thereby produce departures in strength from a theoretically uniform value, they may be considered as flaws in the bond. This experiment was planned to show what influence known flaws might have on the observed strength of the cross-lap specimen.

The effect of flaws in the specimen may be obscured or accentuated by the grips and loading mechanism. Grips, or test fixtures, are usually designed to reconcile the inaccuracies of the specimen with the inaccuracies of the testing machine and permit load to be applied uniformly at a point, at a line, or at an area. Two broad types of grips may be defined, i. e., rigid, and self-aligning. The self-aligning grip, as the name implies, is flexible in all planes parallel and perpendicular to the direction of applied force, and thus tends to

equalize stresses. The rigid grip, on the other hand, is inflexible and can do nothing to change the direction of an applied load. The self-aligning grip is therefore considered to compensate for machine and specimen inaccuracies, while the rigid grip compounds them into the final strength value.

It may be reasoned that the self-aligning grip in tending to equalize stresses, will continually attempt to conform to the resistance pattern set up by the specimen during testing. If a weakness develops, a shift in loading automatically occurs. Thus the grip, in a sense, is capable of pursuing a weakness, and therefore should be sensitive to local defects in the bond. The rigid grip, in being unable to conform to the changing stress pattern occasioned by such irregularities, should be insensitive to them.

A choice seems to exist between a grip which will equalize stress but accentuate the defects in a bond, and a grip which will equalize the defects in a bond but which may be sensitive to testing machine and specimen shape factors. In normal testing work it is usually considered of the utmost importance to assure the equalization of stress in the specimen. Most grips are therefore of the self-aligning type. For evaluating adhesive properties by means of a strength specimen which has been bonded with the adhesive in question, it would appear that a rigid grip would tend to overlook fortuitous defects in the bond and present a more accurate picture of the bond as a whole.

An ideal grip for evaluating adhesive properties would thus be a combination of the self-aligning and the rigid type. Such a grip would compensate for gross irregularities in the testing apparatus and in the machining of the specimen, and at the same time be insensitive to local defects in the bond. The grip which is used with the diaphragm machine, Figure 17, was intended as a compromise and may be regarded

as a semi-rigid type. Each pair of bearing edges are mutually rigid, the upper pair being in addition, fixed. The lower pair, by virtue of floating on the diaphragm, is somewhat flexible and can accommodate to some unevenness of the bearing edges. This semi-rigid grip is referred to as the compression saddle, or simply as the "saddle" in subsequent discussion.

The self-aligning type of grip has been used almost exclusively in the experiments reported in this paper, Figure 18. It was felt that since the emphasis was on the specimen, it was desirable to assure the elimination, as much as possible of the effects of the testing machine, eccentric loading and other sources of variation not associated with the quality of the bond being measured. This grip is referred to as the swivel grip. The chief features of this grip are that each of the four bearing edges are individually suspended and pivoted at right angles from a circular connecting beam. The beam in turn is joined to the loading mechanism through a universal joint. Thus each bearing edge can adjust itself independently of the other three. The actual bearing edge is comprised of a short rod $1/4$ -inch in diameter, positioned so as to contact the specimen 0.20 inches from the edge of the glue line. This grip may be mounted on any machine capable of delivering tensile loads.

One of the purposes of this experiment was to compare the revealing power of the swivel and saddle grips. This was done by incorporating certain defects in the bond of the cross-lap specimen and then noting which grip reflected the presence of the defect in the observed strength. Superimposed upon these defects was a graded series of glue line quality created by the addition of varying amounts of wheat flour extender. The purpose of the quality variation was to determine which grip would reflect a quality change, and do so in spite of the presence of

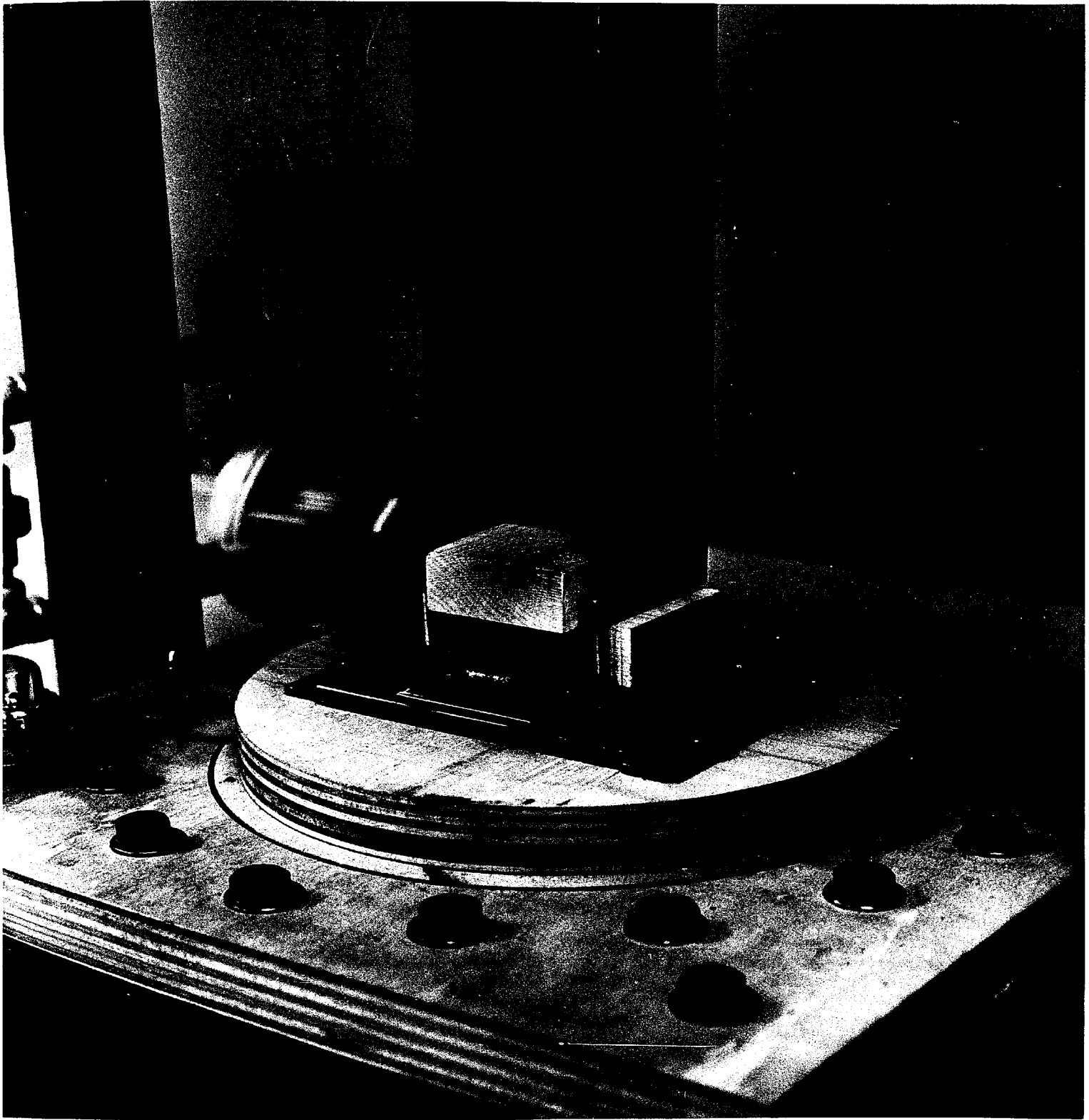


Figure 17. Compression saddle used in the diaphragm machine to hold the cross-lap specimen during testing

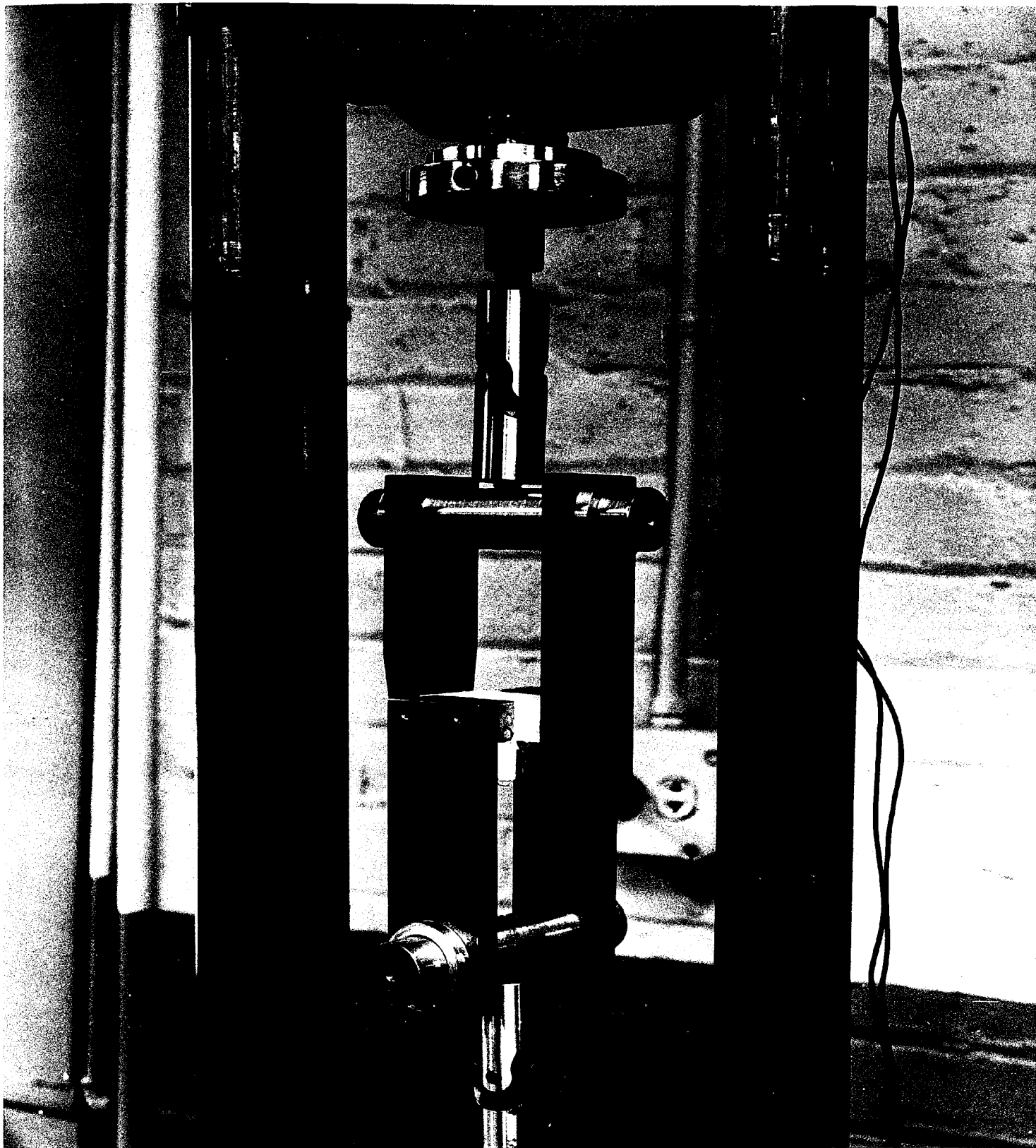


Figure 18. Self-aligning grip used in the Dillon Tensile Tester and other machines

a flaw.

In order to determine whether the response to a quality change could be improved by altering the stress concentration situation, two circular reductions in bond area were also included. It was felt that if the bond area was reduced from the outside inward by means of the blocking technique previously described, an additional element of stress concentration, due to change of section, would be introduced at the glue line, thus bringing more stress to bear at the point of weakness.

The data resulting from the inward reduction of bond area was then restudied in connection with data from an outward reduction of bond area to observe the response of the specimen to the amount and location of varying symmetrical increments of bond area. This study provides an insight into the magnitude of stress concentration which may exist in the normal cross-lap specimen.

Design of Experiment

(1) Five levels of flaws (Figure 19)

- F1 - 0, or no flaw
- F2 - 1/4 square inch, one-corner flaw
- F3 - 1/2 square inch, two-corner flaw
- F4 - 1 square inch, four-corner flaw
- F5 - 2 square inch, four-corner flaw

(2) Four levels of adhesive quality

- Q₁ - 0 percent wheat flour extension
- Q₂ - 20 percent wheat flour extension
- Q₃ - 40 percent wheat flour extension
- Q₄ - 60 percent wheat flour extension

(3) Two methods of test

- S1 - Swivel grip
- S2 - Saddle grip

(4) One adhesive - Adhesive A

(5) Four replications for each combination of conditions,
making a total of 160 specimens

(6) Set up for three-factor analysis of variance

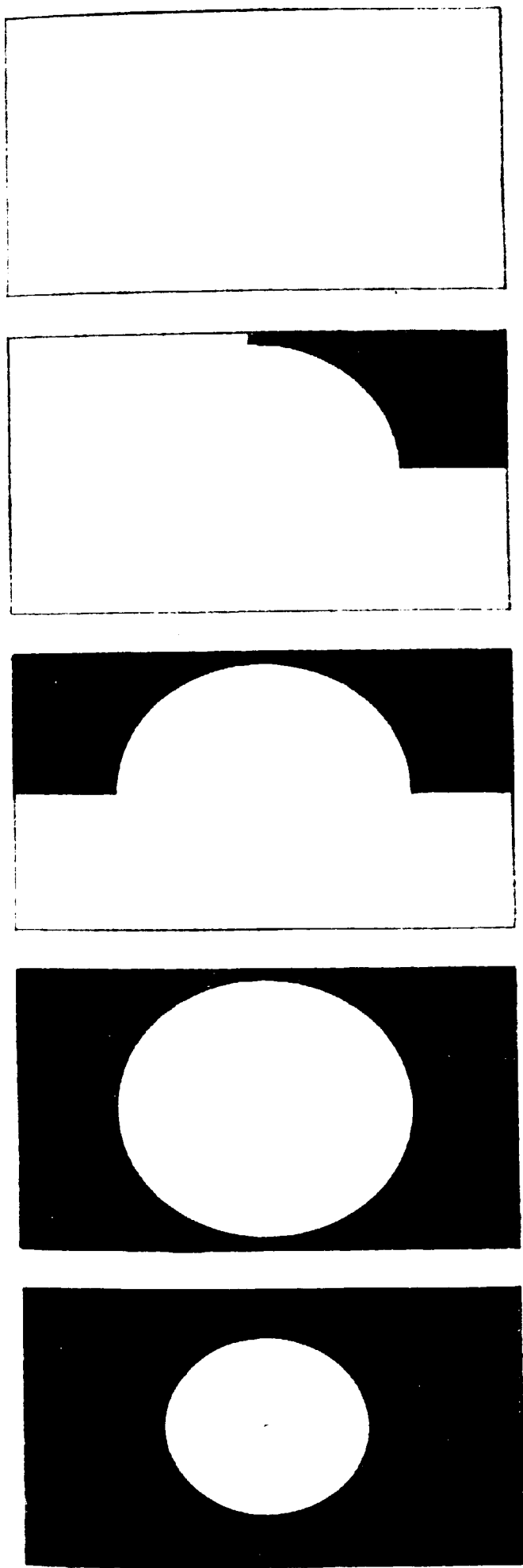
Procedure

The wood blocks were prepared and selected as before, using billets of one specific gravity conditioned to 9.4 percent moisture content. Approximately 400 blocks were made. Of these, 128 were divided into four different groups of 32 each to be given a flaw treatment, and the rest were set aside for untreated controls and for forming the other half of the specimen. Only one of the two surfaces comprising a specimen was given the flaw treatment.

All the wood blocks to be treated were then center-pricked using a template cut for that purpose. An arc of the necessary length and radius was struck from this center using a compass carrying a sharp, soft lead. To scribe the 1/4-square inch corner area, the arc of a circle enclosing 2.0 square inches was used. Since the total bond area is 3.0 square inches, such a circle would exclude 1.0 square inches of this total. By halving or quartering the circle it was possible to define accurately the area to be treated for conditions F2 and F3. F4 was the full circle, and F5, a full circle enclosing an area of 1.0 square inches thereby excluding 1.0 and 2.0 square inches of the total bond area respectively, Figure 19.

The flaws, or blocked areas as they may be called, were created by the application of a light grease, vasolene. The grease was applied by means of a sharpened wood spatula which permitted the spreading of a thin layer of grease to the precise area required. Extreme care was exercised to assure that no grease appeared on the areas which were to form the bond. A template, cut to the correct semi-circle, was used to aid in controlling the application of the grease.

After the flaw treatment, the wood blocks were immediately



F 5	F 4	F 3	F 2	F 1
Flaw Area 2.00	Flaw Area 1.00	Flaw Area 0.50	Flaw Area 0.25	Flaw Area 0.00
Bond Area 1.00	Bond Area 2.00	Bond Area 2.50	Bond Area 2.75	Bond Area 3.00

Areas are in square inches.

Figure 19. Configuration of flaws placed in exterior locations of the glue line.

assembled into specimens with the designated adhesive quality levels, the adhesive being applied to the untreated surface. The specimens were assembled five per jig with each of the five flaw conditions appearing in each jig. Eight jigs of specimens for each adhesive produced eight specimens of each flaw condition.

The adhesive mixtures used were as follows:

Quality 1	100 parts resin 60 parts water
Quality 2	100 parts resin 20 parts flour 80 parts water
Quality 3	100 parts resin 40 parts flour 100 parts water
Quality 4	100 parts resin 60 parts flour 130 parts water

In making the mixtures, the flour and resin were first mixed dry, and then the water was stirred in so as to make a smooth, lump-free mix.

Assembly of the specimens was similar to previous experiments. After pressing, the jigs full of specimens were placed in the controlled humidity rooms to cure and condition as before. The glue squeeze-out was removed while still soft.

At the end of seven days, the specimens were randomly separated into two identical groups each having four specimens representing every combination of flaw and quality. One group was tested on the Dillon Tester using the swivel grip and the other group was tested on the diaphragm machine using the saddle grip.

Results

The results were recorded in micro-inches of dynamometer

assembled into specimens with the designated adhesive quality levels, the adhesive being applied to the untreated surface. The specimens were assembled five per jig with each of the five flaw conditions appearing in each jig. Eight jigs of specimens for each adhesive produced eight specimens of each flaw condition.

The adhesive mixtures used were as follows:

Quality 1	100 parts resin 60 parts water
Quality 2	100 parts resin 20 parts flour 80 parts water
Quality 3	100 parts resin 40 parts flour 100 parts water
Quality 4	100 parts resin 60 parts flour 130 parts water

In making the mixtures, the flour and resin were first mixed dry, and then the water was stirred in so as to make a smooth, lump-free mix.

Assembly of the specimens was similar to previous experiments. After pressing, the jigs full of specimens were placed in the controlled humidity rooms to cure and condition as before. The glue squeeze-out was removed while still soft.

At the end of seven days, the specimens were randomly separated into two identical groups each having four specimens representing every combination of flaw and quality. One group was tested on the Dillon Tester using the swivel grip and the other group was tested on the diaphragm machine using the saddle grip.

Results

The results were recorded in micro-inches of dynamometer

deflection and were converted to pounds by use of the calibration factor determined for each machine. A summary of the results showing averages for each combination of factors is given in Table 12. Included in the table are the breaking strength values as observed, and also the unit stress obtained by converting to pounds per square inch to account for differences in bond area. * This table is later broken down into smaller tables of regrouped data for purposes of illustrating the various comparisons which are made. Wood failure values are given in Table 13 for both the original estimate and the estimate adjusted to account for the area occupied by the flaw.

Further data on the effect of varying bond areas which was accumulated as part of another experiment is presented in the section of "Response of the Cross-Lap Specimen to Flaws in the joint."

A summary of an analysis of variance is given in Table 14 for both breaking strength data and the adjusted data.

Discussion

At first glance the data in Table 12 appears to answer negatively, for the most part, the questions raised in the introduction. The two methods of test give strikingly similar results, varying from the grand mean by only 20 pounds. Neither method of test reflected the change in adhesive quality, and both methods responded to the presence of flaws in the glue line although not exactly in the same manner. Despite the negative tenor of the results, a number of inferences can nevertheless be drawn regarding the inherent properties of the specimen and the testing fixtures used.

* The unit stress was calculated by dividing the breaking load by the area of the bond and not by the area of the joint which remained constant at 3.0 square inches.

TABLE 12

The Effect of Joint Flaws, Percent Wheat Flour, and Grip Type upon the Observed Strength

Percent Flour	Breaking Load Pounds												Row Average
	Swivel Grip						Saddle Grip						
	Area of Flaw Sq. In.						Area of Flaw Sq. In.						
	0	0.25	0.5	1.0	2.0	Avg.	0	0.25	0.5	1.0	2.0	Avg.	
0	1394*	1200	1139	1037	743	1103	1351	1359	1016	1028	595	1070	1086
20	1203	1290	1043	988	645	1034	1224	1252	1075	1049	539	1028	1031
40	1366	1424	1075	1116	660	1128	1340	1248	1231	1022	630	1094	1111
60	1282	1377	1045	1055	593	1070	1317	1055	952	974	629	985	1028
Average	1311	1323	1075	1050	660	1084	1308	1229	1068	1018	598	1044	1064
Unit Stress in Pounds Per Square Inch of Bond Area													
0	464	436	456	519	743	524	450	494	407	514	595	492	508
20	401	469	417	494	645	485	408	455	430	525	539	471	478
40	455	518	430	558	660	524	447	454	492	511	630	507	516
60	427	501	418	527	593	493	439	383	381	487	629	464	479
Average	437	481	430	525	660	507	436	447	428	509	598	484	495

* Each value is the average of four observations.

TABLE 13

Average Percent Wood Failure for Flaw Study

Percent Wood Failure Based on Total Joint Area													
Percent Exten- sion	Swivel Grip						Saddle Grip						Row Average
	Area of Flaw Sq. In.						Area of Flaw Sq. In.						
	0	0.25	0.50	1.0	2.0	Avg.	0	0.25	0.50	1.0	2.0	Avg.	
0	26*	20	35	29	23	27	11	14	26	12	4	12	20
20	21	23	24	20	22	22	16	31	26	18	4	19	21
40	29	31	10	29	15	23	27	20	46	14	10	23	23
60	8	23	12	13	4	12	4	26	10	23	9	14	13
Average	21	24	20	23	16	21	15	23	27	17	7	17	19
Percent Wood Failure Based on Area Bonded													
0	26	21	42	44	69	40	10	15	31	18	11	17	29
20	21	25	29	30	66	34	16	34	30	28	11	24	29
40	29	34	11	43	45	33	26	23	56	21	30	31	32
60	8	25	14	19	12	16	4	28	11	35	26	21	19
Average	21	27	24	34	48	31	15	25	32	25	20	23	27

* Each figure is the average of four observations.

TABLE 14

Analysis of Variance Summary for the Flaw Study

A. For breaking loads

Source	N(SS)	DF	N(MS)	F	P
Total	1,975,348,791	159			
Subtotals	1,648,355,871	39			
Quality	32,837,451	3	10,945,817	4.02	.01
Flaws	1,510,755,406	4	377,688,851	138.60	.001
Grips	9,979,281	1	9,979,281	3.66	.05 NS
Quality X Flaws	18,347,794	12	1,528,983	-	NS
Quality X Grips	5,274,563	3	1,758,188	-	NS
Flaws X Grips	7,683,174	4	1,920,794	-	NS
Q X F X G	63,478,202	12	5,289,850	1.94	.05
Error	326,992,920	120	2,724,941		

B. For values reduced to pounds per square inch

Total	241,902,741	159			
Subtotals	172,866,592	39			
Quality	7,246,617	3	2,415,539	4.20	.01
Flaws	139,544,125	4	34,886,031	60.64	.001
Grips	3,424,350	1	3,424,350	5.95	.05
Quality X Flaws	3,727,793	12	310,649	-	NS
Quality X Grips	373,087	3	124,362	-	NS
Flaws X Grips	3,335,616	4	833,904	1.45	.05 NS
Q X F X G	15,215,004	12	1,267,917	2.20	.025
Error	69,036,149	120	575,301		

Since many subjects are discussed in this experiment, some separation of topics is desirable in order to maintain clarity of presentation. The topics are presented in the order in which they occur in the analysis of variance table.

(a) Response of the Cross-Lap Specimen to Quality of the Adhesive

The analysis of variance indicates that the quality of the adhesive was responsible for variation, that is, for differences between means representing the strength of the four adhesive mixtures. This variation was of such magnitude that it could have occurred by chance less than one time in a hundred. That a true difference between adhesives existed is therefore accepted with a high degree of confidence.

Upon examination of the data however, it is evident the conclusion that the cross-lap specimen is responsive to changes in quality due to flour addition, is not warranted. The specimen is responsive to some type of quality, but not necessarily that due to flour. The data of Table 12 may be accumulated horizontally to reveal this fact.

TABLE 15

Average Accumulated Strength Values
for Each Level of Adhesive Quality

Percent Flour Extension	0	20	40	60	Avg.
Pounds Average Strength	1086	1031	1111	1028	1064
Unit Stress FSI	508	479	516	478	495

If the specimen had responded to the flour addition, it would have yielded strength values highest for Quality 1 and grading down in uniform steps to Quality 4. Instead, Quality 3 has come out the strongest, with Quality 1 in second place. The question which therefore arises: if not

responsive to quality due to flour, what quality attribute is being measured, or is there a superimposed influence of some kind?

One answer to the question may lie in the composition of the quality series. Flour, as a modifier of quality, may be considered to have more than one function, at least in the quantities used in this experiment. It is generally conceded that urea adhesives derive benefit from the addition of small amounts of inert, finely ground, materials which act as fillers, providing additional "body" to the adhesive, and regulating the flow and penetration properties. The materials commonly used for this purpose are walnut shell flour, wood, flour, and soluble blood. Wheat flour and other starch flours are not normally used as fillers but as extenders to reduce the cost of an adhesive mixture. However, they do possess filler properties, and in this regard they may be considered beneficial rather than harmful to the bond.

The beneficial filler action is however limited to small quantities, generally comprising not more than 10 to 20 percent of the weight of the resin. The resin used in this experiment contained approximately 10 percent walnut shell flour as part of the normal ingredients incorporated by the manufacturer. It was assumed that the filler necessity was thus already satisfied and that the addition of more flour would be in the nature of a true extender. It is possible that some additional filler action played a part in the results. However, this is not a complete explanation as the need for more filler would also have evidenced itself in an orderly manner.

Another possibility which may be considered deals with changes in consistency characteristics perhaps occurring with the changes in flour addition. With each increment of flour, additional water must also be introduced, and this brings one more factor into the situation. The

operation of this factor, i. e., water, is not known, but it too must influence the movements of the adhesive mass.

In summary, it may be said that the cross-lap specimen is sensitive to adhesive quality, but that the quality it responds to may not be easily defined. The practice of adding wheat flour extenders to urea adhesives is in need of much study. There is little agreement on the specific result of adding various amounts of flour. One of the reasons for lack of agreement is evidenced by this experiment in indicating that either something besides flour affects joint strength, or that something besides joint strength is affected by small additions of flour.

(b) Response of the Cross-Lap Specimen to Flaws in the Joint

For purposes of this discussion the data of Table 12 was summarized with respect to flaws, that is, the results for each method of test were combined in order to obtain the total reaction to the factor under study. Table 16 presents the data thus accumulated.

TABLE 16

Effect on Strength of Flaws Located at Exterior
Portions of the Cross-Lap Joint Area

Flaw	F1	F2	F3	F4	F5
Bonded Area Sq. In.	3	2.75	2.5	2	1
Breaking Load Pounds	1310	1276	1072	1034	629
Unit Stress (PSI)	437	464	429	517	629

The analysis of variance showed high significance for the effect of this factor. It is noteworthy that the F ratio was considerably reduced for the data which had been converted to pounds per square inch. This indicates that the differences were related in some degree to the area of the flaw. When the area of the flaw is removed by conversion to pounds per square inch of bonded area, the values tend toward equality. They

remain however, far from equality as illustrated in Figure 20.

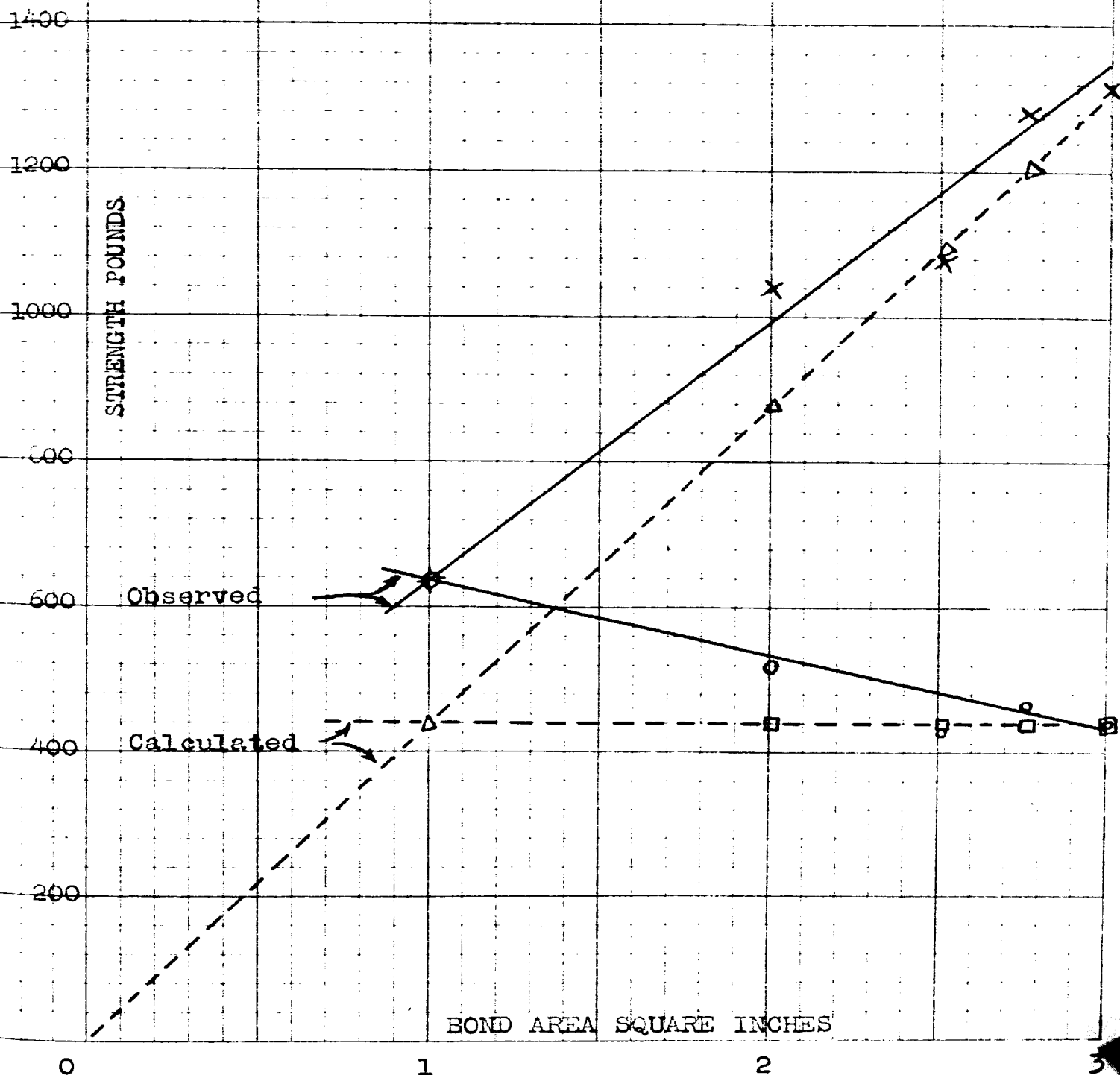
Figure 20 is a plot of the data of Table 16 in which both the breaking load and the unit strength had been graphed as a function of the area of the joint which was bonded. Included also, in dotted lines, is the calculated strength situation which would have resulted had the strength remained completely proportional to the area.

Of particular interest are flaws F2 and F3 one-corner, and two-corner flaws respectively. F2 reacted as a straight reduction in area although not in proportion to the area. F3, on the other hand, reacted as a reduction in area with which however, it was in close proportion as shown by its plotted nearness to the anticipated strength. This would tend to indicate that the one-corner flaw is immune to pursuit by the grips used, while the two-corner flaw can be subjected to some abnormal stresses. As will be shown later, the grips responded differentially to F2. It is unfortunate that a two-corner flaw oppositely oriented was not included to observe whether it would behave as F2 or as F3.

In earlier discussion the theory was raised that circular reductions in the bond area from the corners inward should result in increased stress concentration. The plot of Figure 20 indicates that such is not the case. In the Figure, the dotted lines represented by the triangular and rectangular symbols, indicate the strength that should have resulted if it had been proportional to the bond area, based upon the strength of the three square inch area. The actual strength is seen to be above the estimated strength; further, the difference between observed and estimated strength increases with decreasing bond area. If a factor of increasing stress concentration had been in operation concomitantly with the reductions in area, the situation would have been reversed. The decline in strength due to a stress concentration factor would have been additive to the decline due to reduction in area, and this

Figure 20. Effect on strength of the cross-lap specimen produced by flaws located at exterior portions of the joint, plotted as a function of bond area.

- X - Breaking load (pounds)
- O - Unit stress (psi)
- Δ - Calculated breaking load
- - Calculated unit stress



would have resulted in lower observed strengths than estimated strengths.

The increase in unit stress with decrease in bond area may be taken as evidence that no increase in stress concentration has occurred. However, the cause for the increase in unit stress is still unexplained. Lack of increase in stress concentration would only account for a constant value of unit stress. Three possible causes for the increase in unit stress with decreasing bond area may be postulated:

- (1) A decrease in stress concentration occurs with decreasing area.
- (2) The bond is actually stronger at the center than near the edges.
- (3) The strength of the joint is governed more by edge effects than by the size of the bond.

Justification for assuming that stress concentration could decrease, is difficult to substantiate. It is possible that with a lower level of strength involved at the smaller bond areas, less bending might occur. However, along with the smaller area and lower breaking load comes a longer cantilever system to multiply the bending factor. The resulting interactions are unassessable from the present data.

That the bond strength may actually be higher near the center of the joint is a matter of some concern. One implication is that the bond encounters some unfavorable condition at the edges of the joint during its formation. A differential pressure effect would be most likely to be operative over the area. At a free boundary, fluid pressure on the adhesive must reduce to zero. Thus there would be varying fluid pressure on the adhesive, increasing from the edges to some maximum value at the center. While the over-all pressure effect is shown in the following experiment to be non-influential upon strength, the presence of an edge effect due to pressure cannot be completely discounted.

Another factor which could be responsible for an apparent improvement of the bond at the center is the internal stress created by the glue water. Since a different amount of wood is engaged in the variously restrained swelling and shrinking during cure, it is conceivable that the internal stress situation could vary with bond area. The presence of grease on parts of one surface may also influence the total reaction with water.

The third postulate mentioned above seems to offer the most plausible basis for explaining the increased unit stress with decreasing bond area. If the situation is stated in reverse, i. e., decreased unit stress with increasing bond area, the results are seen to correspond with those of other investigators such as de Bruyne⁽²⁰⁾, Volkersen⁽²¹⁾, and Goland and Reissner⁽²²⁾ who worked with simple lap joints. Their experimental and theoretical findings lead to the same general conclusion that the lowest ratios of peak stress to mean stress occur in the shortest lap joints. Koehn⁽²³⁾ studied the action of varying joint area on simple cleavage specimens and found that while width affected strength linearly, the length produced an asymptotic value of strength after a certain dimension had been reached.

Reduced to simple terms the results obtained by the above researchers indicate that increasing the area of a joint does not proportionately improve its resistance to incipient rupture which occurs at the edges. In other words, the center portions of a joint contribute comparatively little to the observed strength. These deductions were based upon strength observations where both the size of the specimen and the area of the bond were changed inseparably. The present results were obtained on specimens of constant size but with varying bond area and bond boundary, and the same situation appears to exist. (In subsequent pages the case of varying bond area with constant boundaries is considered.)

The varying bond boundary permits an additional tentative analysis of the data by way of showing the influence of the edges upon strength of the cross-lap specimen. If the breaking loads for F1, F4 and F5 are plotted as a function of the length of the bond boundaries, being 7.0, 5.0 and 3.54 inches respectively, a fairly good line passing through the origin results, Figure 21. The slope of this line may be estimated as $1330 \div 7$ or 190 pounds per lineal inch of bond. This slope compares favorably with a slope of 207 pounds per lineal inch of bond estimated from the breaking load plot of Figure 20 and contrasts with a slope of 252 pounds per lineal inch for the estimated plot in the same Figure. It can be seen also that reducing the load to pounds per lineal inch of bond yields a line which is nearly horizontal, indicating the close relationship of unit strength with length of bond.

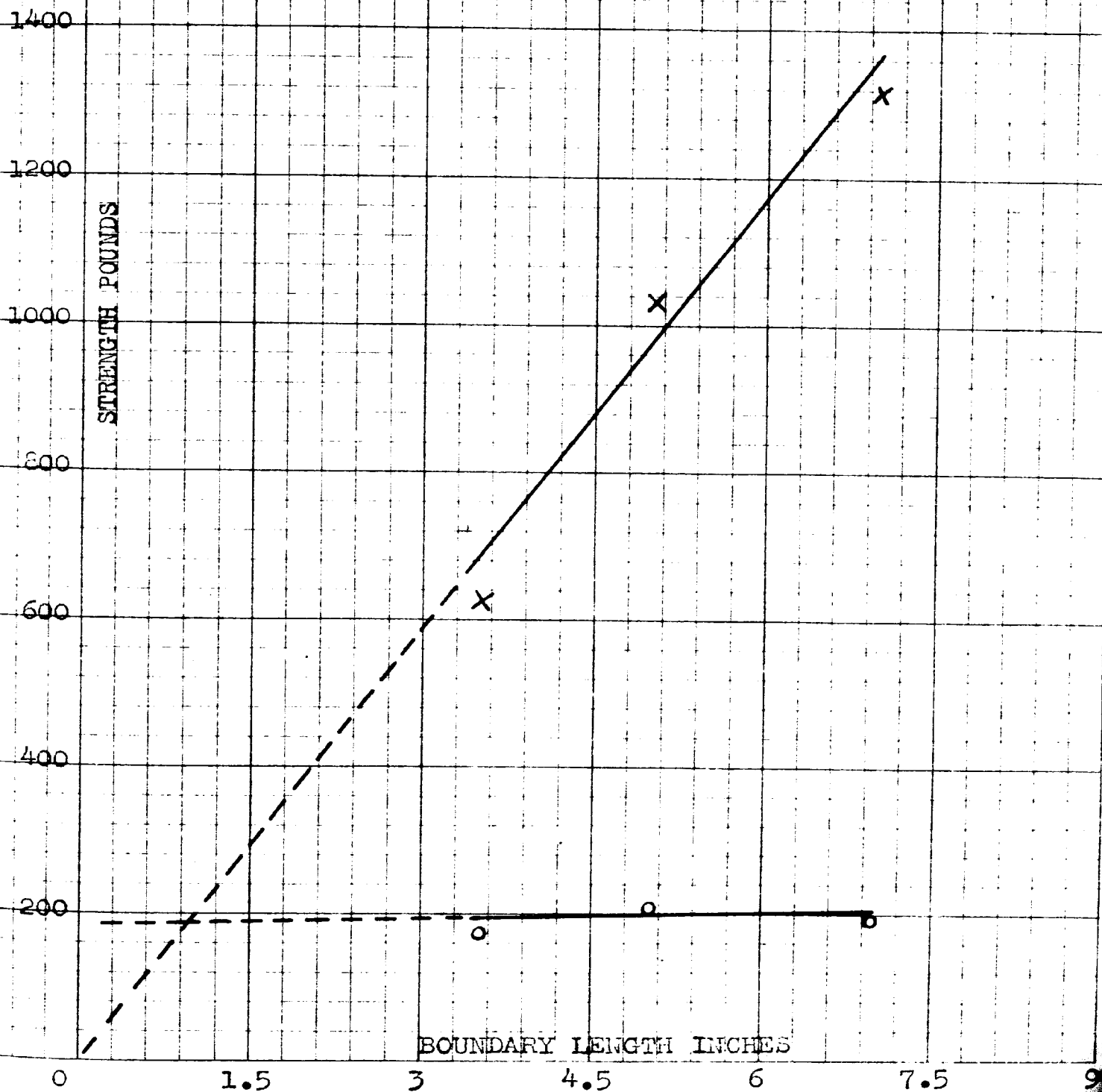
The suggestion ensues that a factor representing the edges of a bond in the cross-lap specimen appears to provide a better means of estimating changes in strength due to changes in size of the bond than a factor representing area. Pending further tests to substantiate this inference, the cross-lap specimen may more properly be regarded as a multiple cleavage specimen than a simple tensile specimen.

The points plotted in Figure 20 have been related by straight lines. The plots of breaking load as a function of area and as a function of length however, cannot both be represented by straight lines. The length does not change at the same rate as area. If it is taken that the boundary length of a bond in the cross-lap specimen is a better parameter for strength than area, the area plot of Figure 20 should in reality have been curved. This may also be justified independently.

Considering first that at zero bond area the strength would be zero, it must be concluded that all lines must pass through the origin. To do so would require some curving of the breaking load line and a rather sharp curve by the unit stress line. At the other end of the scale,

Figure 21. Plot of strength as a function of the length of the bond boundary in the cross-lap specimen.

X - Breaking load (pounds)
O - Unit load (pounds per lineal inch)



it is inconceivable that the total strength would continue to rise at the same rate had the area been larger than three square inches. In fact it is apparent that the rate of strength increase is already less between two and three square inches than it is between one and two square inches. If point F3 can be disregarded on the basis that it received undue influence by the grips, a smooth curve can be struck through the remaining points passing through the origin and tending toward an asymptote with the area axis, Figure 22.

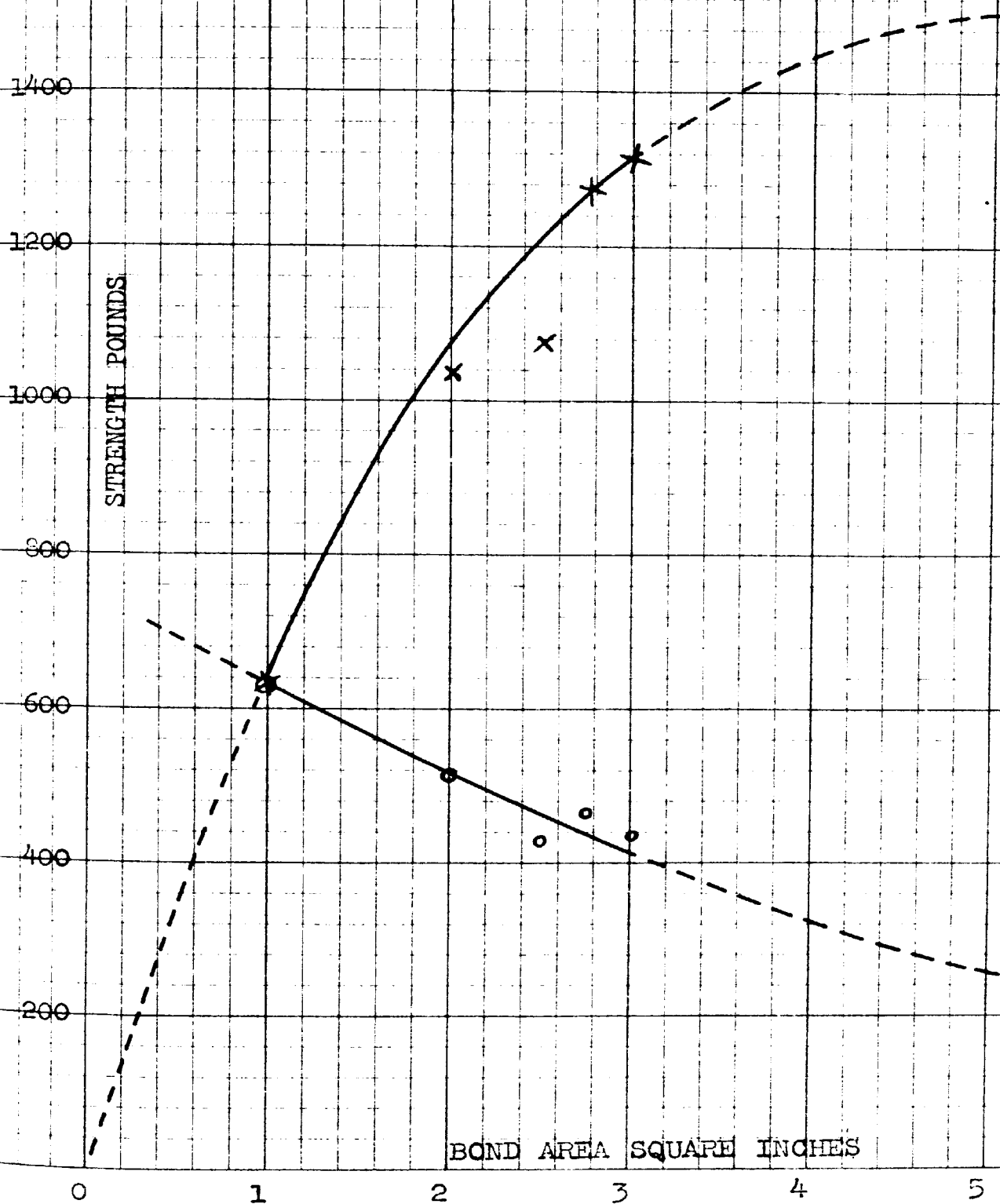
The unit stress line appears to be definitely straight, although, as mentioned, it too must pass through the origin. Beyond three square inches it would have to become asymptotic with the area axis to be in agreement with the breaking load curve. This situation is depicted without further confirmation in Figure 22. Although the extensions of the curves are unreliable, the curve of unit stress offers one means of estimating a maximum value at the point of projected intersection with the strength axis.

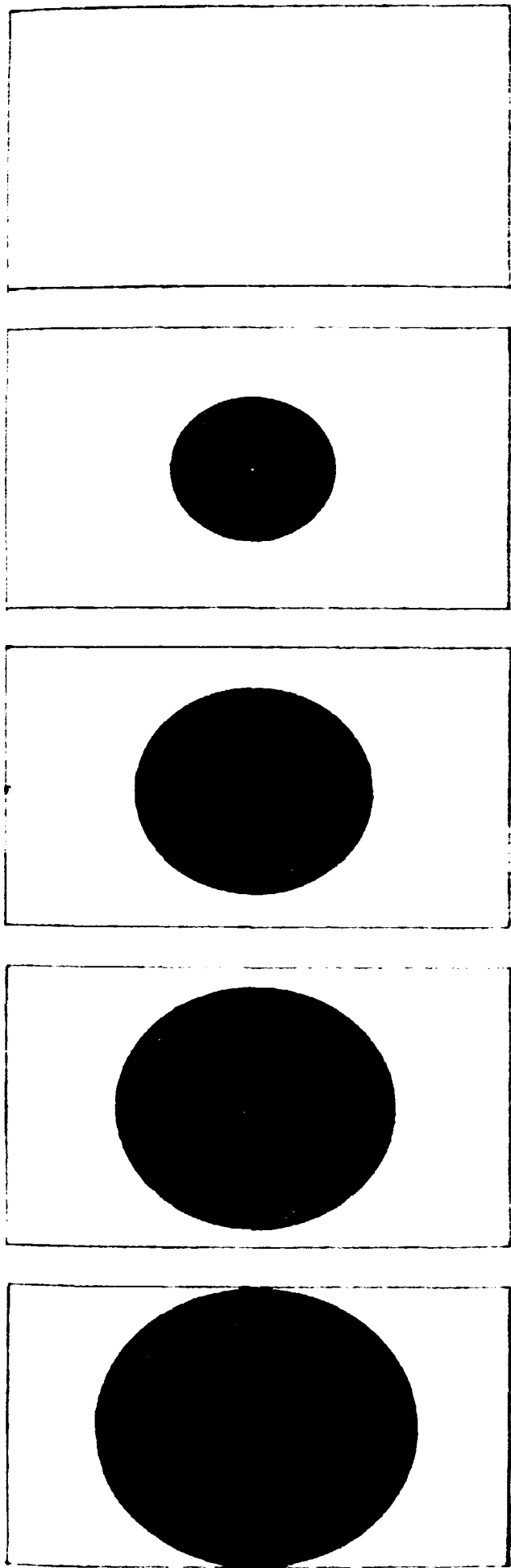
The preceding discussion has concerned the situation where flaws were introduced at the exterior portions of the bond area, and it was shown that the specimen responded strongly to the changes in bond area. It is of interest to compare these results with those in which the flaw is introduced at the interior of the bond area. In this case the flaws consisted of circular areas varying in diameter from the center outward. The area of flaw was varied in even increments of 0.6 square inches giving five levels of flaws, 0, 0.6, 1.2, 1.8, and 2.4. These flaws thus corresponded to bonded areas of 3.0, 2.4, 1.8, 1.2 and 0.6 square inches respectively, Figure 23.

Ten specimens for each bond area were made and tested in a manner similar to previous experiments except that in this case Adhesive D was used. The results obtained are given in Table 17 using the averages of the 10 specimens. The data is plotted in Figure 24 as it

Figure 22. Response of the cross-lap specimen to exterior changes in joint area depicted as curved functions.

X - Breaking load (pounds)
O - Unit stress (psi)





Flaw Area 2.40	Flaw Area 1.80	Flaw Area 1.20	Flaw Area 0.60	Flaw Area 0.00
Bond Area 0.60	Bond Area 1.20	Bond Area 1.80	Bond Area 2.40	Bond Area 3.00

Areas are in square inches.

Figure 23. Configuration of interior flaws placed in glue line.

TABLE 17

Effect on Strength Produced by Flaws Located at Interior Portions of the Cross-Lap Joint Area

Bonded area square inches	3.0	2.4	1.8	1.2	0.6
Breaking load pounds	1214*	1284	1168	1260	1195
Unit stress (PSI)	405	535	650	1050	1992

*Each figure is the average of ten observations.

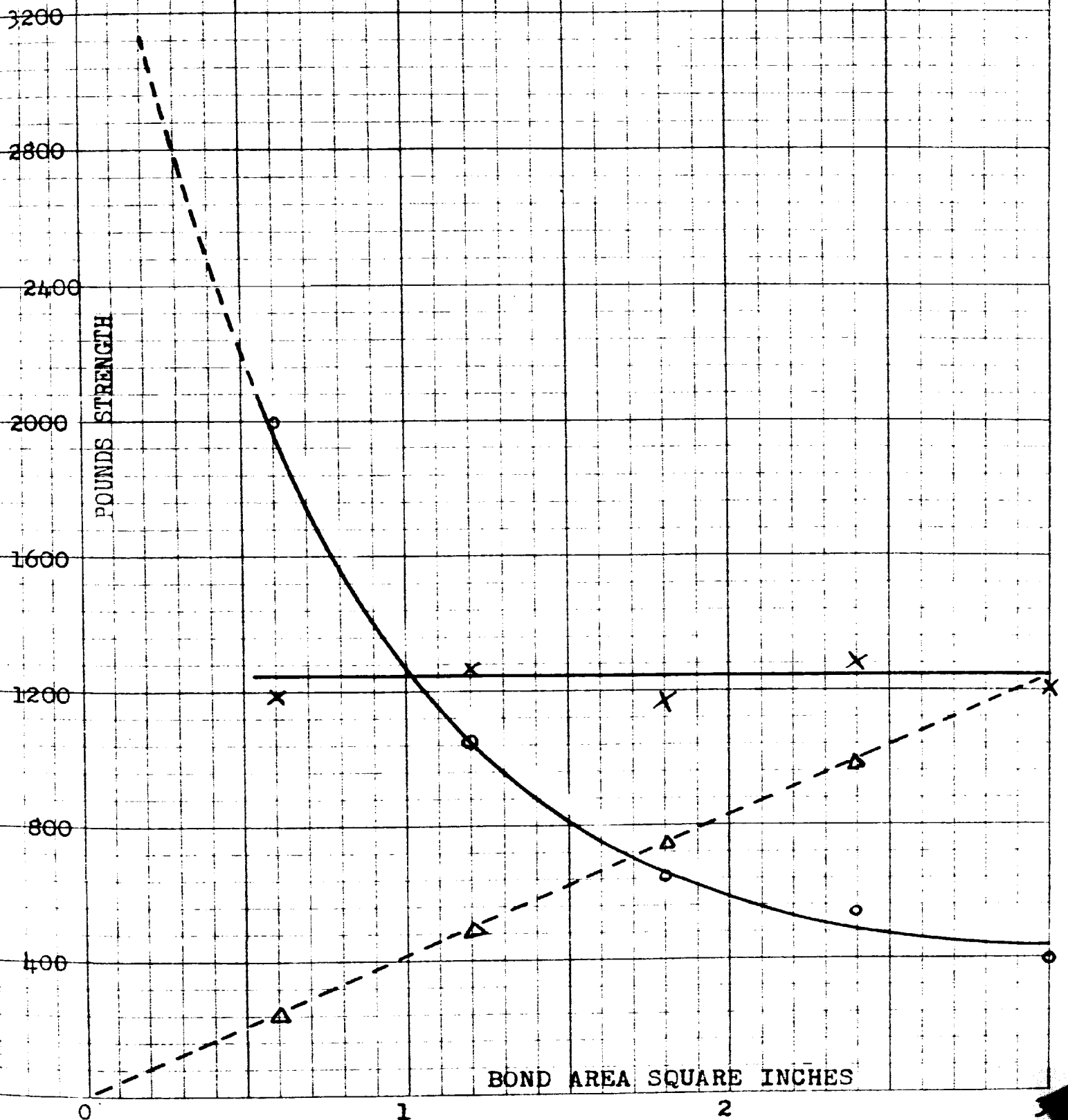
TABLE 18

Analysis of Variance Summary for the Effect of Internally Located Flaws

Source	N(SS)	DF	N(MS)	F	P
Total	63,129,225	49			
Bond Area	4,502,850	4	1,125,712	0.86	NS
Error	58,626,375	45	1,302,808		

Figure 24. Effect on strength of the cross-lap specimen produced by flaws located at interior portions of the joint, plotted as a function of bond area.

- X - Breaking load (pounds)
- O - Unit stress (psi)
- Δ - Calculated breaking load



was in Figure 20, that is, as a function of area.

An analysis of variance test, Table 13, indicated that no additional variation was introduced by varying the bond area. The data for breaking load may be plotted as a straight horizontal line through the grand mean of 1224 pounds.

It is evident that the cross-lap specimen possesses a remarkable insensitivity to flaws covering a major portion of the interior of the joint area. This is in marked contrast to the situation where the flaws are located at the exterior of the joint area. The conclusion is inescapable that the corners and edges of the cross-lap specimen are its main source of joint strength. When these fail, the rest of the joint area also fails whether a bond is present or not.

These results point to an extremely high level of stress concentration operating in the cross-lap specimen. As can be observed in Figure 24, the unit stress rises sharply as the bond area decreases. While it must eventually fall to zero when the bond area reaches zero, it shows no sign of doing so at an area of 0.6 square inches. At this point the unit stress is 2000 pounds per square inch, and it appears safe to predict that a peak stress considerably higher may exist before the drop to the origin. On the basis of a unit stress of 2000 pounds per square inch, the theoretical maximum strength of the cross-lap specimen glued with Adhesive D would be 6000 pounds. At a failing load of 1200 pounds, this represents a stress concentration factor of five. In other words 80 percent of the strength of the joint is unrealized due to stress concentration.

That the unit stress is capable of rising above 2000 pounds per square inch warrants additional attention. This stress is exerted in tension in a direction perpendicular to the grain of the wood. Published values for the strength of sugar maple in tension perpendicular to the grain are approximately 1000 pounds per square inch. Thus it appears that the cross-

lap specimen is reflecting a strength which the wood does not have. Several explanations are possible: the published data are in error; the specimen is actually capable of sustaining tensile loads in excess of the tensile strength of the wood; the load is not all borne in tension normal to the grain; or combinations of strains occur which cancel each other. It is felt that each explanation has an element of plausibility, and it is possible that each may apply in varying degree.

Whatever the explanation for the high concentrated unit stress, it is apparent that greater stress can be imposed on a bond in the cross-lap specimen than was at first supposed possible. Thus it would follow that a stated disadvantage of the cross-lap specimen, namely, that test loads applied normal to the grain in a wood to wood specimen cannot impose very high stress on a bond, is not warranted.

This relationship of breaking load to unit stress with changes in bond area are also in general agreement with the observations of de Bruyne (20) on simple lap joints. He found that the unit stress tended toward a zero asymptotic value as the length of the overlap increased, and rose sharply as the overlap decreased below a certain length. A peak stress of approximately 6000 pounds per square inch may be estimated from his curves for metal lap joints. With a breaking load of 4000 pounds for a one-inch overlap, a stress concentration factor of 1.5 is indicated. With a two-inch overlap the stress concentration factor rises to 2.4, and a three-inch overlap produces a factor of 4.0.

Stress concentration may be said to play a dominant role in the apparent strength of joints, and factors which affect stress concentration can easily overpower many other factors which affect bond quality.

Apart from the relationship of observed strength to area of bond per se, is the question of how fortuitous defects in the bond area,

such as represented by the flaws included in this study, might affect an estimation of the quality of a joint if the presence and magnitude of the flaws were unknown. An appraisal of the data would lead to the conclusion that large amounts of the internal bond area might be defective without change in an estimation. Likewise the presence of a defect in one corner of the joint may go unnoticed. The presence of external flaws greater than one corner would however seriously affect the strength and would introduce a high degree of error in the observation of other factors.

(c) Effect of the Method of Test, i. e., Grip Type on the Observed Strength of the Cross-Lap Specimen

As was discussed in the introduction, the main purpose for including grip type in the experiment was to determine whether one grip would reveal differences in treatments better than the other. It was presumed that differences in levels of strength might occur chiefly as a result of errors in calibration. Hence the main effect of grip type is of secondary importance. It is included in the discussion as a separate topic to maintain the continuity previously decided upon, and to emphasize the close agreement in results which were obtained. Further discussion of grip type occurs under interactions.

For the direct effect of grip type, the data of Table 12 are accumulated into the two vertical groups and averaged. The essence of the relationship between grips is shown in Table 19.

TABLE 19

The Effect of Grip Type on the Observed Strength of the Cross-Lap Specimen

Grip Type	Swivel	Saddle	Average
Breaking Load	1084	1044	1064
Unit Stress	507	484	495

The analysis of variance on the breaking load data produces an F ratio of 3.66 which, with one degree of freedom, indicates the probability that the differences between the two means could have occurred by chance more than five times in a hundred. The significance of the difference is therefore in doubt and the two means may be assumed to belong to the same population, i. e., that they reflected the same level of strength. Since the same level of strength existed in the two groups of specimens by design, it may be inferred that the two methods of test are essentially identical. It follows that either both methods responded to treatments of the specimens in the same manner or they did so differentially in a manner that canceled out in producing the averages. In the latter case, an interaction should be evident and this is discussed later.

When the data which had been reduced to unit stress is analyzed statistically, the direct effect of grips becomes more significant, having an F value of 5.95 and a level of probability of less than five in a hundred. The increase in significance appears to be associated with a sharp reduction in the variance between flaws. A further examination of Table 12 shows that each of the individual means which were averaged for Table 19 are lower for the saddle grip than for the swivel, also that approximately half the difference is due to the reaction with F2, the one-corner flaw.

In view of the latter results it must be assumed for the present, that a real difference between grips or methods of test exists. Whether this is due to the calibration or to an actual response to the different means of applying load remains a question.

(d) The Relationship of Adhesive Quality to Glue Line Flaws
Quality X Flaw Interaction

The observation of quality of the adhesive involving rather small variations, requires maximum freedom from side effects introduced by defects in the bond area. There is a possibility however, that the presence of certain types of defects in the bond may cause local stress accumulations to which the varying quality bonds might respond more decisively either in a proportionate or in a differential manner. If such were the case, the judicious placement of flaws in a joint could serve as a means of improving the sensitivity of the specimen. The data of Table 12 may be reorganized in a manner to reveal whether a differential response of quality to flaw has occurred. Table 20 is a compilation in which the results for the two methods of test have been averaged for each combination of flaw and quality.

The analysis of variance shows that the variation which existed among the means of Table 20 after the individual variation due to flaws and quality had been statistically removed, was no more than would be expected from samples taken at random from the same population with neither variate present. This indicates that there is no interaction between the two factors, that is, that the presence of one factor does not influence the effect of the other. To be specific, the effect of flaws is independent of the quality of the adhesive, and vice versa.

It may be inferred therefore, that the presence of flaws do not accentuate the type of adhesive weakness incorporated into the bond, as had been postulated. Increased stress concentrations which may occur with flaws F4 and F5 where the bond is confined to a circular area some distance within the joint, apparently are not effective in revealing a difference between quality levels. It had been thought that a sudden change in section occurring at a bond boundary should produce added stress concentrated directly at the edge of the bond. Incipient failures might thus be more quickly generated if any tendency toward

TABLE 20

The Interaction of Flaw with Quality

Percent Extension	Flaw					Avg.
	F1 3.0	F2 Square 2.75	F3 Inch Area 2.5	F4 Bonded 2.0	F5 1.0	
0	1373	1279	1078	1033	669	1086
20	1213	1271	1059	1019	592	1031
40	1353	1336	1153	1069	645	1111
60	1300	1216	998	1014	611	1028
Average	1310	1276	1072	1034	669	1064

weakness existed in the bond. Had this been the case, a gradation in the strength values, from one to four in quality, should have been evident for flaws F4 and F5.

The fact that an interaction between flaw and quality failed to appear may be taken as further evidence that the situation with respect to stress concentration did not change appreciably when the bond area was changed.

(e) The Relationship of Adhesive Quality to Method of Test
Quality X Grip Interaction

There is little theoretical reason to suppose that one method of test would be likely to be affected by one level of quality any more than another level. It is difficult to visualize a property associated with changes in quality, which might be reflected differently as changes in strength by virtue of differential response of the grips or method of test used.

TABLE 21

The Interaction of Quality with Grips

Quality	Grip		Avg.
	Swivel	Saddle	
1	1103	1070	1086
2	1034	1028	1031
3	1128	1094	1111
4	1070	985	1028
Avg.	1084	1044	1064

The data confirms that both grips are influenced equally by the changes in imposed quality. No interaction is statistically evident between these two factors. This can be observed visually in Table 21 which is a regrouping of the data in Table 12 to eliminate flaws.

It would appear that neither method of test possessed attributes which would make it particularly sensitive to adhesive quality. On this basis, there would be no advantage, or disadvantage, in selecting one or the other method for observations on adhesive quality. This statement however, is subject to the same qualification imposed in the previous section, i. e. that while a difference in adhesive quality may have existed, a great enough difference in bond quality as reflected by strength, may not have existed. Therefore a possibility must be entertained that an interaction was not evident because there was not sufficient opportunity to show one.

(f) The Relationship of Flaws to Method of Test
Flaw X Grip Interaction

One of the important comparisons to be drawn from this experiment was whether one grip would reveal the presence of a flaw better than the

other. In other words, is one grip more immune to flaws. It would appear that the grip most insensitive to flaws might be the one selected for observations on adhesive quality. This grip would tend to be less influenced by such factors as the surface quality of the wood blocks, which produce local flaws in the joint. On the other hand, a grip which was sensitive to flaws might be chosen for evaluation of surface quality.

The differences between grips was expected to arise from their relative flexibility, that is, from their ability to conform to a changing load distribution as the resistance of the joint became unbalanced through the operation of the flaws. The flaws incorporated in the normal bond area of the cross-lap specimen were designed to produce varying degrees of asymmetry in the joint and thus provide a means for the grips to demonstrate their sensitivity. It was expected that the swivel grip, being universally self-aligning in all planes, would be most likely to "feel" the presence of the one-corner flaw, F2, since it could act as if that corner had already broken and proceed from that point with the progressive rupturing of the joint. The saddle grip, with two pairs of mutually rigid bearing edges, would be unable to conform to the weak corner, and no readjustment could occur to transmit additional load to that area. Thus the weak corner would not be as inclined to continue rupturing, and a higher strength should result.

The data of Table 22 is a regrouping of the original data to facilitate the desired comparison of the grips. Both the breaking load and the unit stress results are given since a different level of significance emerged from the statistical analysis.

The analysis of variance, carried out on the breaking load data, showed that, after removing the variation caused by the grips and flaws separately, the variation that remained and attributable to the combined effects of the two factors, was not significant. This must be interpreted

as indicating that the two grips responded the same to the location of flaws in the bond area. The conclusion would follow that neither grip possessed an advantage over the other.

This conclusion however, cannot be completely accepted in view of the increased significance of the interaction variance when the data was reduced to unit stress. While significant below the five percent level of confidence, it does not appear wise to discount the interaction. It may be noted, for example, that the difference between F1 and F2 is markedly different for the two grips, being +12 for the swivel and -79 for the saddle.

Of further interest in connection with the differences between F1 and F2 is that it was the swivel which produced the small positive difference, while the saddle yielded the comparatively large negative difference. Further confirmation of the reality of these differences would lead to the refutation of the reasoning concerning the responsiveness of the two grips. It appears that the most rigid grip, the saddle, responded better to the presence of the one-corner flaw. If this is the case, another theory regarding the reaction of the grips to this type of flaw should be considered. An alternate theory, which may be explored by future, more extensive experiments, concerns the possibility that while the swivel grip is capable of pursuing an initial failure, the unit stress is, in the meantime, maintained fairly uniformly around the restraining points of the specimen. The saddle grip, on the other hand, being comparatively inflexible, is unable to maintain uniformity of unit stress. Hence the sound corner, adjacent to the corner flaw, will be subjected to a disproportionately high unit stress with consequent premature failure.

In the case of flaw F3, where two adjacent corners were defective, both grips showed essentially identical strength. It may be reasoned, on the basis of the above alternate theory, that the remaining bond area was symmetrical with respect to the applicable bearing edge

TABLE 22

Interaction of Flaws with Grips

Grip	Flaw					
	F1	F2	F3	F4	F5	Avg.
Breaking Load						
Swivel	1311	1323	1075	1050	660	1084
Saddle	1308	1229	1068	1018	598	1044
Avg.	1310	1276	1072	1034	669	1064
Unit Stress						
Swivel	437	481	430	525	660	507
Saddle	436	447	428	509	598	484
Avg.	437	432	429	517	629	495

and therefore it did not matter whether the grips were self-aligning or not.

(g) The Interaction of Quality, Flaws, and Grips

The analysis of variance indicates that the second order interaction of quality, flaws and grips is significant to less than the five percent level on the basis of the breaking load data, and to less than the two and a half percent level on the data after reducing to unit stress. There is a strong inference therefore, that the total variance of the means cannot all be accounted for by the direct effects of quality, flaws and grips, nor by their first order interactions which were shown to be negligible. Some additional variation remains which may be attributed to the combined effects of the three main factors on each other, or to the effect of some other factor which had been uncontrolled in the experiment.

The latter possibility is not beyond reason, although factors

which were believed to influence the results were randomized out of consideration, or were controlled. Due to the relative newness of the specimen, however, unknown factors could exist. The interaction effects of the three main factors may take three different forms and involve the first order interactions at different levels of the third variable:

- (1) The effect of flaw on quality may be different with the two grips,
- (2) the effect of grip on quality may be different with different flaws,
- and (3) the effect of grip on flaws may be different at different levels of quality. Some evidence for this source of variation may be observed directly in the data of Table 12. For example, an effect of quality on the flaw x grip interaction may be seen in the difference between F1 and F2 for each grip at quality 1 and quality 2. These differences are

	<u>Swivel</u> <u>F1-F2</u>	<u>Saddle</u> <u>F1-F2</u>
Quality 1	+ 194	- 8
Quality 2	- 87	-28

Thus it is evident that the difference produced between flaw F1 and flaw F2 by the two grips was again different at quality 1 than at quality 2.

Similarly an effect of flaw upon the quality x grip interaction may be discerned by considering the differences between quality 1 and quality 2 for flaws F1 and F2 with each grip:

	<u>Swivel</u> <u>Q1-Q2</u>	<u>Saddle</u> <u>Q1-Q2</u>
Flaw F1	+ 191	+ 127
Flaw F2	- 90	+ 107

The difference between quality levels is different for each grip and for each flaw.

An effect of grips on the quality x flaw interaction is shown by

the difference between results for the swivel and the saddle at flaws F1 and F2 with quality levels 1 and 4:

	Flaw F1 <u>Swivel - Saddle</u>	Flaw F2 <u>Swivel - Saddle</u>
Quality 1	+ 43	- 159
Quality 4	- 35	+ 322

The above analyses by differences indicate how the effect of two variables on each other is influenced by the third variable. This is disconcerting in a sense for it implies, among other things that the ability of the grips to reveal the presence of flaws depends upon the quality of the adhesive. On the other hand, a strong inference is thus supplied that, had there been a more marked strength-wise difference in quality of the bonds, it is possible that a particular grip-flaw combination would have been shown to possess a special sensitivity to quality.

In this experiment, two methods of testing the cross-lap specimen were studied against variations in configuration of flaws in the bond area and against variations in adhesive quality created by small additions of wheat flour. The design of the experiment permitted statistical evaluation of the data by a three factor analysis of variance technique. Definite response to the presence of flaws was shown, as well as to differences in adhesive quality. The latter however, was not in agreement with the designed variations in quality, and it must be presumed that other quality effects were also in operation, such as changes in rheological properties accompanying the addition of flour. Differences between methods of test, i. e., grips, was found to be not very pronounced. All first order interactions were found to be insignificant. The second order interaction however, was of sufficient significance to indicate a strong influence of one factor upon the other two.

The variations in bond area provided an insight into the matter

of stress concentration in the cross-lap specimen. It was found that when different size circular areas are prevented from bonding on the interior of the joint, no change in observed strength occurs. This indicated that the corners and edges of the specimen are chiefly responsible for the strength. Upon conversion to unit stress in recognition of the change in bond area, it was found that the stress may exceed 2,000 pounds per square inch, a value in excess of the published strength for maple wood in tension normal to the grain.

When the bond was prevented from forming at the corners and progressively inward, the breaking load was approximately proportional to the area. Some evidence toward curvilinearity however, was evident within the limits of the data, and this suggested an approach to an asymptotic value as the area increased beyond three square inches. Upon further analysis, it was found that the breaking load appeared to be more closely related to length of the bond boundary than to area. This led to the suggestion that the cross-lap specimen might be considered a multiple cleavage specimen rather than a tension specimen.

EXPERIMENT VI

Response of the Cross-Lap Specimen to Some Bonding Factors

The quality of an adhesive bond is dependent as much upon the manner in which the adhesive is applied, as upon the inherent properties of the adhesive itself. Consequently, observations on bond strength invariably reflect the play of both factors, and it is necessary for the experimenter to exercise considerable judgement in interpreting results relating to causes of discrepancy. Usually, in evaluating adhesive properties by means of a bond strength test, an element of doubt exists when results are below expectations. It is then difficult to state whether the low values are due to the properties of the adhesive, or to some unfavorable circumstance in the way it was handled.

In the converse situation in which it is desired to determine the bonding procedures, the doubt is not as great because the adhesive can be considered as a uniform mixture and hence does not contribute to the variation directly. The adhesive does however, affect variation indirectly. By virtue of its particular sensitivity, or lack of it, to factors in the bonding procedure, the adhesive can accentuate or obscure the effect of these factors.

The commonly accepted method of evaluating the quality of an adhesive is to observe the strength produced in a specified specimen when bonded in a specified manner and subjected to some exposure treatment. The author feels that such a test provides inadequate information with which to predict the performance of an adhesive in

actual practice since only the level of strength is observed, and this under only one combination of use conditions. A more reliable test would include observations under varying conditions and this then would enable an estimate to be made (1) of the average strength which might be regarded as the basic strength of the adhesive, (2) of the variation of this strength with regard to differing bonding conditions, and (3) of the sensitivity of the adhesive to bonding factors.

One of the purposes of this experiment was to demonstrate how the cross-lap specimen might be used in a test procedure to yield the type of information described. As will be noted, the chief advantage of the cross-lap specimen for this purpose lies in the ease with which variations in bonding factors may be incorporated in the specimen. Three bonding factors were selected for variation on the basis of their importance to the success of a gluing operation. They were pressure, assembly time, i. e., the interval between applying the adhesive to the joint surface and the application of pressure,* and the age of the adhesive mixture.

The function of pressure in a normal gluing operation is basically two-fold. It brings the joint surfaces together as intimately as physically possible, and it serves to force some of the adhesive into the pores of the wood for deeper anchorage. Considering these two functions separately and more rigorously, a number of side-effects may be defined. Not all the pressure which is applied to an assembly reaches the adhesive film. Some is consumed in the act of bringing the surfaces together if the parts are warped, twisted, or cupped, or if they must be

* The assembly time interval is classified as "open" when the spread adhesive is exposed to the atmosphere during this time, and "closed" when the joint surfaces are brought together immediately after spreading but without the application of pressure. In all the experiments here reported, a "closed" assembly period has been used, because, while not as severe in its effect on the bond, it is easier to control in view of possible atmospheric changes.

bent in order to conform to a curved shape. Of the pressure which reaches the adhesive layer, some will be consumed in compressing local elevations in the joint which may exist as a result of improper preparation of the wood surface. If there are local elevations, frequently present also are local depressions. Thus it may be inferred that pressure is not necessarily a constant between different joints, or in different parts of the same joint, even though the amount applied is maintained at the same value. It is possible therefore to have areas in a joint where the pressure is too great, and areas where the pressure is zero. It is conceivable that both such areas would be defective in bond strength if the adhesive were sensitive to the amount of pressure applied.

Forcing the adhesive into the pores of the wood to obtain better anchorage, seems to be a superfluous function. If it is accepted that the strength of a bond is due principally to chemical bonding forces, it would appear unnecessary for the adhesive to penetrate into the wood. Whether or not chemical bonding or mechanical bonding systems are responsible for the strength of an adhesive joint, the need for penetration of the adhesive is based on the probability that the outermost elements on a wood surface have been damaged and weakened in the surfacing operation. By penetrating through these to sounder fibers within, the overall strength of the bond is improved.

The penetration of the adhesive under the impetus of an externally applied force is a matter of some criticalness since an optimum level must be attained such that the adhesive reaches sound wood but does not go too far beyond, thereby either depleting the joint itself, a condition known as "starving," or reaching the opposite surface, producing a "bleed-through" condition. In some types of joints the action of pressure may cause the adhesive to flow excessively laterally in the plane of the surface and emerge as "squeeze-out," again causing a "starved" joint.

With interacting factors in the anatomical structure of the wood, the moisture content and physical properties of the wood, and the rheological properties of the adhesive, the effect of the pressure factor is difficult to assess in a given case. Woods with large, open pores would be expected to result in different adhesive action under a given pressure than close-grain woods. This action could further be strongly influenced by the viscosity characteristics and other manifestations of the rheology of the adhesive mixture.

Viscosity characteristics are normally considered to be inherent in the adhesive, and therefore constant like other properties. This is true only to a limited extent. As measured by standard viscosimeters immediately after manufacture the viscosity is indicative of important properties in the adhesive. It should be noted that a viscosity measurement does not completely define how a fluid will behave when subjected to an impelling force. A time, or rate, factor is also involved. Moreover, there is constant change in these properties subsequent to manufacture. The changes are minor during the stated storage life of the adhesive, provided proper storage conditions existed. However, after the adhesive has been prepared for use, the changes become more pronounced and more rapid, particularly after it has been applied to the surface of the wood. These changes occur through continued polymerization of the adhesive molecules after mixing and while in a container, and through further polymerization plus loss of water to the wood after spreading on the surface.

The above implies that while certain rheological properties are inherent in the adhesive, large changes occur after mixing and spreading and these changes are properly associated with, and may be considered as bonding variables. During the mix life of an adhesive, the continued polymerization results in increase in the size of the resin molecules. This in turn causes an increase in viscosity, and greater

resistance to flow and penetration. After the adhesive has been applied to the wood surface, the rate of viscosity increase is greatly accelerated by water loss. Depending upon the time elapsed after mixing and after spreading, the adhesive film should present different flow properties when the pressure is applied. Hence, varying the mix age and the assembly time should provide an experimental means of observing the effect of fluid state on the strength of a bond. At the same time it should permit an appraisal of the sensitivity of the cross-lap specimen to these application variables.

Design of the Experiment

- (1) Five bonding pressures: 0, 50, 100, 200 and 300 pounds per square inch.
- (2) Four mix ages: 0, 40, 80, and 120 minutes.
- (3) Four assembly times: 0, 20, 40, and 60 minutes.
- (4) Four specimens assembled per jig.
- (5) Each jig containing all four mix ages.
- (6) Twenty jigs in all, each spread identically, and each pressed after the designated time lapse and with the designated pressure.
- (7) All specimens, 80 in number, conditioned identically and tested on the Dillon machine with swivel grips.
- (8) Specific gravity and moisture content controlled at 0.68 and 9.4 percent respectively.
- (9) Analyze by three-factor analysis of variance, one observation per cell.
- (10) One adhesive, Adhesive A.

Procedure

The wood blocks for the specimens were prepared as before and assembled in the same manner except for the introduction of the variables.

The essential feature of the procedure is the means by which the controlled factors are incorporated. In order to vary the mix age independently of assembly time, with no replications, for each interval of pressure, it was necessary to have each age level available at the same time. This was done by making the four mixes in reverse order 40 minutes apart. At the end of 120 minutes the following mixes were ready for use:

- A1 - 0 minutes old
- A2 - 40 minutes old
- A3 - 80 minutes old
- A4 - 120 minutes old

The total usable life of these mixes at 75°F was approximately 160 minutes. At 120 minutes, the mixture was quite stiff and brushed with difficulty.

In assembling the contents of each jig, one specimen was spread with each adhesive mix. A dummy block was then placed in each jig to fill the space that would otherwise be occupied by a fifth specimen. The four jigs representing each assembly time for zero pressure were assembled first and laid aside. It should be noted that with no pressure applied, these four jigs of specimens are identical since the assembly time difference became meaningless. Four jigs were included, nevertheless, in order to preserve the design of the experiment.

Following this, four jigs of specimens were immediately assembled and set aside for the 60-minute assembly time, and in quick succession, the 40-minute and the 20-minute assembly time groups were spread and assembled in the jigs. Thus all the specimens were assembled in the shortest possible time, so as to minimize the effect of continued aging of the mixes. The total clasped time for each mix was about 20-minutes.

The rapid assembly of the specimens necessitated rapid pressing

in order to maintain uniform assembly time intervals. The jigs were allowed to dwell in the press under fluid pressure for only one minute instead of five minutes, as in previous experiments. After the one-minute press period, the thumb-nuts were tightened as before and the jigs of specimens were placed in the controlled humidity room for the curing and conditioning period.

Code symbols were assigned for assembly times as follows:

T1 - 0 minutes
T2 - 20 minutes
T3 - 40 minutes
T4 - 60 minutes

Code symbols for pressure were:

P1 - 0 pressure
P2 - 50 pounds per square inch
P3 - 100 pounds per square inch
P4 - 200 pounds per square inch
P5 - 300 pounds per square inch

Thus, a specimen carrying the symbols A3P4T2 represented an adhesive 80 minutes old, pressed with a pressure of 200 pounds per square inch after an assembly time of 20 minutes.

The specimens, after seven days of curing and conditioning, were tested in the Dillon testing machine using the swivel grips.

Results

The results were recorded in micro-inches of dynamometer deflection and converted to pounds by the conversion factor 1.509. They are presented in full in Table 23. In this table, averages have been drawn horizontally and vertically at each major grouping of the data. Table 24 is a rearrangement of this data to permit a comparison of the different age classes of the mixes.

The data indicate a striking uniformity of values apparently devoid of variation due to the imposed variables. The analysis of variance,

Table 25, confirmed that no effect, measurable as significant departures from the grand mean, had been produced on the strength by varying the three bonding factors of assembly time, age of the mixed adhesive and bonding pressure. These results were unexpected and the following discussion is somewhat in the nature of an analysis leading to a basis for planning more experiments to confirm the points raised.

Discussion

It would appear that the lack of a demonstrable effect on the observed strength by the three factors, illustrates an advantage of the cross-lap specimen. If it can be shown that the specimen is in fact insensitive to these application variables, then a particular strength observation can be viewed with more assurance that it is a reflection of the adhesive rather than the way in which it was used. Such a situation would represent a definite enhancement of evaluation procedures for measuring properties of the adhesive itself.

The basic question of whether the data of Table 23 reflects insensitivity of the specimen to the factors varied, or, the adhesive used is particularly tolerant of these variables, cannot be completely answered. Some evidence and reasoning for both conclusions may be cited. Taking first the apparent lack of response of the specimen, much substantiation may be found in the manner in which the specimen is prepared. The joint surfaces are flat, true and sound. Hence the need for pressure is largely eliminated since the surfaces will come together without the application of force and it is not necessary to obtain deep penetration of the adhesive in search of undamaged wood fibers. Maxwell⁽²⁴⁾ has demonstrated how the effect of pressure is influenced by the preparation of the joint surfaces. A well planed surface, he showed, does not respond to increases in pressure as much as a sanded or combed surface.

TABLE 23

Results of Varying Assembly Time, Mix Age and Pressure with the Cross-Lap Specimen

Pressure PSI	Age Minutes	Strength - Pounds				
		Assembly Time - Minutes				Row Aves.
		0	20	40	60	
0	0	1707*	1818	1705	1675	1726
	40	1657	1737	1640	1607	1660
	80	1744	1661	1675	1871	1738
	120	<u>1895</u>	<u>1796</u>	<u>1622</u>	<u>1965</u>	<u>1820</u>
	Average	1751	1754	1661	1780	1736
50	0	1406	1627	1536	2052	1655
	40	1758	1856	1796	1928	1835
	80	1595	1910	1720	1680	1726
	120	<u>1811</u>	<u>1855</u>	<u>1664</u>	<u>1963</u>	<u>1823</u>
	Average	1643	1812	1679	1906	1760
100	0	1885	1358	1630	1723	1649
	40	1750	1603	1811	1584	1687
	80	1536	2070	1607	1859	1768
	120	<u>1809</u>	<u>1693</u>	<u>1686</u>	<u>1838</u>	<u>1757</u>
	Average	1745	1661	1684	1751	1715
200	0	1750	1405	1752	1554	1615
	40	1839	1901	1673	1826	1810
	80	1672	1746	1630	1882	1733
	120	<u>1690</u>	<u>1950</u>	<u>1826</u>	<u>1670</u>	<u>1784</u>
	Average	1738	1751	1720	1733	1735
300	0	1710	1720	1962	2200	1898
	40	1609	1805	1550	1877	1710
	80	1856	1856	1630	2067	1852
	120	<u>1737</u>	<u>1909</u>	<u>1874</u>	<u>1506</u>	<u>1757</u>
	Average	1728	1823	1754	1913	1804
Column Averages		1721	1764	1699	1816	1750

* Each figure represents one observation.

TABLE 24

The Effect of Age of the Adhesive Mixture on
the Observed Strength

Age Minutes	0	40	80	120
Pounds Strength	1708*	1740	1763	1788
Percent Wood Failure	48	39	46	56

* Each figure is the average of twenty observations.

TABLE 25

Analysis of Variance Summary for the Effect of
Mix Age, Pressure, and Assembly Time

Source	N(SS)	DF	N(MS)	F	P
Total	152,578,976	79			
Assembly Time	12,801,064	3	4,267,021	2.09	.05 NS
Age of Mix	5,460,912	3	1,820,304	0.89	NS
Pressure	5,974,026	4	1,493,506	0.73	NS
Assembly Time X Age	19,773,960	9	2,197,107	1.07	.05 NS
Age X Pressure	12,036,206	12	1,003,017	0.49	NS
Assembly Time X Pressure	22,918,398	12	1,909,866	0.93	NS
Assembly Time X Age X Pressure	73,614,410	36	2,044,844		

TABLE 26

Percent Wood Failure for Assembly Time,
Mix Age, Pressure Study

Pressure PSI	Age Minutes	Percent Wood Failure				
		Assembly Time - Minutes				Row Aves.
		0	20	40	60	
0	0	25*	60	55	70	53
	40	30	70	16	30	37
	80	51	26	55	70	51
	120	45	55	21	65	47
	Average	38	53	37	59	46
50	0	6	31	50	100	47
	40	25	30	60	80	49
	80	1	5	45	100	38
	120	41	30	100	100	68
	Average	18	24	39	95	50
100	0	95	71	20	50	59
	40	11	30	80	50	43
	80	35	50	70	51	52
	120	90	96	70	91	87
	Average	58	62	60	61	60
200	0	11	10	96	30	37
	40	30	100	3	45	45
	80	6	40	100	20	42
	120	10	65	26	50	38
	Average	14	54	56	36	40
300	0	6	21	85	60	43
	40	11	16	11	50	22
	80	20	21	55	100	49
	120	20	20	60	40	35
	Average	14	20	53	63	37
Column Averages		29	42	49	62	47

* Each figure represents one observation.

One possible source of confounding for the pressure factor should be mentioned. It occurs in all gluing procedures where rigid clamping is employed to retain pressure, but has never been fully investigated. Reference is made to the swelling of the wood due to imbibition of glue water. When the wood is confined, large pressures can be developed by this action and these pressures are additive to those imposed by the pressing mechanism. Maintaining constancy of pressure by means of springs or air cushions is a refinement which was incorporated in the earlier procedures with the diaphragm machine, but were subsequently omitted for the sake of simplicity. Further research may show the desirability of reintroducing constant pressure devices in experiments involving this factor. Maxwell⁽²⁴⁾ used a dead weight lever system in conjunction with a coil spring to maintain pressure both uniform and constant. While his system was intended mainly to provide "follow-up" pressure as the adhesive layer penetrated into the wood and contracted upon drying, and to compensate for creep of the wood under load, it inevitably also equalized the reverse effect of swelling of the wood. It would be of interest to follow the history of the pressure factor during the course of bond formation under different types of clamping devices.

Notwithstanding the possibility of additional pressure supplementing the controlled variable, a constant difference between pressure levels could nevertheless still exist since the same amount of swelling would be involved in each specimen. This would be dependent on the condition that the sum of the imposed pressure and the generated pressure did not exceed the elastic limit of the wood normal to the grain. Assuming such a condition, the evidence remains that differences in pressure do not seem to affect observed strength. Further evidence that pressure was not an influential factor is derived from the observation

that no pressure at all produced strength equal to that where some pressure was applied.

While pressure may be deemed unimportant to the formation of a strong bond with the cross-lap specimen using Adhesive A, some reduction in observed strength can be postulated at zero pressure due to other reasons. Since the adhesive is applied to one side only of a block, the swelling action would produce forces such as to cause crowning of the joint surface. With crowning occurring in the two members of a specimen at a 90° angle, considerable misfitting of the joint can result while the adhesive is curing. This crowning action will, of course, recede as the glue water dissipates, and its effect upon joint strength may therefore be dependent upon the balance between rate of water loss and rate of curing.

Another reason for possible strength loss at zero pressure is based upon the observations of Experiment II where it was shown that an internal stress was created as the result of wood swelling before curing followed by subsequent shrinking after curing. In the case of zero pressure, the frictional resistance to swelling would be less. Hence more swelling should occur and more shrinkage stresses would therefore be generated to subtract from the total strength.

The lack of effect of assembly time as shown by the data goes hand in hand with the lack of effect of pressure. Since the conditions for maximum strength appear to be met by the placement of the two blocks together with the adhesive between, it does not matter if, nor when, the pressure is applied. The age of the adhesive likewise does not seem to matter as long as it is fluid enough to wet the wood substance at the surface. A steady trend toward increased strength with increased age is, in fact, evident, (Table 24). Although not significant, it is probable that further changes in viscosity in either direction might have produced a definite effect.

First order interactions are also absent in this sequence of variables. Ordinarily it would be expected that pressure, for example, might be most needed at long assembly times and at advanced age of the adhesive when maximum resistance to flow exists. Conversely, at short assembly times and fresh adhesive, when the adhesive is in its most fluid state, it is conceivable that pressure might have an inverse effect, that is, a "starved" condition would be caused by increasing the pressure. A trend in the direction of this situation could be observed visually in the thickness of the adhesive layer after rupture. The glue lines were progressively thinner as pressure increased and as assembly time and age decreased.

It is of interest to compare the above results with those obtained in an earlier study in which a different though similarly compounded adhesive was used, Adhesive B. In this study the pressure was held constant at 100 pounds per square inch, the assembly time was varied at 5, 20, 45 and 60 minutes and the age of the adhesive mixture was varied at 5, 60, 180, and 240 minutes. Each combination of conditions was represented by 12 specimens, making a total of 192 specimens. The results are tabulated in summary form in Table 27 in which each figure is the average of 12 observations. Table 28 gives the analysis of variance summary for this data.

Adhesive B was formulated to give a slightly longer mix life than Adhesive A; otherwise they appeared to be identical. Without considering the levels of strength between the two adhesives, it is obvious that Adhesive B is much more sensitive of the two application factors, assembly time and mix age; further, that this sensitivity seems to be associated with the shortest time intervals of both factors. This suggests that Adhesive B requires some thickening, i. e., reduction in fluidity, before pressure is applied.

The interaction between assembly time and mix age, is fairly

TABLE 27

Summary of Results with Adhesive B under Variations
of Assembly Time and Age of the Mixture

Age Minutes	Strength - Pounds				
	Assembly Time - Minutes				
	5	20	45	60	Average
5	1246*	1608	1399	1288	1385
60	1258	1688	1410	1590	1487
180	1319	1689	1624	1685	1579
240	<u>1363</u>	<u>1373</u>	<u>1630</u>	<u>1669</u>	<u>1509</u>
Average	1297	1590	1516	1558	1490
Percent Wood Failure					
5	0	42	12	3	14
60	5	25	18	3	13
180	6	39	32	3	20
240	<u>15</u>	<u>17</u>	<u>48</u>	<u>12</u>	<u>23</u>
Average	7	31	28	5	18

* Each figure is the average of twelve observations.

TABLE 28

Analysis of Variance Summary for Assembly Time and
Age Variation on Adhesive B

Source	N(SS)	DF	N(MS)	F	P
Total	4,290,083,775	191			
Subtotals	1,025,715,375	15			
Assembly Time	479,841,075	3	159,947,025	8.62	.0005
Mix Age	185,920,875	3	61,973,625	3.34	.025
Interaction	359,953,425	9	39,994,825	2.16	.025
Error	3,264,368,400	176	18,547,548		

significant and appears to be the result of a consistent operation of the two factors. Except for the widely divergent results at the 20-minute assembly time interval for 5-minute and 240-minute age levels, the strength tends to increase with increasing assembly time and mix age, with no clear optimum apparent within the limits of the data. The increases in strength however, are different for the different levels of the variants, being most pronounced between the first and second level in each direction.

Although the two sets of data, representing Adhesive A and Adhesive B, may not be statistically comparable owing to the large difference in variance, an attribute of an adhesive has been revealed which may be independent of the level of strength obtainable under a given set of conditions. This attribute may be designated as "tolerance," i.e., tolerance to variations in application conditions. It may be said that Adhesive A possesses more "tolerance" than Adhesive B, and can therefore be expected to perform more satisfactorily under use conditions.

The assembly times used in these experiments were characterized as "closed." They were considerably longer than is recommended for the adhesives used since maximum assembly time is usually taken to be 20 minutes. With assembly times up to 60 minutes showing no loss in strength of joint, a difference between assembly time in the cross-lap specimen and assembly time in ordinary adhesive usage is suggested. It is possible the difference lies in the probability that in actual practice where the gluing of larger areas is involved, the surfaces do not come into total contact as envisioned for a "closed" assembly. Instead some parts of the joint may be undergoing "open" assembly which is regarded as more effective in reducing bonding power.

While the effect of "open" assembly time was not observed in relation to the cross-lap specimen, a tentative recommendation may

be stated for using the assembly time factor in evaluation procedures. To maximize the effect of assembly time as an application variable, it should be used "open." To minimize the effect of assembly time in procedures where it is desired to observe only constituent properties of an adhesive, the assembly time should be "closed." In either case, a controlled variation in assembly time and age is desirable to assure that differences in strength are not due to differences in fluidity of the adhesive.

For example in determining the effect of catalyst addition, under a standard procedure it would be possible to conclude that one catalyst was better than another when actually the aging characteristics may have contributed heavily to the observed strength. On the other hand, it might be possible to choose a combination of conditions where all the mixes would appear to be the same. If a time factor were included in the test, its effect could be accounted for and the true effect of catalyst extracted.

It should be noted that the results of this experiment are too limited to be freely applicable to adhesives other than the ones used, and other than the way they were mixed and handled. While pressure was not an influential factor with Adhesive A, with other adhesives it may well be an important element of bond formation. It is likely that a particular adhesive may have a negative reaction to the application of pressure. Adhesive B shows tendencies in this direction, when first mixed, due to excessive flow. It appears that the main implications to be drawn are that pressure can be a more precisely controlled factor with the cross-lap specimen, and that it, of itself, need not be a source of undue variation. Likewise, assembly time can be closely controlled with respect to "open" and "closed," and in addition, the "closed" condition may be further immune to variation after a certain point has been reached.

WOOD FAILURE

Wood failure values are visual estimates of the percent of the surface area of a joint which has failed in the wood as a result of the test load. These estimates are used as indexes to the quality of the bond either independently, or in conjunction with strength figures. The estimation of wood failure however, is not considered to be a very precise measurement due to the human element involved. Estimations of the same specimens by different individuals can vary over approximately 80 percent of the complete range, and the same individual occasionally will estimate widely different values on succeeding days with the same specimens.

The amount and type of wood failure, whether shallow or deep, often varies greatly, responding to many variables in addition to the ones responsible for a particular strength observation. Grain direction is perhaps one of the most important factors influencing wood failure at a given level of bond quality. Others may be mentioned: specific gravity, stress concentrations, surfacing procedure, moisture content, existing checks in the wood, and annular ring orientation. Although only 0 and 100 percent wood failure values have definite meaning i. e., the bond is weaker than the wood, or the bond is stronger than the wood, interpolation between these two extremes is usually done with the intention of denoting intermediate levels of quality.

On the basis that 0 and 100 percent wood failure imply bonds "weaker than" and "stronger than" the wood respectively, interpolation would define "equal to" as being 50 percent wood failure. If this is

accepted, the regions between 0 and 50, and between 50 and 100 percent become further areas of undefinable quality. For this reason, estimates of wood failure between 0 and 100 percent cannot be properly interpreted unless they represent a series of observations showing progressive increments of wood failure.

When used in connection with strength figures, it is obvious that the more wood failure, the less the strength test can reflect the actual condition of the bond. In other words, when a variation in some gluing factor results in wood failures of 100 percent in every case, it would be impossible to determine the effect of the variable upon strength even though a statistically different strength value was observed. With wood failure values of 0 percent, strength differences can be regarded as valid reflections of the variable. It follows that means of reducing the wood failure should improve the sensitivity of the test.

A specimen which would show 100 percent wood failure when the bond strength truly existed, and would minimize wood failure when the bond strength was below the strength of wood, would improve the observation of border-line situations. Theoretically, in an idealized system, the difference between 0 and 100 percent wood failure may be caused by a one-pound difference in the strength of the bond. A specimen which is sensitive to bond strength could therefore show drastic changes in wood failure with comparatively minor changes in bond strength.

It is perhaps more pertinent therefore to inquire whether the wood failure is reduced by the cross-lap specimen over other accepted specimens such as the block shear and the plywood shear specimens. If it is capable of reducing wood failure in this instance, then it might be expected to eliminate it under border-line conditions. The data of the experiments performed do not provide a direct comparison. However, it is known from past experience that the adhesives used, normally exhibit 100 percent wood failure in block shear and plywood shear tests

on maple. Since the present data, on the average, shows wood failures of about 30 percent, it would appear that some basis exists for assuming that a reduction may be attributed to the cross-lap specimen.

One of the original hypotheses concerning the cross-lap specimen was that stress concentration, both shear and tension, due to bending is diverted to the bond area where it might serve to increase the sensitivity of the specimen toward bond qualities, and lessen the influence of wood variables. Support for this hypothesis should appear in the data of wood failure for Experiment II, Table 3. With increasing thickness of the wood blocks, bending of the specimen, which is one cause of stress concentration, is reduced. Wood failure should therefore increase with increasing thickness. The data show a slight trend in that direction, although not of sufficient magnitude to command much weight. The trend is non-existent in the data of wood failure for Experiment III, Table 6, indicating a possible interaction with moisture content of the wood. What the nature of this interaction might be is not clear, although it could conceivably be associated with differences in the internal stress situation.

In addition to the stress concentration factors, another source of advantage for the wood may be visualized, and this also is created by the bending of the specimen. The origin of this action lies in Poisson's ratios which relate the imposed strain in one direction with the induced strains in perpendicular directions within a material. Tension in one direction induces compression in perpendicular directions. Conversely compression in one direction induces tension in perpendicular directions. The bending which occurs in the cross-lap specimen during loading, produces tension parallel to the grain in the wood adjacent to the glue line. In accordance with Poisson's law, a compressive deformation perpendicular to the grain should thereby arise. This compression, being directed toward the center of each block, would be opposing the testing strain being applied to the bond. Before wood failure could occur,

it would appear that the tension forces normal to the grain would first need to overcome the induced compression. The result should be lower wood failure for a given quality bond than would otherwise occur.

The above reasoning is highly theoretical, implying that the wood is in a sense self-strengthening under load. If this action could be proven, the anticipated results would still depend upon a further unproven theory that strain rather than stress is the limiting factor in the strength of wood normal to the grain. Ductile, isotropic materials are considered to fail by exceeding a strain limit. In the case of an anisotropic material such as wood, it is difficult to predict the mode of failure since it could conceivably be by a stress limit in one direction, and by a strain limit in another direction. The data of Experiments II and III provide no clue as to the possible operation of these effects.

In general it may be stated that the wood failures observed with the cross-lap specimen do not always appear to follow a trend. Rather they fluctuate in a manner that suggests control by factors other than those varied in the experiments. For example, while some strength-wise trends were followed closely by wood failure values, others showed indifferent behavior. In most cases bonds that were definitely low in quality, such as those on low moisture content wood, did show low wood failure. Bonds that were exceptionally high in strength, such as the series in Table 26 at 50 pounds pressure and 60 minutes assembly time, showed mostly 100 percent wood failure. Intermediate strength values were characterized with wide variations in wood failure associated with comparatively small changes in strength.

The most plausible factors that may influence wood failure are grain direction and annular ring orientation with respect to the joint surface. These factors were not studied, but it can be reasoned that a change in grain direction results in a change in resistance to stress. Grain direction also influences the depth of penetration of the adhesive.

The combination of these two situations can result in unpredictable interactions. Blocks with a slight grain angle might provide the best anchorage for the bond but the lower modulus would act to increase stress concentration and hence to decrease the observed strength of an otherwise strong bond.

It was hoped at the outset of this research that valid interpretations based solely upon the observed strength values could be made without the necessity for appraising wood failure. This has largely proven to be the case within the range of observations herein made. There is no doubt however, that the use of other adhesives would alter this finding. A more thorough study of this element of the test needs to be undertaken.

STATISTICAL CONSIDERATIONS

Terminology

The value of a test method is often stated in terms which imply sensitivity, reliability, precision, repeatability, reproducibility, accuracy and variability. These terms unfortunately mean different things to different people, and even among experimenters there appears to be no unanimity of meaning. Some of the above terms are identical in meaning; others connote different characteristics of a test method. All however, derive substance from the statistical properties of the data produced by the method. Recently statisticians have attempted to associate definite statistical concepts with such terms, with the view of reducing them to universally understood numerical units. Peakes (26), Wernimont (27), and Youden and Cameron (28) among others, have illustrated the meanings which may be derived from statistical analysis of data.

Broadly speaking, sensitivity refers to the ability of the method to respond to the properties of the material under test. Reliability is the faithfulness with which this sensitivity is registered, that is, whether changes in properties are reflected in a proportionate manner. Precision is the agreement between successive measurements made under identical conditions. As such, it determines the magnitude of real differences which may be observed with a given degree of confidence. Repeatability may be regarded as synonymous with precision since it implies the ability to repeat an observation. Reproducibility signifies that a test method will give the same result anytime, anywhere.

Repeatability is generally taken as a measure of the variation to be expected with a single operator in a single laboratory, while reproducibility is the variation to be expected between different operators in different laboratories. Accuracy is the ability of the method to produce the true value of the measured property.

With the exception of accuracy and reliability, all of the above properties of a test method can be defined in terms of the standard deviation which is a statistical measure of variability. Accuracy and reliability are best defined by a correlation coefficient since their evaluation involves comparisons with known quantitative differences in the material being tested.

The author feels that first considerations in a test method are the sensitivity toward factors whose effects are to be measured, and the precision with which valid differences in measurements can be observed. Reliability also requires early confirmation as Wernimont (27) suggests. Reliability, however, may be considered a special case of sensitivity, being a combination of insensitivity to some factors or properties and hypersensitivity to others; in other words, reliability, in a sense, is controlled sensitivity. The foregoing research was concerned largely with observations of factors which were believed to affect strength measurements. Hence, the results may be used as a means of observing the sensitivity of the method. It should be noted that the term sensitivity as here used is not the same as used in reference to measuring instruments. In the latter instance, sensitivity refers to the smallest difference which can be observed, i. e., one thousandths of an inch, or one hundredth of a milligram etc. The present concern is to determine what the method is sensitive to, and also what might be the magnitude of that sensitivity. The precision of the method then establishes the smallest difference which can be observed.

In dealing with adhesive strength tests generally, the control

of sensitivity is one of the major obstacles to successful experimentation. This is because, as previously mentioned, there are five categories of factors covering several scores of variables which affect the strength of a bonded assembly. Many of these variables affect one another and hence provide endless sources of interaction which are virtually impossible to control. If the effect of one factor is to be observed among the many which inevitably operate, it appears that in order to take advantage of a high degree of sensitivity, either the method used should be immune to the other factors, or a means of circumventing the side effects must be incorporated in the procedure. A method which was immune to all but one factor would find only limited application since it would yield comparatively little information. Thus the problem reduces to one of circumvention and control, achieving reliability through proper manipulation of the procedure, and through subsequent statistical treatment.

Two forms of manipulation are usually employed: (1) complete randomization of materials and experimental factors such that unknown effects have an equal chance of influencing all specimens, and (2) controlled uniformity or controlled distribution of factors known to cause variation. Controlled variation is regarded as the most efficient form of experimentation since it yields a maximum of information having high statistical value. Both forms were used in this research; opportunity to manipulate factors being one of the major advantages of the cross-lap specimen. The results were subjected to statistical treatment by analysis of variance in order to separate the various effects which were in evidence.

Eleven factors were observed under close control in these experiments. In addition to the eleven direct effects, they provided nine first-order interactions and one second-order interaction. The statistical analysis permitted an estimate to be drawn regarding the sensitivity of the cross-lap specimen to these factors, and also a measure of the precision

of that estimate.

Sensitivity

The sensitivity of a test is an expression of how well an effect of a variable can be evidenced against variations inherent in the method due to deviations on the part of operator, machines or materials. If a variable has an effect upon a measurement, it should produce variation in excess of that produced by vagaries of the method. The analysis of variance technique is essentially a means of separating the variation produced by the variables being observed from the variation inherent in the method. Comparison of the two sources of variations, i. e. , variances, yields a ratio, the significance of which depends upon the number of observations which contributed the variation. The magnitude of this ratio, the F ratio, does not depend upon the degrees of freedom and hence can be used as a general index to sensitivity as above defined. The F ratios calculated for all the factors studied are regrouped in Table 29. It should be emphasized that the F ratios given in Table 29 cannot be directly compared for significance as they stand because they represent different degrees of freedom according to the design of the experiment from which they were derived. For example an F ratio of 4.0 can be as significant as an F ratio of 8.0 if it represents sufficient degrees of freedom. At the same degrees of freedom, however, F ratios of 4.0 and 8.0 can be directly related. Assuming that the F ratios of Table 29 all were to bear the same degrees of freedom, some broad comparisons may be made.

The F ratios show an overwhelming sensitivity toward some factors, a lack of sensitivity toward others, and varying degrees of sensitivity toward the remainder. While much of the variance shown was dependent largely on the size of the intervals between levels of the

variates, several generalizations may be made at this point. The magnitude of the intervals is accounted for subsequently under considerations of precision.

Adhesive factors, that is factors inherent in the adhesive by virtue of its composition, e. g. catalyst, and flour extension produced variance of approximately three to four times the chance variation in the procedure.

Factors which are considered to be associated with the manner in which the adhesive is used, produced variation of one to eight times the chance variation. There was evidence, however, that the response observed was a reflection of an unmeasured adhesive property, "tolerance," rather than a particular sensitivity on the part of the specimen. Actually, a likelihood exists that the "closed" assembly time factor would become inoperative after a certain period of elapsed time. Bonding pressure was also shown to be a non-effective factor, although, as indicated, this may be due to the properties of the adhesives as well as to the properties of the specimen.

Of the factors connected with the specimen itself, thickness, moisture content of the wood, and the presence of certain types of flaws in the exterior portions of the joint, produced an overwhelming source of variation. The specific gravity of the wood also showed strong influence upon the observations. Apparently, without extremely close control of these factors, the results obtained would be meaningless. It should be mentioned that the effect of moisture content was, in these experiments, exerted chiefly upon the bonding power of the adhesive, and in this sense, it is an important source of information relative to an adhesive property.

Among the method-of-test variables, rate of loading did not appear to influence the results within the range studied. The manner of applying load introduced some variation but it was not clear whether this was due to difference in calibration of the two machines or due to an

TABLE 29

Calculated F Ratios for Several Variables and
Interactions on the Cross-Lap Specimen

<u>Variable or Interaction</u>	<u>F Ratio</u>
Rate of loading	1.02
Specific gravity	6.31
Thickness (pooled)	109.70
Specific gravity x thickness	0.99
Moisture content (pooled)	65.10
Moisture content x thickness	2.57
Catalyst	3.17
Catalyst x moisture content	3.96
Flaws (exterior)	138.60
Flaws (interior)	0.86
Grips	3.66
Quality	4.02
Flaw x grip	0.70
Flaw x quality	0.56
Quality x grip	0.64
Flaw x grip x quality	1.94
Assembly time (Adhesive A)	2.09
Assembly time (Adhesive B)	8.62
Age of mix (Adhesive A)	0.89
Age of mix (Adhesive B)	3.34
Pressure (Adhesive A)	0.73
Assembly time x age (Adhesive A)	1.07
Assembly time x age (Adhesive B)	2.16
Assembly time x pressure (Adhesive A)	0.49
Pressure x age (Adhesive A)	0.93

actual difference in response to the strength situations present in the specimens.

It is seen that many of the factors studied produce variation in excess of inherent variation existing in the method. Some of these factors normally occur as random variates in experiments, while others are the sources of information. Whether or not the sensitivity shown can be harnessed to reveal desired effects efficiently, depends upon how well each category of factors can be controlled. The precision of the method reflects the control attainable.

Precision

The factors which were responsible for random variation in the experiments concluded are evidenced as a pooled quantity in the error term of the analysis of variance for each group of data. If all the error terms are pooled (with the exception of that from Adhesive B in Experiment VI which appeared to be influenced by additional factors) to give an average variance for error, a good estimate of the standard deviation can be obtained representing 485 observations and 390 degrees of freedom. As previously mentioned, the standard deviation provides a statistical measure of the repeatability of the method as well as the precision. The standard deviation was calculated to be 156 pounds. This means that in a given sample of identically made specimens with factors controlled as in these experiments, 67 percent of the observations would fall within ± 156 pounds of the mean and 97 percent would fall within ± 312 pounds of the mean.

An estimate of the precision may also be obtained by expressing the standard deviation of single observations as the standard deviation of means. This "standard error of the means" takes into account the fact that averages do not vary as much as single observations. The

variation of an average decreases inversely with the square root of the sample size. Thus, if the standard deviation is represented by S, the standard error:

$$S_m = \frac{S}{\sqrt{N}}$$

would provide a measure of how samples of size N would vary about the true mean. In normal experimental procedures, a true mean is seldom known. The usual situation involves a decision as to whether the difference between two means is such as would be expected if they were both varying about the same grand mean or about different grand means. This would lead to a deduction on whether the two means in question could be considered the same or really different.

Means representing the same value and influenced by the same random causes of variation will vary about that value in accord with the standard error of means S_m . These means however, will vary among themselves in accord with another normal distribution law which accounts for the fact that the magnitude of the variations between individual means is greater than the variations of the means from a grand mean. The statistical measure of variation between means is provided by a second modification of the standard deviation, the standard error of a difference

$$S_D = (S) \sqrt{\frac{N_1 + N_2}{N_1 \times N_2}}$$

where N_1 and N_2 are the number of observations in sample 1 and sample 2 respectively. If the sample size for both means is the same, the standard error of a difference reduces to

$$S_D = \frac{S\sqrt{2}}{\sqrt{N}}$$

The magnitude of the difference between a pair of means when measured in terms of the standard error of a difference, may be referred

to statistical tables to determine the significance. Thus the standard error of a difference is a statistic which represents the precision of a method of test for it indicates in terms of the inherent variability, what constitutes a significant difference between sets of measurements. Stated in another way, it can indicate the smallest difference which meets a prescribed level of significance with a given sample size. This is illustrated in Table 30.

The values in the table were obtained by the equation for the "t" test, i. e.,

$$"t" = \frac{\text{Difference between means}}{S_D} = \frac{\text{Difference } (\sqrt{N})}{S\sqrt{2}}$$

The value of "t" represents a ratio the magnitude of which can be interpreted in terms of the probability it could be exceeded by chance. Thus if the probability is very low for chance alone to cause a given "t" value, it can be inferred that a real cause for the difference has registered. The criterion magnitude of "t" depends upon the number of degrees of freedom used to calculate S. In this case, 390 degrees of freedom were used. For degrees of freedom in excess of 120, a value of "t" = 1.96 indicates that such a value would be exceeded by chance only five times in a hundred tries; a value of 2.58, that it would not be exceeded more than one time in a hundred.

By inserting a series of hypothetical differences in the above equation for "t" and equating to 1.96 or 2.58, the value for N, the size of sample, was determined for the desired levels of significance. It can be seen from Table 30 that a sample size of five specimens would not measure a difference less than 200 pounds with the commonly accepted significance of 5 percent. This means that the precision of a sample size of five is 200 pounds. To measure a difference of 25 pounds would require 300 specimens. Expressed in another way, a difference of 10 percent of a mean of 1500 pounds, would require 33 specimens.

TABLE 30

Number of Specimens Required for Observing Given Differences
between Means with 5 Percent and 1 Percent Significance

Strength Difference Between Means Pounds	Number of Observations Required to Obtain Significance Level of	
	5 Percent	1 Percent
25	300	502
50	75	103
75	33	58
100	19	32
125	12	21
150	8	14
175	6	11
200	5	8

It would appear that the precision of this method is rather low since large sample sizes are required to register differences less than 5 percent of the average strength. As was mentioned earlier, an important cause of the low precision is the variability introduced by deviations in the wood. Some causes of variability are largely inescapable and a means of circumventing them would be desirable. Others may be controlled by appropriate selection and conditioning of the materials, if the critical levels are known.

Improving Precision by Control of Factors

The variations produced by the factors varied in the experiments were observed against controlled levels of the variables. The magnitude of the intervals between different levels therefore exercised an influence upon the magnitude of the variation observed. In order to be useful in a test method, it is necessary to know the effect produced by a practical unit of the variable. This then would lead to an indication of how closely certain factors would need to be controlled during observations of other factors in order to obtain the maximum precision. Assuming that the method is intended mainly for observing properties of the adhesive, it would be desirable to reduce the effect of all factors which affect strength but do not reflect adhesive effects. The factors which usually require control are those relating to the specimen, i. e., dimensions and wood characteristics, and those relating to the manner of producing the test joints. Among the latter factors, pressure, assembly time, and age of the adhesive mixture were shown to be negligible per se, although they can affect strength through causes assignable to the adhesive. Interest thus centers on specimen and wood factors.

The specimen and wood factors which can be restudied with respect to degree of control in experimental procedures are: thickness

of the wood blocks, width of the wood blocks, specific gravity of the wood, and moisture content of the wood. Since moisture content of the wood affected mainly the quality of the bond, other types of adhesives would no doubt respond differently to this factor. Moisture content might therefore be more properly considered an adhesive factor rather than a wood factor. However, such a powerful effect was produced by small changes in moisture content of the wood, it appeared appropriate to include the factor in this group by way of emphasizing its importance with the type of adhesive used.

Thickness

In attempting to define the effect on strength of small changes in thickness of the wood blocks, it is evident from the plot of Figure 7, that the effect varies with the thickness, being more critical at the lower values of thickness and decreasing in effect toward 2 1/4-inches. A quantitative measure of the effect of thickness upon strength is provided by the values obtained from dividing the average load for each thickness by the thickness. Thus they represent pounds strength per inch of thickness. They are mean values for the thickness levels however, and do not portray the effects of various increments within a thickness level. Interest is now directed at the final increment of thickness within a thickness class because small changes in thickness would be reflections at such points. Since the effect of thickness decreases with increasing thickness, it follows that the final increment of strength would represent a lower unit value than the mean strength. For example, considering the strength per inch of thickness at the 3/4-inch level, 2010 pounds is a mean which includes the effect of the first thousandth inch thickness and the 750th thousandth inch thickness.

The effect on strength of the 750th thousandth inch increment of

thickness would provide an estimate of the variability which might be introduced by the standard 3/4-inch thick specimen with small variations in thickness. An approximation to the effect of thickness variations may be calculated from the plot in Figure 10. The slope of the line in Figure 10 represents the change in the logarithm of the strength per unit thickness with changes in the thickness. The equation of this line was found to be:

$$\text{Log}_{10} \frac{Y}{X} = 3.4661 - 0.3432X$$

where Y is the breaking load and X is the thickness in inches. Substituting values of 0.749 and 0.750 for X in this equation, representing a change in thickness of one mil (one thousandth of an inch) produced a change in Y, the strength, of 0.67 pounds, approximated to 0.7 pounds.

The thickness variation resulting from the planer in surfacing the wood for the experiments was plus or minus 0.005 inch as measured with a machinist's micrometer. According to the foregoing calculations, a variation in strength of approximately 3.5 pounds could be attributed to thickness variation and this entered into the error term in the analysis of variance. It may therefore be inferred that when the thickness varies randomly within narrow limits, the precision of the method should not be seriously impaired. However, when the variation in thickness is not random, as in comparison of results between experiments, the figure 0.7 pounds per thousandth inch of thickness may serve as a means of removing one source of extraneous difference between observed averages.

It is recognized that a statement of a unit effect can only be a broad generalization since the quantitative response to a dimension or material change is controlled largely by the quality of the bond, as shown in Experiment III. Recognition of this limitation extends as well to calculations of the unit effects for width, and specific gravity.

Hence, the values obtained cannot as yet be considered constants of the specimen but only as orders of magnitude. Had sufficient data been available, it is possible that a means of modifying these values to account for the level of strength could have been proposed. In the meantime, the validity of these effects is restricted to situations where the bond strength approaches the strength of the wood. This then would be the maximum effect that could be produced and other quality bonds would involve lower level effects.

Width

An estimate of the effect of small changes in width of the blocks cannot be made directly since this factor was not varied in any of the experiments. On an assumption that changes in width would produce changes in bond area or bond boundary similar to those represented by Figures 20 and 21, an approximation of the effect can be deduced.

It was inferred in Experiment V that the length of the bond boundary appeared to have a closer relation with observed strength than the bond area. Changes in the width of the blocks may be considered as changes in the length of the bond boundary. Considerations of the geometry of the specimen lead to the fact that a unit change in the width of the specimen results in a four unit change in the bond length. The plot of Figure 21 indicates that a change of 1.0 inch in the length of the bond caused a change of 195 pounds in the observed strength. In terms of one thousandths of an inch, this is equivalent to 0.195 pounds per mil of bond length, or 0.78 pounds per mil of block width. Thus the effect of block width is nearly identical to the effect of block thickness.

The width of the specimens was produced in the same manner as the thickness in the foregoing experiments. Hence a variation of 0.005 inches also existed in the width of the blocks. Under the assumption

previously made, this could create a variation in bond strength of 3.9 pounds. Again, it would seem that small changes in dimension, in this case, width, should not seriously affect the precision of the method.

Specific Gravity

The equation relating the observed strength with the specific gravity provides a direct assessment of the strength variation that might be produced by unit variations in this factor.

$$Y_1 = Y_0 + 2320 (\text{SpG}_1 - \text{SpG}_0)$$

If the specific gravity is expressed in hundredths, a change of 0.01 would cause a strength change of 23.2 pounds. Under the method used to select specific gravity classes, viz. on the basis of 10 gram intervals for billet weights, each class encompassed a range of .016. Thus a variation of 1.6 times 23.2, or 37.12 pounds existed within a specific gravity class as a result of the operation of this factor alone. The necessity for close control of specific gravity is evident, and this will be governed in each case by the precision desired.

Wood Moisture Content

Moisture content is one of the most powerful factors influencing the strength of bonds made with urea type adhesives. The plots of Figure 13, while showing some interaction with thickness, all show a sharp decline in strength as the moisture content reduces below 9.4 percent. Above 9.4 percent, the strength does not vary as widely with the moisture content. Considering the 3/4-inch thickness specimens, strengths of 859, 1502 and 1605 were observed for moisture contents of 5.4 percent, 9.4 percent and 15.0 percent. It was not possible to rectify these data into a linear relationship which would permit general-

ization concerning minute effects. A useful correspondence, however, does appear to exist between the lower two values.

If the strength is divided by its corresponding moisture content, the strength per percent moisture content is seen to be more nearly the same for the lower two values:

$$\frac{859}{5.4} = 171.5$$

$$\frac{1508}{9.4} = 160.5$$

Furthermore, if the difference between these strengths is divided by the difference between moisture contents the same general ratio is obtained:

$$\frac{1508 - 859}{9.4 - 5.4} = \frac{649}{4} = 162$$

These ratios represent slopes of a line connecting plotted points of the function strength versus moisture content. The close agreement between slopes suggests a straight line relationship between the two points. Moreover, the slope of the difference, in agreement with the slope of the whole, suggests that the line passes through the origin. The latter situation implies that wood at zero percent moisture content cannot be bonded with urea adhesives such as used in these experiments. Most bonding of wood is done below a moisture content of 10 percent. The relationship developed above therefore covers many gluing applications.

It is seen that below a moisture content of 9.4 percent, the strength changes approximately 160 pounds per percent change in moisture content. This could be a large source of variation. The wood used in the experiments had been equilibrated with their respective atmospheres for a period of two years. This is considered ample time for wood to reach a uniform moisture content equilibrium. Upon testing, however,

it was found to vary approximately half a percent from the average, or a total variation of one percent. Thus a variation of 80 pounds in strength about an average could have been caused by moisture content variation. It would appear that the precision of this method is heavily dependent upon the control of moisture content of the wood, this being true for adhesives which are particularly sensitive to moisture content.

In summary of the above discussion on effects of small changes in specimen conditions, it is evident that variations in strength can be easily controlled to negligible levels as far as thickness and width of the blocks are concerned. Cutting tolerances of ± 0.005 can be maintained on well-operated woodworking equipment. This would introduce a variation of approximately seven pounds or less than 0.5 percent based upon a theoretical average strength of 1500 pounds.

The control of specific gravity within the limits necessary for high precision is more difficult. If the requirement for the control of specific gravity in a test procedure is $\pm .05$ from a stated average, such a control limit with the cross-lap specimen would allow a variation of 232 pounds in the strength of the specimen. On the basis of an average strength of 1500 pounds, this would represent a variation of 15.5 percent which is considerably more than can be tolerated. In order to reduce the range of variation to 5 percent of the average strength, the specific gravity would need to be controlled to approximately ± 0.016 from a given average.

The control of moisture content is again more difficult than specific gravity since under complete equilibrium conditions, a variation of 1 percent occurred. This was sufficient to cause a variation of 160 pounds in strength or 11 percent based upon a 1500 pound average. Normal moisture content variation in laboratory procedures usually range ± 1.0 to 1.5 percent. This would cause variations of 21 percent and 32 percent respectively, a situation which would virtually preclude

efficient experimentation with adhesives such as those used here.

It would appear from the amount of variability that can be introduced by specific gravity and moisture content variations, that rather large differences between factors under study would need to exist before they could be revealed with a degree of confidence. In the next section, this aspect of the situation is considered. An experimental means of improving the precision of a test is proposed.

Improving Precision by Experimental Design

It is generally accepted that no two pieces of wood are exactly alike. It is also true, but to lesser degree, that the properties vary in different locations of the same piece of wood. Considerable differences, however, exist among the various species, depending upon anatomical features and growth conditions. Nevertheless, for one species, maple the properties of specific gravity, moisture content and grain direction, which account for a large portion of variation in the cross-lap specimen, may be regarded as significantly more uniform within a given piece of wood than between two pieces of wood taken at random.

This fact suggests one means of improving the precision in comparisons of treatments. If all comparisons could be made with specimens cut from the same board, the error would be sharply reduced. Thus, in considering a randomized block experiment, a "block" would be one board. The size of the block then would be governed by the size of the board which could be depended upon to maintain homogeneity throughout its volume. It is patent that the smaller the board, the more uniform it can be considered. Hence there is a limit to the size of block which may be exploited in this manner. As an arbitrary point of reference, a board eight feet long by six inches wide would, assuming complete yield, produce 96 pieces

of wood which could be assembled into 48 specimens. These 48 specimens would provide a block sufficiently large to accommodate one $4 \times 4 \times 3$ factorial experiment with one replication. By replicating the experiment with additional boards of the same size, the effect of differences between boards can be removed from the error before comparisons are made between treatments.

A procedure for doubling the size of the experiment without loss in precision is also evident. If each board can be considered to contain a homogenous population of error, then two boards superimposed, one over the other, should also present a homogenous error. Hence if the two members for each specimen were paired from two different boards, it should be possible to create 96 specimens which would be statistically identical as far as wood factors are concerned. By replicating the experiment with pairs of boards, the error resulting from differences between pairs of boards can also be eliminated from the comparisons.

For experiments requiring a base larger than 96 specimens, several alternatives are available. The simplest of these involves the specimens resulting from two or more pairs of boards. By repeating at least one treatment in each pair of boards, the remaining treatments in each pair may be adjusted by the amount indicated with the overlapping treatment. The precision with which the adjustments can be made will of course, affect the final results. A design incorporating the principles of the balanced incomplete block, Youden Squares, or Lattice Squares is therefore recommended because of their greater efficiency. These designs permit a more precise accounting of the differences between blocks, in this instance boards or pairs of boards, even though each treatment does not appear in each block the same number of times.

An experiment using 96 specimens would perhaps be as large as needed for most purposes. The broadest experiment in the present

research required 80 specimens without replication. Thus in many cases, boards smaller than six inches by eight feet could be used as the unit block, particularly if the boards are used in pairs.

It is apparent that the analysis of the results of these experiments could have been greatly improved had the billets been identified in a manner to permit regrouping into suitable blocks according to the boards from which they had been cut. Actually, considerable improvement could have been made in the smaller experiments by maintaining the identity of each piece cut from a billet. This would permit a split plot design with comparisons between specimens rather than between boards. This is the strongest recommendations which can be made for future research.

An "Intolerance Index"

Throughout this research, the theme has persisted that, at the present level of knowledge, adhesives are not adhesives because they possess certain definite chemical or physical properties, but because they can be made to form a bond between two substances. It follows that adhesives owe at least a portion of their utility to the material being bonded and to the agents creating the joint. In evaluating an adhesive, it would appear delusory to determine how strong a bond can be formed under a system of fixed factors as is usually found in adhesive specifications. Such inflexible prescription of influential factors produces a somewhat sterile media in which the adhesive is unable to register its full potentialities because no latitude is provided for the development of side effects. Thus it is possible for many adhesives to appear identical when under actual usage they may perform differently due to varying conditions of materials and operations.

A more realistic test would seem to be one in which as many

factors as possible were varied at several levels, and in this way obtain not only the average strength, but also the reaction of the adhesive to a few common combinations of critical factors. There does not now exist either a standard procedure, or the knowledge for interpreting data resulting from observations on the performance of an adhesive under varying conditions. Following is a tentative proposal for such a procedure. It draws upon the versatility of the cross-lap specimen as regards the ease of introducing variables. The interpretation of the data however must still await the accumulation of experience and the correlation with actual performance.

Among the critical factors under which a wood adhesive is called upon to function, the ones which are most amenable to controlled variation in experimental procedures are: moisture content of the wood, assembly time, age of the adhesive mixture, and pressure. If each of these variables is controlled at three levels in a factorial design, $3 \times 3 \times 3 \times 3 = 81$ specimens would be required to cover all possible combinations with each replication. Such a design could be handled in the maximum precision pattern suggested in the preceding section.

The factors and levels which may be taken as an example to characterize the performance of a wood adhesive are:

Moisture content	4, 8, 12 percent
Assembly time (open)	0, 15, 30 minutes
Age of mixture	0, 60, 120 minutes
Pressure	0, 50, 100 pounds per square inch

It is perhaps premature to attempt to prescribe the exact levels of the variates without further study to determine how they might fit the different types of adhesives. For the present, it may be considered that these conditions reflect the practical range likely to be encountered by a wood adhesive under typical usage.

Eventually, it might be possible to prescribe combinations of

conditions typifying different bonding operations. For example, a furniture factory may demand compliance to a set of conditions permitting rapid production of parts. On the other hand, laminating of arches may require slightly different conditions to permit long assembly times. Thus if a set of conditions could be developed to closely represent particular fields of adhesive use, the selection of the best adhesive for the job could be done with a greater degree of confidence.

When the data obtained in the above design are analyzed statistically by the analysis of variance technique, the variation produced by each variable and each combination of variables can be isolated and quantitatively measured in terms of the variation due to the chance operation of other uncontrolled factors. The total variation produced by the controlled factors can be considered as the total reaction of the adhesive to the changes in moisture content, assembly time, age, and pressure. The greater this reaction, the more the adhesive can be said to be sensitive to them. Also it may be inferred that the greater the variation, the more intolerant the adhesive is to changes in conditions, and hence the less "fool-proof" the adhesive might be under factory conditions where these factors might vary uncontrollably. An adhesive yielding a low variation could be considered as safe, while one with a high variation could be expected to produce a high percentage of defective bonds.

The criterion for what might be termed the "intolerance" of an adhesive can be based upon the variance for each of the direct effects, and the interactions. This total effected variance can be used to extract a type of standard deviation for controlled variables, just as the variance for error is used to derive the standard deviation for chance factors. The standard deviation for controlled factors would thus represent an "Intolerance Index" which might be visualized as indicating a relative

effect on the variation in quality of bonds due to the operation of these factors.

Numerically then, the index for intolerance of an adhesive to the conditions imposed by the test, would be equal to the square root of the sum of the individual variances. The individual variances may be calculated from the mean squares of the analysis of variance table. These mean squares represent the total variance associated with the operation of the particular factor or combination of factors. Each mean square is therefore made up of components, all of which can be isolated. Brownlee (29) and others give the components of variance for a four factor analysis of variance. Bennett and Franklin, (30) however, have recently shown that many of the components do not exist under experimental conditions where factors are held constant at arbitrary levels and are not free to operate randomly.

A four factor experiment having p assembly Times, q mix Ages, r Pressures, s Moisture contents and n replications would, according to Bennett and Franklin, have components of variance as given in Table 31.

Equating the components to the mean squares determined by the analysis of variance, permits solving for the desired variance. For example the variance for assembly time may be obtained by setting

$$\text{mean square for } T = \sigma_o^2 + nqrs \sigma_T^2$$

from which

$$\sigma_T^2 = \frac{\text{mean square for } T - \sigma_o^2}{nqrs}$$

Similarly, the remaining variances may be calculated. The summation of the variances thus obtained leads to the determination of the "Intolerance Index":

$$\text{"Intolerance Index"} = \sqrt{\sum_1^i \sigma_F^2}$$

TABLE 31

Components of Variance for a Four-Factor
Analysis of Variance

<u>Factor</u>	<u>Mean Square</u> <u>Components of Variance</u>	<u>Degrees of</u> <u>Freedom</u>
T	$\sigma_o^2 + nqrs\sigma_T^2$	$p-1$
A	$\sigma_o^2 + nprsq\sigma_A^2$	$q-1$
F	$\sigma_o^2 + npqsr\sigma_F^2$	$r-1$
M	$\sigma_o^2 + npqrs\sigma_M^2$	$s-1$
TA	$\sigma_o^2 + nrs\sigma_{TA}^2$	$(p-1)(q-1)$
TP	$\sigma_o^2 + nqs\sigma_{TP}^2$	$(p-1)(r-1)$
TM	$\sigma_o^2 + nqr\sigma_{TM}^2$	$(p-1)(s-1)$
AF	$\sigma_o^2 + nps\sigma_{AF}^2$	$(q-1)(r-1)$
AM	$\sigma_o^2 + npr\sigma_{AM}^2$	$(q-1)(s-1)$
PM	$\sigma_o^2 + npq\sigma_{PM}^2$	$(r-1)(s-1)$
TAP	$\sigma_o^2 + ns\sigma_{TAP}^2$	$(p-1)(q-1)(r-1)$
TAM	$\sigma_o^2 + nr\sigma_{TAM}^2$	$(p-1)(q-1)(s-1)$
TFM	$\sigma_o^2 + nq\sigma_{TFM}^2$	$(p-1)(r-1)(s-1)$
APM	$\sigma_o^2 + np\sigma_{APM}^2$	$(q-1)(r-1)(s-1)$
TAPM	$\sigma_o^2 + n\sigma_{TAPM}^2$	$(q-1)(q-1)(r-1)(s-1)$
Residual	σ_o^2	$pqrs(n-1)$

where i is the " i "th variance having positive sense, and F is the factor or combination of factors responsible for the variance.

The "Intolerance Index" is an overall assessment of a performance attribute of an adhesive. It is possible also to obtain specific information regarding the influence of each factor upon the adhesive and thus determine where a major weakness in the adhesive existed. The "Intolerance Index", however, could not be used to predict the variation that might occur under production conditions. This is because production conditions permit random occurrence of all, or most, factors, while the experimental conditions are necessarily arbitrary, and occur at fixed levels and fixed frequency. Nevertheless, as an index, this factor could be used to compare adhesives against a common, controlled background of variation which, in a limited way, represents production conditions.

Comparison of Adhesives A and B, for example, assuming comparable experimental conditions, might be attempted on the basis of their intolerance to two factors, assembly time, and age of the mixture. An "Intolerance Index" of 42 is shown for Adhesive A, and 172 for Adhesive B, a four-fold increase. This contrasts with strength observations which differed by less than 20 percent on the average, and were nearly the same under certain conditions. Although the comparison is not strictly valid owing to differences in levels of the variates, a striking magnification of a differentiating attribute appears to exist.

It is anticipated, also that the question of permissible flour extension raised in Experiment V might be better answered if the "Intolerance Index" were observed to vary proportionately with flour additions, even though the average strength remained essentially the same.

The above concepts are completely untried. They require extensive investigation to develop the precise meanings of various values of the "Index." In the meantime it would appear to be a useful tool

for rating adhesives; thereby providing more realistic comparisons for the benefit of both consumers and manufacturers of adhesives.

SUMMARY AND CONCLUSIONS

In the search of a wood adhesive specimen which might be suitable for use in a simplified test procedure, the cross-lap specimen appeared to have important advantages. It could be assembled readily from easily prepared rectangular blocks, and no machining is required after the adhesive hardens. Since the bond is stressed primarily in tension, it was also felt that a critical property would thus be measured. A machine was constructed for assembling and testing the specimens and this conformed to the pattern of simplicity desired in a control type of test method. Much, however, needed to be learned concerning the characteristics of the specimen, its precision, and its sensitivity with regard to many factors which inevitably operate during the formation and testing of an adhesive bond. This research dealt principally with the observation of a number of factors whose effects were believed to be influential in affecting the observed strength of the specimen.

The factors studied were selected to provide an insight into the sensitivity of the specimen toward variations in the wood, in the specimen, in the adhesive, in the manner of using the adhesive and in the manner of testing. It was anticipated that this information would lead to an appraisal of the specimen as an instrument for observing adhesive properties. The effectiveness of the specimen for such purposes was taken to depend upon how greatly it was influenced by other factors and how well the other factors could be controlled in an experiment. The factors selected for study included moisture content of the wood, specific gravity of the wood, thickness of the wood members, presence of flaws

in the joint and in the adhesive, i. e. , flour extender, amount of catalyst in the adhesive, assembly time, age of the adhesive mixture, pressure, rate of loading, and testing machines. The adhesives used in this research were of the urea-formaldehyde type, chosen for the ease with which they may be modified, and for their sensitivity to many conditions. Because of its high strength and uniformity, hard maple was the wood used.

The observation of the effects of these factors and some of their interactions necessitated a broad experimental approach. An outcome of this approach was the exposition of a general lack of knowledge in many areas of adhesive action. Numerous effects were observed which could not be explained. The need for further investigation was thus strongly evident.

Despite the many unanswered questions raised by this research, a number of useful findings emerged:

(1) The rate of loading of the crosslap specimen did not appear to affect the observed strength within the range of 400 to 6,000 pounds per minute.

(2) The thickness of the wood blocks comprising the cross-lap specimen exhibited a striking effect upon strength, being a hyperbolic function with a definite maximum. The observed strength increased with increasing thickness up to a maximum at approximately 2 1/4 inches, beyond which further increases in thickness caused lower strength values. Extrapolation beyond 3.0 inches in thickness could not be done because of the unpredictable nature of the function, although some straight line relationships within the scope of the data were developed. The causes for the existence of a peak strength were not clearly established but a possible explanation was made on the basis of internal stresses created by adsorption and dispersal of glue water.

(3) While thickness of the wood blocks exerted a powerful effect

upon strength, it was shown that this was largely due to the magnitude as well as the level of the intervals chosen for variation. When the interval was reduced to thousandth's of an inch, at a level of $3/4$ inches the variation in strength was negligible, being about 0.7 pounds per thousandth.

(4) The specific gravity of the wood affected the strength of the specimen linearly within the range studied. This linearity yielded a correction factor of 23.2 pounds per .01 difference in specific gravity. The necessity for extremely close control of this factor was suggested.

(5) Specific gravity showed no significant interaction with thickness, implying that the effect upon strength is manifested through actual change in bond strength rather than through change in the elastic moduli of the wood.

(6) Moisture content was shown to have the strongest influence upon strength, particularly below 9.4 percent where a change of one percent was shown to cause a change of 160 pounds in strength, with the type of adhesive used.

(7) A significant interaction between moisture content and thickness occurred. This was believed to be due to the level of strength produced at each moisture content interval, and not to a real change in relationship. Hence moisture content affected the strength of the specimen more through quality of the bond than through changes in elastic moduli.

(8) The effect of catalyst, or rate of cure, was found to be different for each level of moisture content. Increasing catalyst resulted in increasing strength on low moisture content wood, and decreasing strength on high moisture content wood. The intermediate moisture content level showed an optimum catalysis situation. The interaction of rate of cure with rate of water loss to the wood was believed to be responsible for the results observed.

(9) Changes in quality of the adhesive brought about by additions of wheat flour, caused statistically significant variation. This variation, however, was not in agreement with the imposed levels of quality, and it was deduced that some other undetermined factor besides flour had affected the strength.

(10) The cross-lap specimen was found to be sensitive to flaws existing at the periphery of the joint but not to flaws located at the center of the joint. The former situation was interpreted to mean that the specimen might more properly be called a multiple cleavage specimen rather than a tensile specimen. The latter situation permitted an estimation of the peak stresses which exist at rupture. These were found to be at least five times the mean stress, and exceeded by 100 percent the published strength values for maple normal to the grain.

(11) The presence of flaws located at exterior portions of the joint did not improve the sensitivity of the specimen to changes in quality of the adhesive.

(12) Neither the self-aligning grip nor the rigid saddle grip displayed a significant advantage in revealing adhesive quality differences. Both reacted essentially the same to the presence of exterior flaws, although the rigid grip appeared to be more affected by the presence of the one-corner flaw than did the self-aligning grip. The mean breaking strength produced by both grips were statistically the same. However, the unit strength was significantly lower with the rigid grip, suggesting a somewhat greater sensitivity to the imposed lowering effects of flaws and flour.

(13) Varying the bonding pressure from zero to 300 pounds per square inch produced no change in the variation of strength. This appears to indicate that pressure might be a non-influential factor with the cross-lap specimen. Such a situation might be ascribed to the flatness and soundness of the block surfaces which therefore do not require pressure.

There is furthermore the possibility that pressure may be developed spontaneously in a set of specimens restrained by the assembly jig, due to the imbibition of glue water and the concomitant swelling of the wood. The possibility that the adhesive used perhaps might not have required pressure to form a strong bond also must be considered.

(14) Assembly time changes produced a significant effect upon strength with one brand of adhesive but not with another, leading to the belief that this factor may be a true property of the adhesive rather than a source of variation inherent in the conduct of a test.

(15) The mixed age of the adhesive likewise showed an effect with one brand but not with another.

(16) The inference that the effects of mix age, assembly time, pressure and moisture content might be reflections of adhesive properties which would be instrumental in affecting the performance of an adhesive under conditions of actual usage, led to a proposal of an experimental design, which expressed the reaction of the adhesive to these factors in a single value, termed the "Intolerance Index".

(17) The precision of the procedures used in this research indicated that individual strength values within a homogenous group may vary from the mean according to a standard deviation of 156 pounds. This is approximately 10 percent of the average strength and suggests the need for large sample sizes and close control of random factors to attain significance. A method is suggested for improving precision by the use of a randomized block technique wherein comparisons are made entirely "within boards" thus eliminating "between boards" variation.

(18) The estimations of wood failure appear to be an unreliable criterion of bond quality except at either extreme. Occasional proportional response was observed but not with sufficient regularity to warrant confidence in the face of the wide variations. The magnitude of wood failure values apparently is controlled by factors other than those studied.

With respect to the main purpose of this research, i. e. , to study the behavior of the cross-lap specimen in view of its possible use in test procedures for evaluating wood assembly adhesives, the above findings appear to support the following general conclusions:

(1) Factors associated with wood, viz. specific gravity and moisture content were the source of important variation in observed strength of the cross-lap specimen.

(2) The amount of wood failure observed after rupture was not a good criterion of bond quality except at the extremes.

(3) The specimen factors of thickness and width of the blocks, when reduced to the variation normally encountered, should not unduly affect the dispersion of results.

(4) Additions of small amounts of wheat flour extender did not reflect a proportionate change in the observed strength with the adhesive used.

(5) The effects of catalysis at different levels of moisture content could be readily observed and are shown to vary with the moisture content.

(6) Among the factors usually contributing to the error variance in making the adhesive test specimens, bonding pressure, assembly time, and age of the adhesive mixture, did not appear to be serious sources of variation in themselves. Insofar as they affect the physical behavior of the adhesive during bond formation, however, their inclusion as controlled variates in a test procedure would yield important information.

(7) The manner of testing the specimens, i. e. , grip type, was of minor consequence, although the self-aligning grip appeared to be more reliable in the presence of one-corner flaws which might occur by chance.

(8) The reaction of the cross-lap specimen to changes in thickness of the blocks, showing a maximum strength at a thickness of approximately 2 1/4-inches, could not be completely explained but was

believed to be associated with the dispersal of glue water.

(9) The high peak stresses, in excess of 2,000 pounds per square inch, confirmed one of the original postulates concerning the cross-lap specimens, i. e., that stress concentrations are removed from the vicinity of vulnerable end grain areas. The latter would limit the unit peak strength to approximately 1,000 pounds per square inch.

(10) Since the cross-lap specimen is made singly, instead of in multiples as is the case with most wood adhesive specimens, it is possible to employ experimental designs having many variables at several levels.

(11) The variation caused by the chance operation of uncontrolled factors was quite large, giving a standard deviation of 156 pounds or approximately 10 percent of the mean under the procedures used in this research. The efficiency of a method using the cross-lap specimen therefore depends upon how closely factors can be controlled, particularly those associated with the wood.

One reservation must be imposed upon the above conclusions. The reactions observed are those of a single type of adhesive, urea-formaldehyde. Other types of adhesives such as casein, animal protein, resorcinol-formaldehyde, and polyvinyl acetate would quite probably have responded differently to some of the imposed variations.

APPENDIX I

DEVELOPMENT OF A TESTING MACHINE AND PROCEDURE USING THE CROSS-LAP SPECIMEN*

In developing a testing machine for the cross-lap specimen, one of the main considerations was simplicity of construction and operation, as well as reliability in delivering the loads necessary. With this in mind, a number of pressing jigs, loading devices, and testing grips were investigated including wood clamps, C-clamps, bar clamps, spring clamps, screw jacks, hydraulic jacks, fire-hose presses, diaphragm presses, rigid compression test fixtures, and self-aligning tensile grips.

Decisions to discard one device and try another were made on the basis of increased simplicity and increased uniformity of operation. Of the pressure devices investigated, the diaphragm appeared to produce the most controllable force with the possibility of magnification through differential areas. It also provided a measure of self-equalization which is necessary for reliability in the hands of variously trained operators. The principle of the diaphragm was therefore pursued through a number of modifications of size, shape and fluid medium, with several different types of frames.

The resulting machine is shown in Figures 25 and 26. It is constructed mostly of rods, pipes, channel irons, and standard pressure control parts such as check and flow valves, regulating valves and

* This phase of the research was carried out under financial sponsorship of the National Association of Furniture Manufacturers. The machine which was developed carries the name "NAFM Glue Tester."

pressure gauge. The diaphragm is a sheet of rubber circularly restrained by a plywood ring, bolted to a sheet steel base. It is actuated by air pressure, although water pressure may also be used. The force generated by the diaphragm is delivered to a circular plate which carries the fixtures for holding the specimens. Since this plate floats on the diaphragm, it has freedom to adjust to the resistance being offered from above. The plate has an area of 50 square inches and hence the force produced is 50 times the line pressure.

By interchanging fixtures, the machine may be used as a press for making specimens, or as a testing machine for breaking them. Specimens are assembled in special jigs, Figure 27, which serve as a means of keeping them in proper alignment and also for retaining pressure until the adhesive hardens. Figure 25 shows the machine set up as a press to make specimens. The stub which contacts the top of the stack of specimens is drilled to receive a 1/4-inch rod. The rod locks the stub in place on the upper cross member and at the same time engages a small hole in the center of the plate on top of the specimens. The rod then guides the jig full of specimens to the center of the stub when the pressure is applied.

Figure 26 shows the machine set up for testing the specimens. The stub has been replaced by a built-up I-beam arrangement, locked in place by the same 1/4-inch rod, and carrying two parallel bearing edges two inches apart on its lower end. These bearing edges span the top member of the specimen to apply a compressive load on the bottom member. The specimen itself is mounted on another fixture, also carrying two bearing edges perpendicular to the upper pair. These bearing edges span the bottom member of the specimen to apply a compressive load on the top member. The combined action of these two pairs of bearing edges exerts a tensile stress on the glue bond.

All fixtures are built on 4 x 4 inch steel plates. Every plate

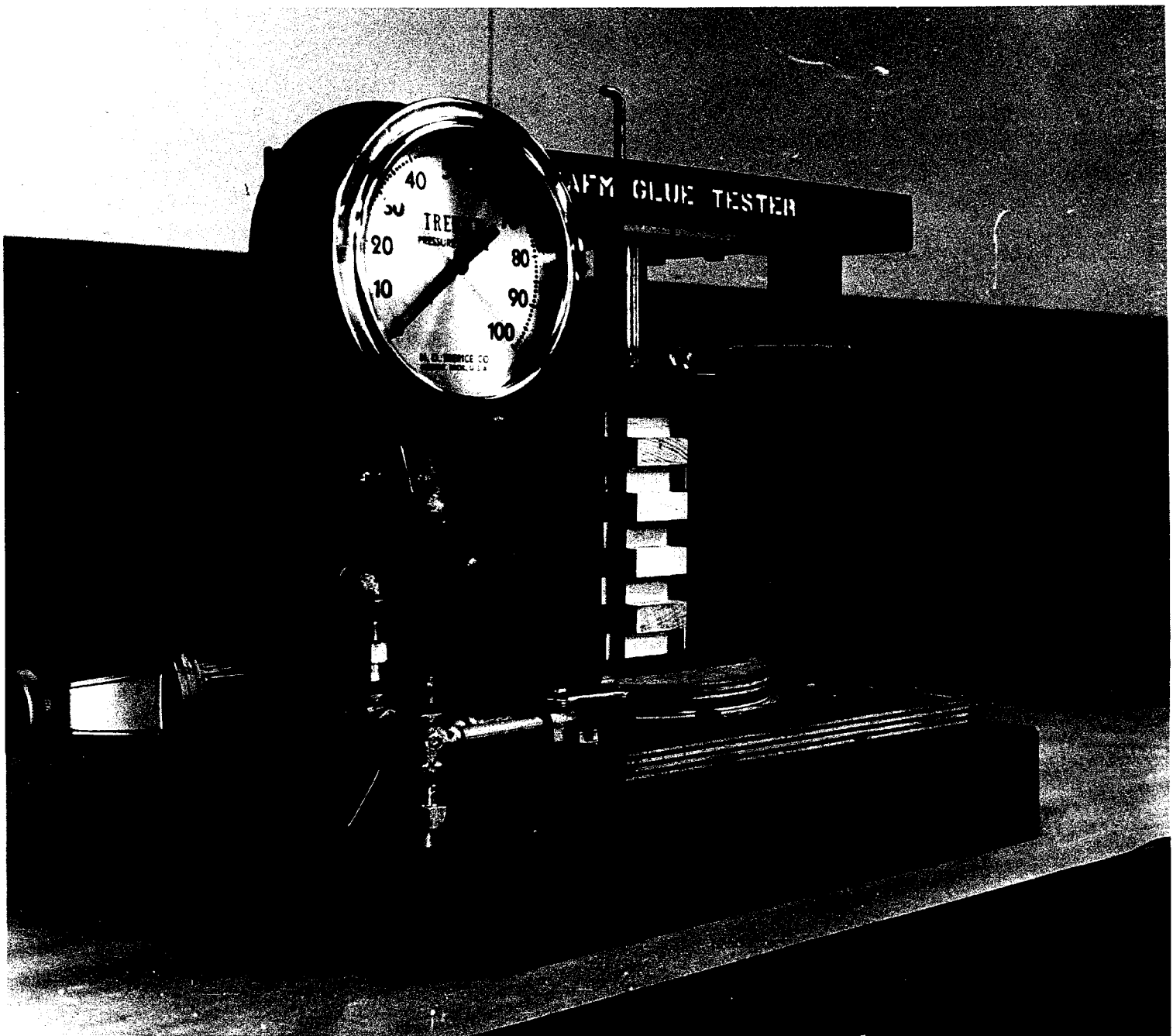


Figure 25. The diaphragm testing machine (NAFM Glue Tester) set up for making specimens

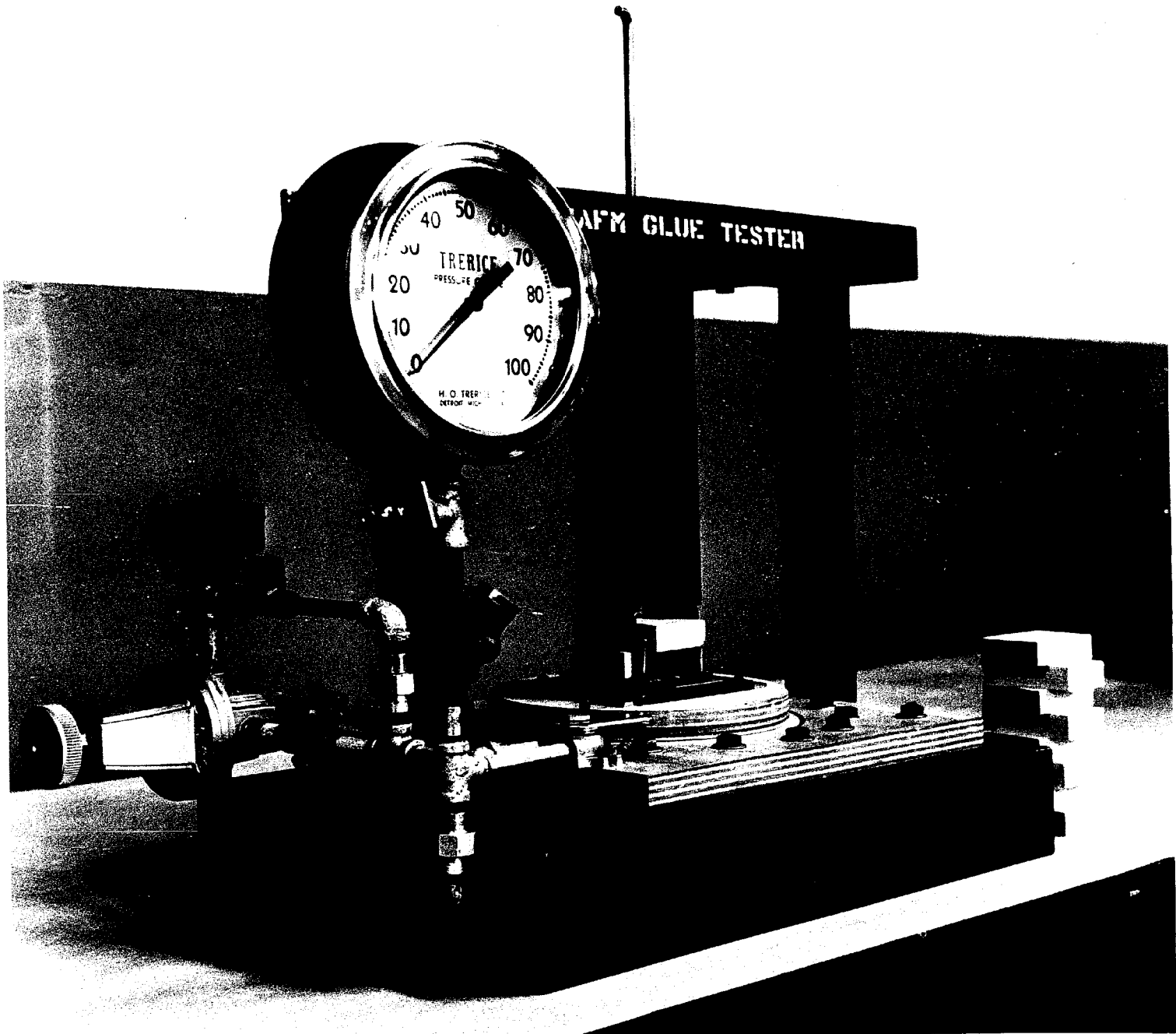


Figure 26. The diaphragm testing machine (NAFM Glue Tester) set up for breaking specimens

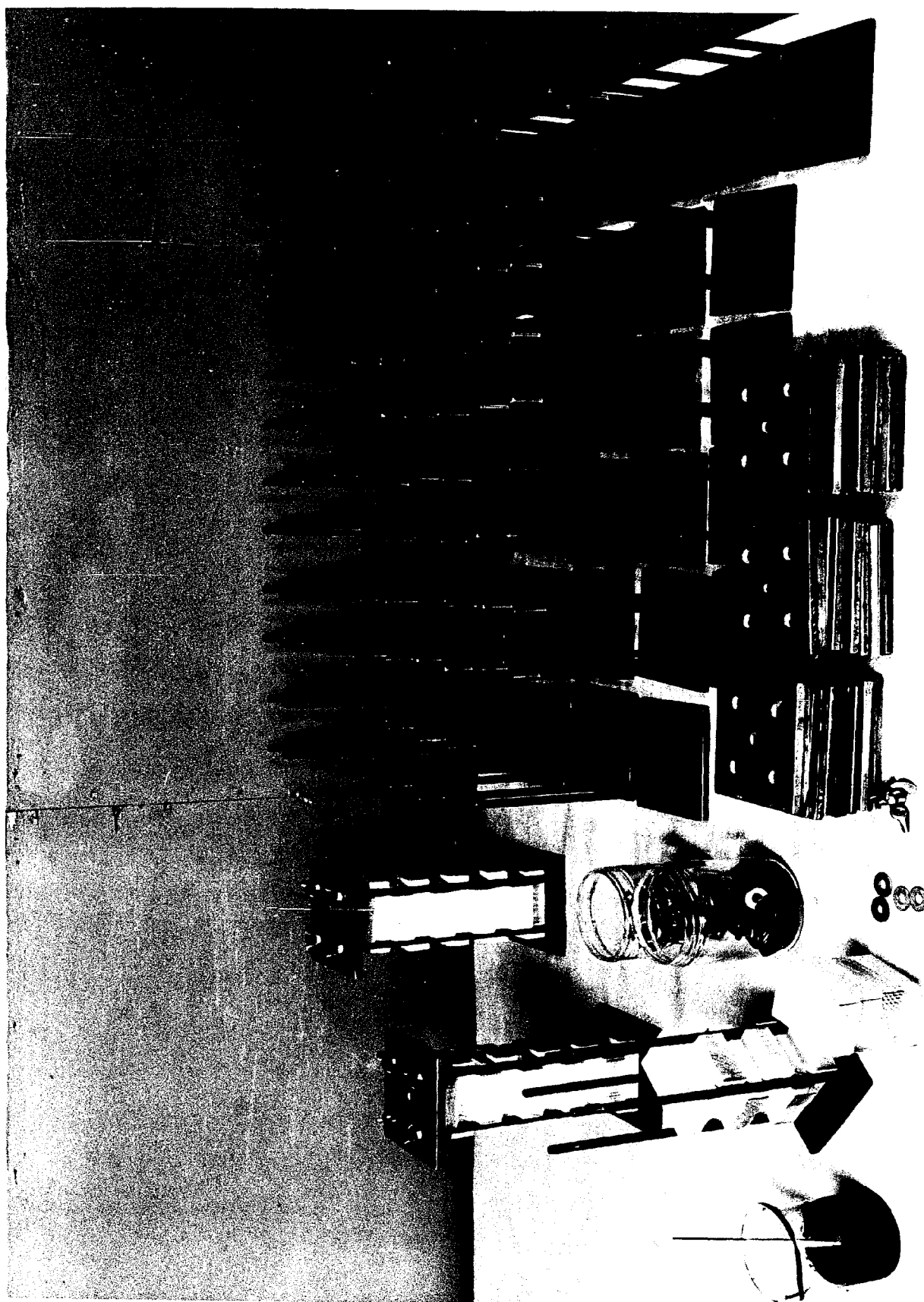


Figure 27. Jigs for assembling cross-lap specimens

is drilled with a 1/4-inch center hole including the pressure plate floating on the diaphragm and the members of the frame. Thus, it is possible to check the alignment of the movable parts by means of a 1/4-inch rod threaded through the entire machine when assembled.

The air being delivered to the machine is first reduced to a uniform 60 pounds per square inch by means of an air regulating valve. For testing specimens, where a constant rate of loading is desired, the air is passed through a flow control valve before it enters the diaphragm chamber.

An ordinary air pressure gauge scaled in one-pound divisions, protected by a check valve, is used to observe the load applied. The gauge dial may be calibrated to read pounds per square inch on the specimen, or total load, by taking into account the 50 square inch area of the pressure plate and the 3 square inch bond area of the specimen. The check valve not only protects the gauge from the shock at rupture but maintains the pressure reading on the gauge for an instant so it can be easily observed. Maximum reading hands were found to be impractical due to the jar that occurs at rupture.

In the conduct of a test, a number of blocks are prepared, usually from strips of lumber yielding 10 or more blocks, incorporating whatever, if any, surfacing variable may be intended. The specimens are assembled, five per jig, imposing glues and gluing variables as desired, and placed in the machine to receive the designated gluing pressure. Thumb-nuts are then tightened onto the rods comprising the assembly jig and the stack of specimens is set aside for the adhesive to harden. When the specimens are ready to be tested, this may be done by placing the appropriate fixtures in the machine, and inserting the specimen. The fixture carrying the specimen is self-locating and force is applied 1/8-inch from all edges of the bond.

A sequence of steps drawn up to provide a measure of standard-

ization and insure maximum reliability of the test procedure during its developmental period is reproduced below, as given in an operations manual. (16)

Preparation of Test Blocks

Cupped or bowed boards should be ripped or cross-cut as a first operation in order to minimize untrue surfaces. Then

- (1) Joint one edge and one side of the board.
- (2) Plane to correct thickness, $3/4$ inch, ($\pm 1/100$ inch).
 - (a) Choose face side before last pass through planer and let that side receive the final cut, marking the back side with a pencil line. Henceforth, protect face side from contact with machinery tables or other soiled surfaces. Store or handle blocks and strips face to face.
 - (b) Run stock through planer at a point where knives are likely to be sharpest, i. e. at one or the other end where daily usage is least.
 - (c) As a guide to uniformity, the finish cut should remove $1/32$ to $1/16$ " of stock and leave 12 to 16 knife marks per inch.
- (3) Rip strips to widths of $1\ 3/4$ inch ($\pm 1/64$ inch).
- (4) Cut blocks to lengths of $2\ 3/4$ inch ($\pm 1/16$ inch).
- (5) Inspect the blocks. Discard
 - (a) The first one or two blocks from either end of a strip if any clipping has occurred in planing.
 - (b) All blocks with knots or short grain coming out of the face.
 - (c) Blocks with mineral streaks or decay.
 - (d) Heartwood blocks unless desired in the test.
 - (e) All blocks with chipped or loose grain.
 - (f) All blocks with ridges on the surface made by nicks in the planer knives.

Untrue surfaces can often be detected by rubbing two blocks together face to face. If there appears to be some drag or frictional resistance to the motion, the surfaces are in maximum contact and

they may be considered true. When surfaces are not true, they will make only point contacts and develop very little friction.

Spreading and Assembly

- (1) Select 10 blocks cut as described in the previous section.
- (2) Brush the glue uniformly over the entire face side of one block and place in the pressing jig. Center the block in the jig (glue side up) as near as possible by eye, noting that an equal portion of the block extends beyond the rods on both sides of the jig.
- (3) Place an unspread block face down upon the first (i. e., face to face at the glue joint) but at right angles to it. Again center by noting that an equal portion extends beyond the rods on both sides. The rods thus pass through the corners formed by the two members of the specimen.
- (4) Continue similarly with the remaining four specimens.
- (5) Place the top plate over the rods followed by the washers and turn the wingnuts part way down.
- (6) Allow to stand for the desired assembly time.

Pressing

- (1) Adjust air pressure to 10 psi for comparative testing (or any other desired pressure) by means of the air regulator. Turn knob on pressure regulating valve clockwise to increase pressure and counterclockwise to decrease. This should be done prior to the insertion of the assembled specimens. (Never adjust pressure with the jig of uncured specimens in the machine, as the fluctuating pressure will have an unpredictable effect on the results.) Since the regulated air line pressure must be read on one gauge, it is necessary to have a filler block in the machine while adjusting the pressure. Usually the filler block used for this purpose may be the testing fixture with a one inch thick block of wood between it and the pressure plate to prevent the diaphragm from rising too far.
- (2) At the end of the assembly period, place the jig on the pressure plate of the machine with the pressing fixture in place. The yellow edge of the jig must be at the front.
- (3) Pass the 1/4-inch locating rod through the press header and pressing fixture and engage the hole in the middle of

of the top plate of the pressing jig. This rod will guide the jig vertically upward as pressure is applied and insure that pressure will be delivered to the exact center of the stack of specimens.

- (4) Admit air to the pressure chamber by pushing the 3-way valve to the "on" position and lock it in that position with the catch provided for that purpose.
- (5) Since the pressing fixtures are coded in yellow, the air should be coming through the yellow side of the intake system.
- (6) Allow jig to remain under pressure for at least 10 minutes.
- (7) At the end of the pressing period, tighten thumb nuts snug to the top plate by hand. Tighten diagonally opposite pairs simultaneously to avoid tilting the top plate.
- (8) Release pressure and remove from the machine.

Conditioning the Specimens

In usual gluing procedures, stock is left under pressure until the glue has hardened sufficiently to hold the members together and to permit light handling. Hardening time varies for different glues but a general practice is to leave stock in clamps overnight. After clamps are removed, additional time is necessary to develop full strength. Adhesive producers always provide information of this nature although some adjustment must be made for the particular construction and the conditions under which it is assembled.

Testing the Specimens

After the specimens have been conditioned sufficiently to develop full strength, they are tested as described in the following paragraph.

Place a specimen in the specimen jig and insert on the pressure plate, pushing until snug in the guides. Check to see that alignment is correct, i. e., that bearing edges engage the specimen 1/8" from edges of glue line. Turn the 3-way valve to "on" position and hold till failure occurs. Immediately release the valve and it will return to "off" position. Failure occurs suddenly, but the indicating hand on the gauge remains momentarily at the maximum point.

APPENDIX II

CALIBRATION OF TESTING MACHINES

In order to improve the accuracy of measuring loads with the diaphragm machine (plus or minus one pound reading on the gauge amounts to plus-or-minus 50 pounds load) SR-4 strain gauges were fixed to the upper head so it could function as a dynamometer, Figure 28. Four gauges were placed on the flanges of the channel iron at the center of the span. Since this member acts as a beam fixed at both ends, the upper two gauges are in tension during loading and the lower two in compression. The tension pair were connected in series and fed into the measuring circuit of a strain analyser and the compression pair fed into the compensating circuit to increase the sensitivity. This setup was then calibrated on a universal testing machine to determine the strain produced by known loads. Strain produced by evenly spaced loads up to 4000 pounds was plotted against load and from this plot a calibration constant was determined which permitted strain to be converted into load delivered by the diaphragm. The calibration constant was found to be 2.725 pounds per microinch of strain.

In calibrating the dynamometer head of the machine the known loads were imposed in the same manner that they would later be delivered through the testing fixtures. To simulate the actual loading characteristics during calibration, the beam was inverted and the entire machine placed under the crosshead of the universal testing machine (Figure 29).

The Dillon Tensile Tester is a hand operated, gear driven apparatus for applying small tensile loads. Loads are read on a direct

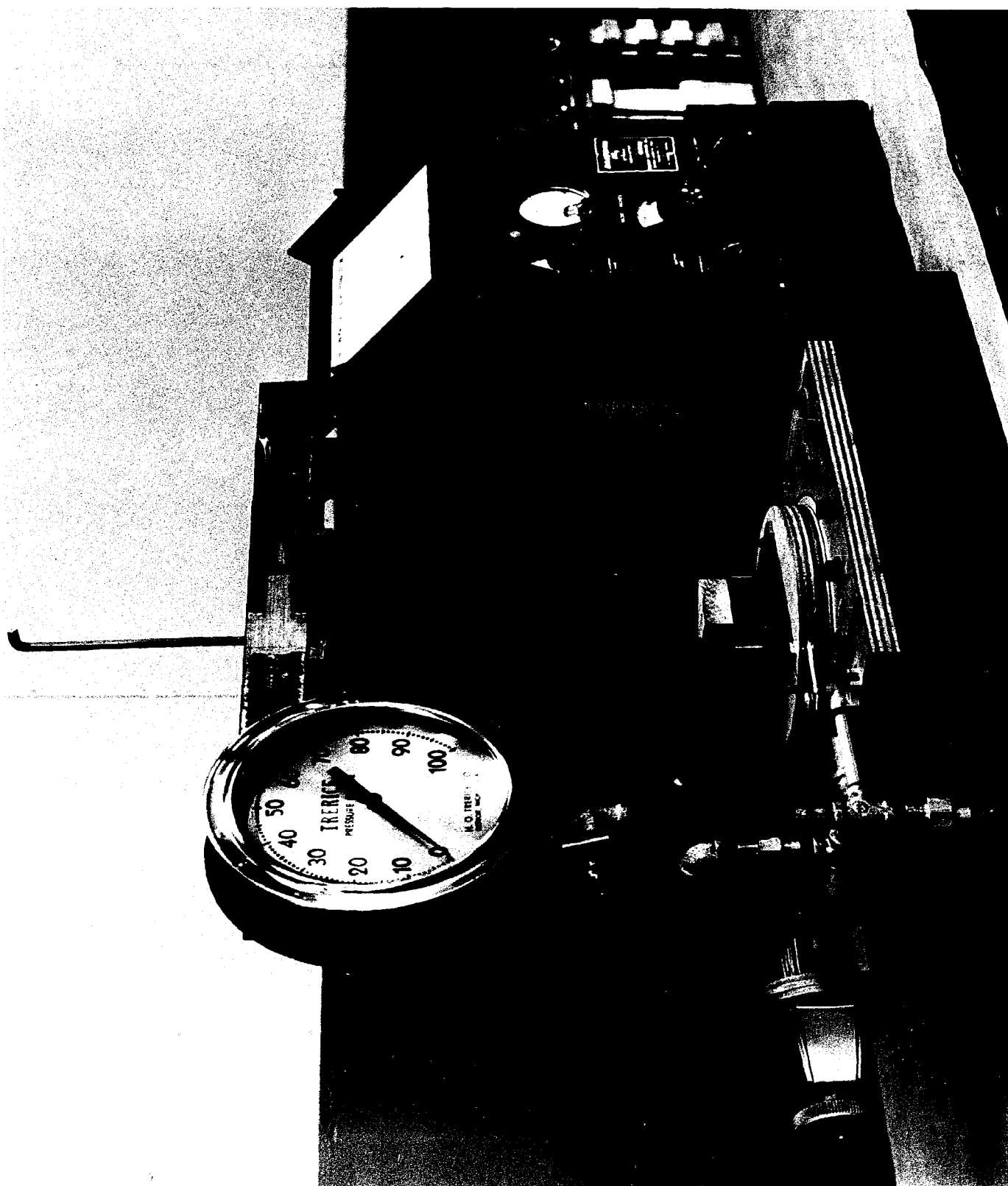


Figure 28. The diaphragm testing machine sensitized by means of SR-4 strain gauges and strain analyser

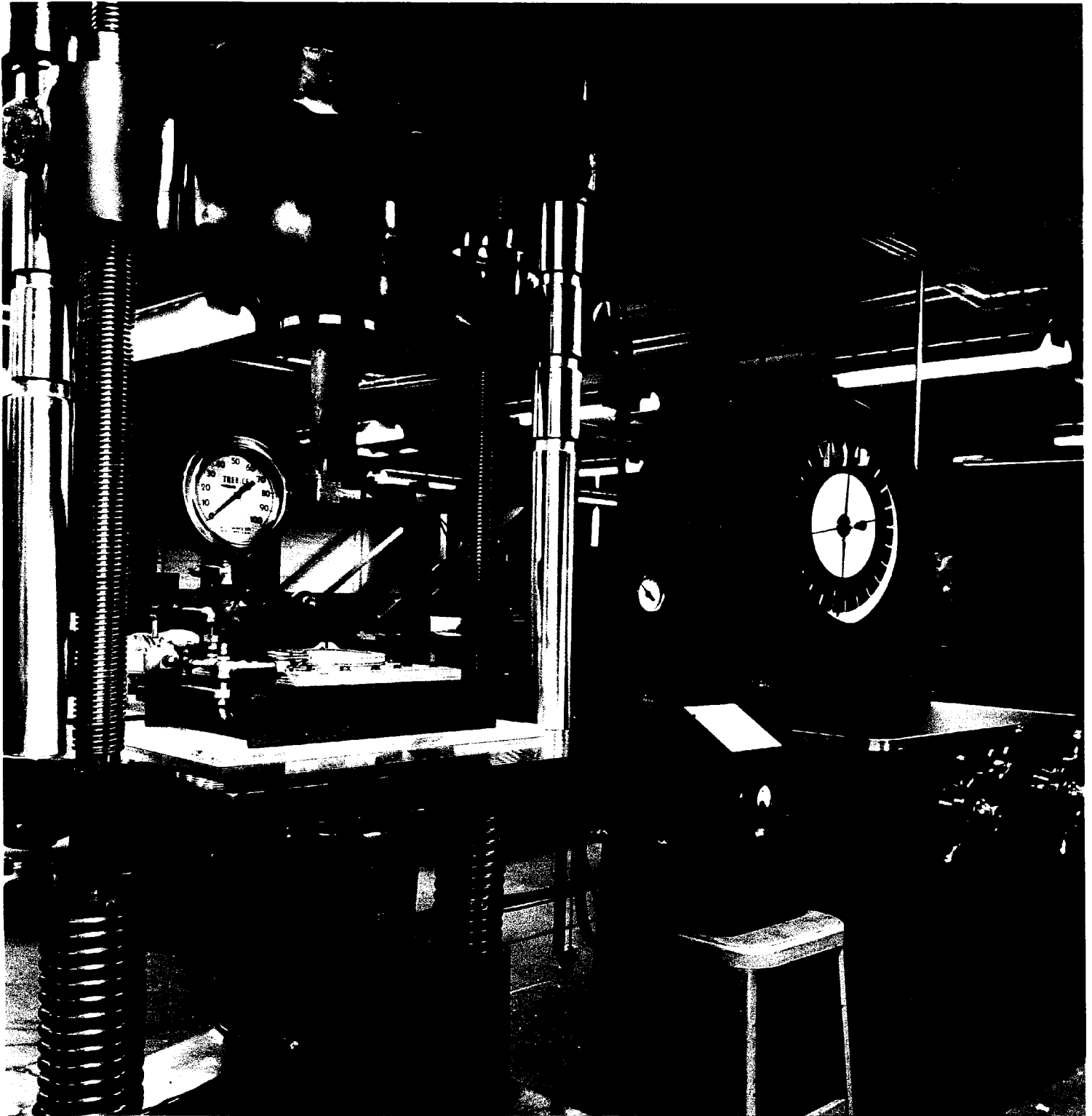


Figure 29. Set-up for calibrating the strain gauge system, showing how the upper beam of the machine was reversed to simulate actual loading

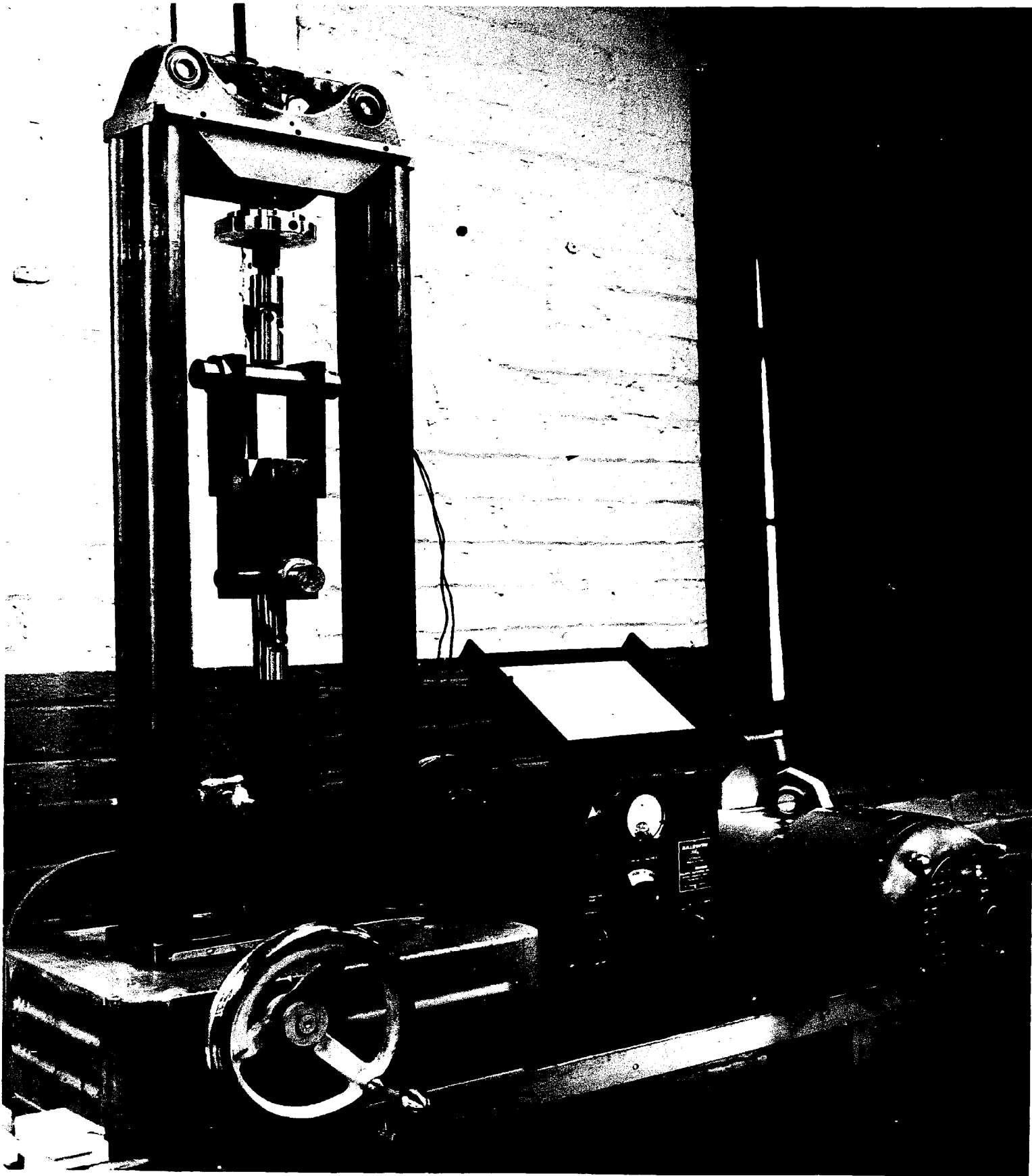
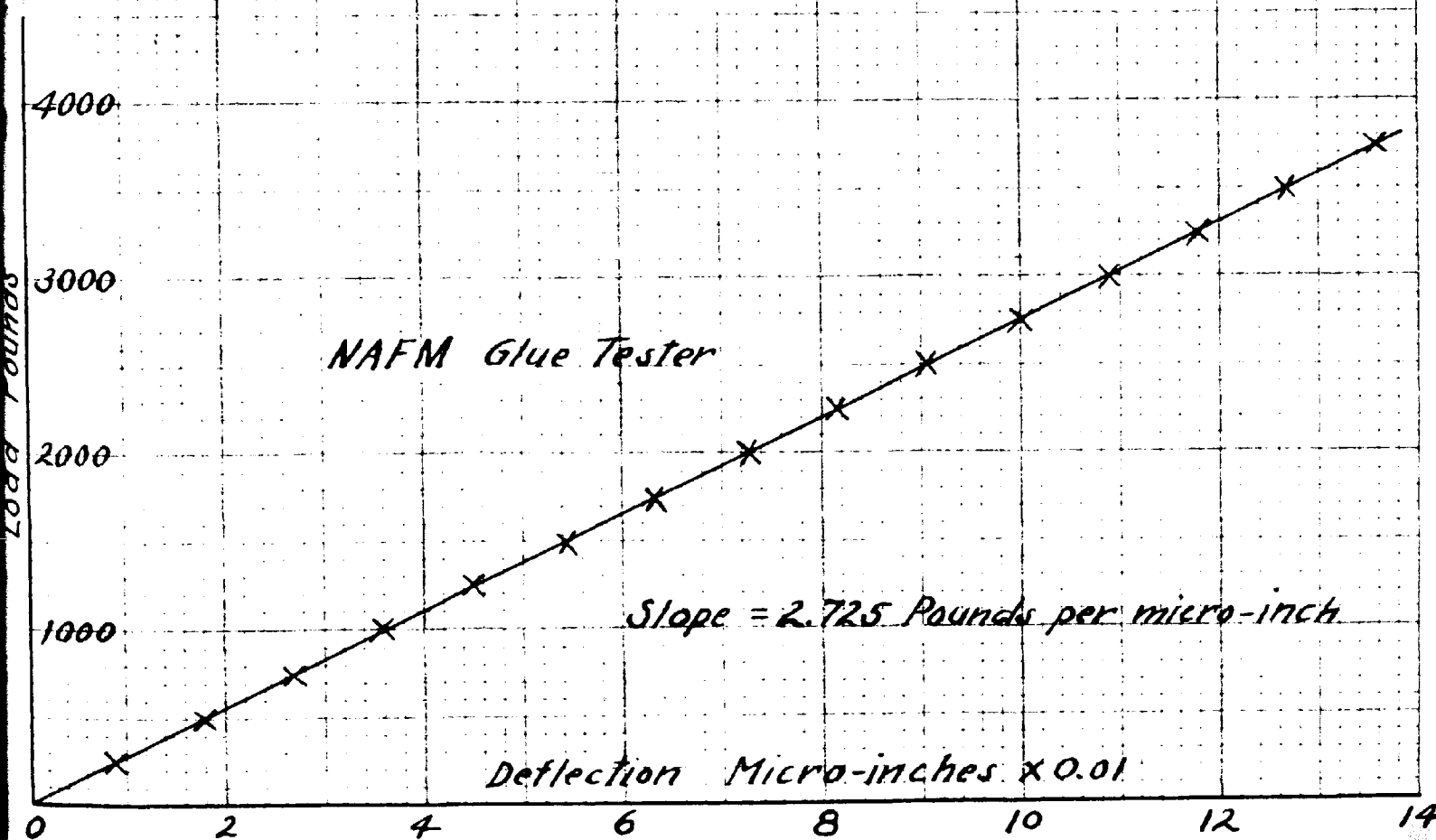
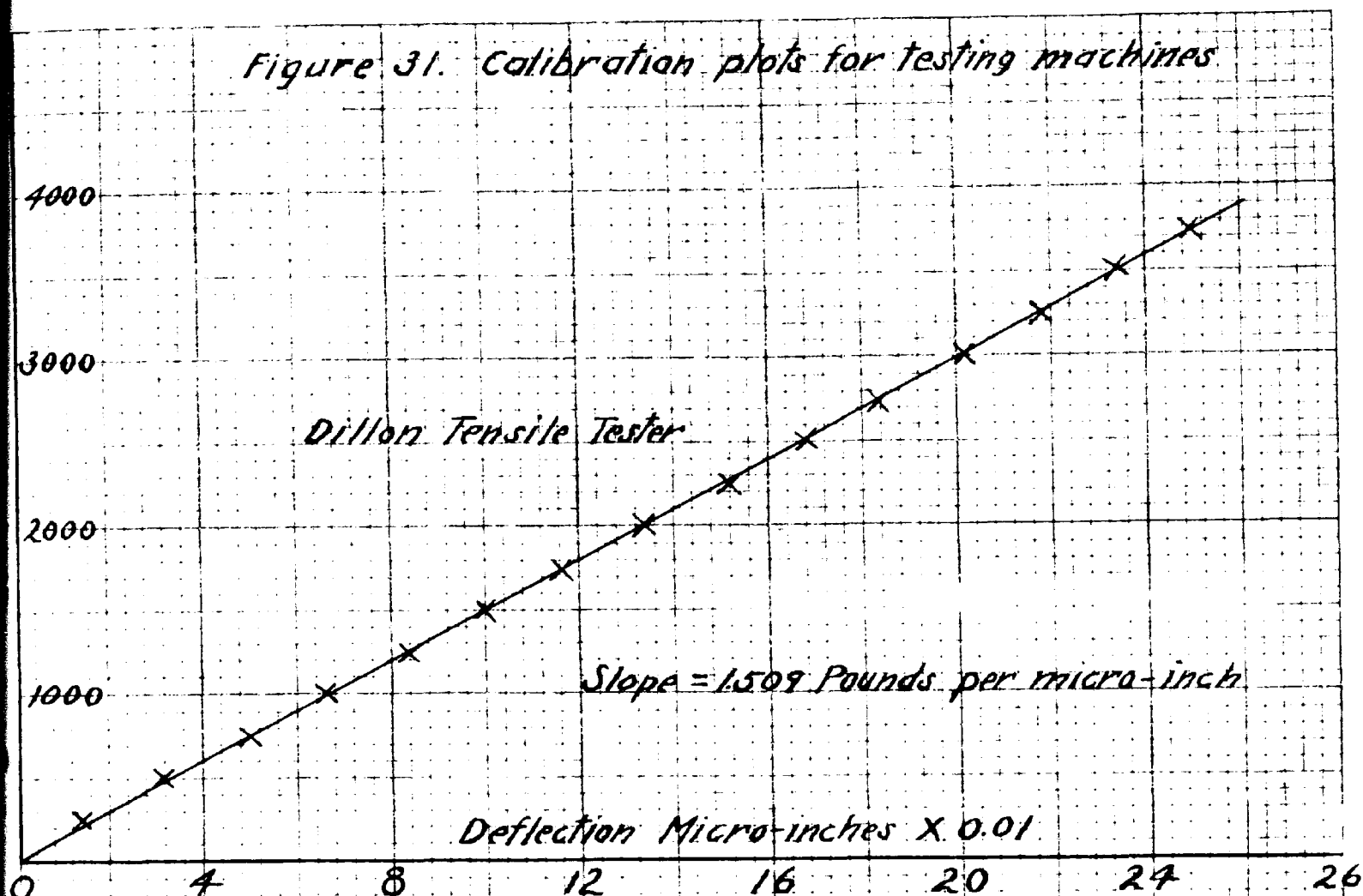


Figure 30. The Dillon Tensile Tester modified with SR-4 strain gauges and variable-speed motor

reading dial gauge actuated by the deflection of a center loaded beam from which the tensile grips are suspended. A maximum reading hand gives an indication of the load at rupture. In the 5000 pound range the dial is calibrated to 50-pound intervals. Readings of plus-or-minus 25 pounds are possible when there is no jarring of the needle at failure. In breaking the cross-lap specimen, the sudden release of load at rupture causes the maximum-reading hand to jump several intervals and this introduces an additional element of variation amounting to 50 to 100 pounds.

The machine was altered in two ways to improve its utility. A variable-speed motor was coupled to the machine with a V-belt to permit closer control of testing speeds, and SR-4 strain gauges were again used to sharpen the accuracy of the readings. In this case, the dial gauge was dismantled and the SR-4 strain gauges were placed on the same beam which actuated the dial indicator. The deflection of the beam was thus converted from a mechanical linkage to a sensitive electrical system (Figure 30). Upon calibration against a universal testing machine, it was found that two tension gauges and two compression gauges gave more accuracy than was necessary. While high accuracy, i. e. , 0.77 pounds per microinch, was welcome, it was undesirable because of the necessity for changing the range during the course of a test. One compression gauge was finally determined to be sufficient when a compensating gauge was attached to an unstressed block of steel. The calibration constant for the one-gauge system was calculated as before and found to be 1.509 pounds per microinch.

Figure 31. Calibration plots for testing machines



APPENDIX III

COMPLETE ORIGINAL DATA

The data given under results in the experiments was, with one exception, in summary form. Averages were presented in place of each replication in order to make the comparisons more clear. The statistical analysis closely accompanying each set of results further served to compact and characterize the data. However, it is sometimes desired to refer to the individual observations for the purpose of confirming local trends or dispersions, and for the purpose of reanalyzing to obtain additional information.

Following are tables containing the complete data for each experiment. The data for the first part of Experiment VI is omitted here since it comprised only one replication, and therefore was complete as originally presented.

TABLE I

The Effect of Rate of Loading on the Observed
Strength of the Cross-Lap Specimen

Rate of Loading*	Strength Pounds	Rate of Loading	Strength Pounds	Rate of Loading	Strength Pounds
400	1555 1555 1400 1300 1500	1250	1555 1605 965 1410 1490	3000	1245 1605 1455 1305 1225
Average	<u>1440</u>		<u>1405</u>		<u>1365</u>
600	1345 1640 1460 1790 1275	1500	1370 1290 1280 1250 1405	4000	1610 1420 1500 1225 1410
Average	<u>1500</u>		<u>1320</u>		<u>1435</u>
800	1245 1255 1410 1510 1365	1750	1150 1435 1275 1250 1275	5000	1290 1580 1290 1480 1100
Average	<u>1355</u>		<u>1275</u>		<u>1350</u>
1000	1470 1320 1290 1445 1530	2000	1490 1250 1190 1445 1270	6000	1160 1340 1325 1195 1470
Average	<u>1410</u>		<u>1330</u>		<u>1300</u>

*Pounds per minute

TABLE II

The Effect of Specific Gravity and Thickness Upon the
Observed Strength of the Cross-Lap Specimen

Thickness Inches	Specm	Specific Gravity			
		0.63	0.68	0.72	0.75
3/8	1	860-45*	834-25	656- 0	963-30
	2	825-30	741-40	898-60	770- 5
	3	699-30	933-20	922-35	1162-35
	4	617- 5	875-35	809-10	1071-25
	Avg	750-28	846-30	821-26	992-24
3/4	1	1503-75	1400-30	1514-10	1479- 0
	2	1328-50	1750-40	1806-50	1578-60
	3	1308-10	1673-25	1681-45	1453-15
	4	1301-30	1207-20	1667-40	1434-10
	Avg	1360-41	1508-27	1667-36	1486-21
1 1/2	1	1844-70	2102-50	1619-60	2073-50
	2	1735-75	1388- 0	1600-30	2098-35
	3	1660-50	1366- 0	1913-10	1744-10
	4	1465-10	1708-10	1977-10	1962-30
	Avg	1676-51	1641-15	1777-27	1967-31
2 1/4	1	1654-40	1944-20	1669-70	2022-25
	2	1723-25	1871-10	1941-25	2039-90
	3	1769-50	2185-40	2188-30	2082-35
	4	1814-100	1435-30	2002-10	2129-100
	Avg	1740-54	1859-25	1950-34	2068-63
3	1	1494-50	1557- 0	1705-30	1750-50
	2	1615-50	1479- 5	1871-50	1826-10
	3	1829-70	1746-50	1836-10	1482- 0
	4	1388-30	1741- 5	1833-10	1503- 0
	Avg	1582-50	1631-15	1811-25	1640-15

*The figure preceding the dash is the strength in pounds and that following the dash is the estimated percent wood failure.

TABLE III

The Effect of Moisture Content and Thickness Upon the
Observed Strength of the Cross-Lap Specimen

Thickness Inches	Specimen	Percent Moisture Content		
		5.4	9.4	15.0
3/8	1	585- 5*	834- 25	954-60
	2	674-25	741-40	874-50
	3	523- 0	933-10	905-30
	4	610- 0	875-25	911-20
	Average	598- 8	846-30	911-40
3/4	1	695- 0	1100-30	1194-10
	2	945- 0	1750-40	1891-20
	3	820- 0	1673-25	1708-50
	4	976-10	1207-20	1329-20
	Average	859- 3	1508-29	1605-25
1 1/2	1	1182- 0	2102-50	2248-90
	2	991- 0	1388- 0	1891- 5
	3	973- 0	1366- 0	1788- 5
	4	900-20	1708-15	2135-40
	Average	1112- 5	1641-16	2016-35
2 1/4	1	1232-10	1944-20	1600-10
	2	1232-10	1871-10	1849-60
	3	1096- 5	2185-40	1827-10
	4	1187- 0	1135-30	1737- 5
	Average	1187- 6	1859-25	1753-21
3	1	1193-10	1557- 0	1888-30
	2	986-10	1479- 5	1897-80
	3	1235- 5	1746-50	1646-10
	4	1048- 0	1741- 5	1829-50
	Average	1116- 6	1631-15	1815-42

*The figure preceding the dash is the strength in pounds and that following the dash is the estimated percent wood failure.

TABLE IV

The Effect of Amount of Catalyst and Wood Moisture Content
Upon Observed Strength

Parts Catalyst	Specimen Number	Percent Moisture Content		
		5.4	9.4	15.0
1	1	619-0*	1977-10	1610-25
	2	560-0	1482-10	1841-10
	3	599-0	1669-60	1491-25
	4	493-0	1554-10	1524-20
	5	561-0	1369-10	1784- 5
	Average	<u>566-0</u>	<u>1610-25</u>	<u>1650-17</u>
2	1	727-0	1343-15	1660-10
	2	682-0	1826-50	1729-50
	3	812-0	2007-70	1449- 0
	4	661-0	2120-80	1811-20
	5	546-0	1680-30	1464- 5
	Average	<u>686-0</u>	<u>1795-49</u>	<u>1623-17</u>
3	1	739-0	1328-25	1397-10
	2	795-0	1556-25	1586-30
	3	827-0	1153- 5	1397-20
	4	816-0	1536-35	1586-30
	5	739-0	1403-30	1388-50
	Average	<u>783-0</u>	<u>1395-24</u>	<u>1471-28</u>

*The figure preceding the dash is the strength in pounds and that following the dash is the estimated percent wood failure.

TABLE V

The Effect of Joint Flaws, Wheat Flour, and Grip Type upon the
Observed Strength

Percent Flour	Swivel Grip					Saddle Grip				
	Flaw Area Sq. In.					Flaw Area Sq. In.				
	0	0.25	0.5	1.0	2.0	0	0.25	0.5	1.0	2.0
0	1351-104	1150-30	1102-20	1114-75	803-80	1292-0	1444-25	1185-50	1022-15	610-15
	1477-60	1099-25	1026-35	996-40	626-15	1322-15	1485-25	894-10	986-0	621-15
	1423-20	1391-25	1222-80	996-30	800-90	1226-0	1362-0	790-35	986-0	578-10
	1325-15	1159-5	1207-35	1043-30	741-90	1564-25	1144-10	1196-30	1117-55	570-5
	1394-26	1200-21	1139-42	1037-44	743-69	1351-10	1359-15	1016-31	1028-18	595-11
20	1132-0	1400-40	1132-15	1103-20	619-75	1382-25	1335-65	1079-15	1079-0	591-10
	1257-60	1367-45	1105-55	1037-15	634-35	1226-5	1221-10	1090-40	1008-10	600-30
	1366-25	1385-15	1023-10	822-60	664-60	1142-15	1234-15	1177-30	1008-100	583-0
	1056-0	1008-0	910-35	990-25	664-90	1144-20	1218-45	954-35	1101-0	382-5
	1203-21	1290-25	1043-29	988-30	645-65	1224-16	1252-34	1075-30	1049-28	539-11
40	1283-10	1524-35	1188-15	1080-75	641-75	1368-0	1194-0	1335-60	948-10	654-30
	1603-70	1615-70	785-0	1183-50	827-65	1254-40	1063-0	1082-55	1036-30	654-80
	1222-0	1243-30	1334-30	1014-15	551-0	1213-25	1281-40	1199-50	1142-10	627-0
	1355-35	1313-0	991-0	1188-35	620-35	1526-40	1452-50	1308-60	962-35	586-10
	1366-29	1424-34	1075-11	1116-44	660-44	1340-26	1248-23	1231-56	1022-21	630-30
60	1349-5	1426-10	966-0	969-0	522-5	1294-0	1019-55	1117-35	1172-70	608-30
	1560-20	1435-35	1373-30	1162-75	613-5	1414-0	1068-0	889-0	1093-60	708-30
	1026-0	1328-30	890-10	1145-0	619-5	1199-10	913-45	708-0	782-0	490-30
	1192-5	1320-25	951-15	943-0	619-30	1362-5	1218-10	1093-10	847-10	708-15
	1282-8	1377-25	1045-14	1055-19	593-11	1317-4	1055-28	952-11	974-35	629-26

* The figure preceding the dash is the strength in pounds and that following the dash is the estimated percent wood failure based upon the area bonded.

TABLE VI

Effect on Strength of Flaws Located at Interior Portions
of the Joint

Flaw Area**	2.4	1.8	1.2	0.6	0.0
Bond Area**	0.6	1.2	1.8	2.4	3.0
Specimen					
1	980*	1335	885	1255	1195
2	1090	1240	965	1240	1185
3	1255	1280	1285	1260	1050
4	1265	1390	910	1600	1515
5	1265	1145	1020	1200	1105
6	1155	1340	1250	1120	1350
7	1280	1050	1285	1480	1015
8	1290	1220	1530	1290	1495
9	1100	1135	1280	1210	965
10	<u>1270</u>	<u>1470</u>	<u>1265</u>	<u>1180</u>	<u>1265</u>
Average	1195	1260	1168	1284	1214

* Strength in pounds.

** Area in square inches.

Effect of Assembly Time and Age of the Mixture upon the
Strength of Adhesive B

Assembly Time Minutes	Age - Minutes			
	5	60	180	240
40	1530-25	1470-10	1875-50	1650-25
	1230- 5	1455- 0	1530-50	1485-50
	1020- 0	1800- 5	1305-40	2010-10
	1770- 0	1740- 5	2070-100	1770-100
	1095- 5	1575-10	1890- 5	1770-50
	900- 5	1815-50	1860-10	1200- 0
	1470-10	1380-50	1515-10	1860-90
	1620- 5	1530-50	1215-20	1365-25
	1485-30	900- 0	1740-60	1635-50
	1770-10	1380-10	1575-10	1620-100
	1575-50	615- 5	1530-25	1710-75
	1320- 0	1260-25	1380- 5	1485-10
	1399-12	1410-18	1624-32	1630-48
60	450- 0	1815- 5	1830- 5	1965- 5
	900- 5	1800- 5	1890- 0	1710-50
	1170- 0	1515- 0	2040- 0	2220- 0
	1590- 0	1710- 0	1365- 5	1740- 0
	1710-10	1530- 0	1680- 0	2100- 5
	1335- 0	1830- 0	1785- 0	1395- 0
	1290- 5	1395- 5	1335- 5	1680- 0
	1530- 0	1635- 0	1605- 5	1305-25
	1350- 5	1230- 0	1875- 0	1335- 0
	1320- 0	1335- 0	1575- 5	1710- 5
	1320- 0	1845- 0	1560- 0	1335-30
	1290- 5	1440-10	1680- 0	1530-25
	1288- 3	1590- 3	1685- 3	1669-12

* The figure preceding the dash is the strength in pounds and that following the dash is the estimated percent wood failure.

BIBLIOGRAPHY

1. Staverman, A. J., Adhesion and Adhesives Chapter 2 edited by N. A. de Bruyne and R. Houwink, Elsevier Publishing Company, New York, 1951.
2. Marra, George G., A Study of Adhesive Action of a Urea-Formaldehyde resin on Certain Hardwoods, Unpublished thesis Duke University, 1949.
3. ASTM Standards on Adhesives, American Society for Testing Materials, September, 1954.
4. de Bruyne, N. A., Adhesion and Adhesives, Chapter 4 edited by N. A. de Bruyne and R. H. Houwink, Elsevier Publishing Company, New York, 1951.
5. Dietz, A. G. H., Grinsfelder, H., and Reissner, E., Glue-Line Stresses in Laminated Wood, Transactions of the American Society of Mechanical Engineers, 68 (1946) 329.
6. Blomquist, R. F. Evaluation of Glues and Glued Products, Journal of the Forest Products Research Society, Vol. IV, No. 5, October, 1954.
7. Marra, Alan A. Glue Line Doctor, Proceedings Forest Products Research Society, Vol. 5, 1951.
8. Moser, Frank, Some Fundamentals of Glass Adhesion, ASTM Bulletin No. 150, January, 1948.
9. Kollman, F. Technologic Des Holzes, Berlin, 1936.
10. Truax, T. R. The Gluing of Wood, U. S. Forest Products Laboratory Bulletin No. 1500, 1929.
11. Lewis, C. C., Heebink, T. B., Cottingham, W. S., Effect of Increased Moisture Content on the Shear Strength at Glue Lines of Box Beams and on the Glue-Shear and Glue-Tension Strengths of Small Specimens, U. S. Forest Products Laboratory Bulletin No. 1551, August, 1945.
12. Rudkin, A. W., A Simple Method of Testing Glue Lines in Tension, Australian Council of Science and Industrial Research Journal, November, 1947.
13. Fryor, M. G. M., Effect of Dispersal Conditions on Joints Made with Casein Glue, Royal Aircraft Establishment, Farnborough, England, Report No. Mat.-N-2-2051 July, 1942.

14. Foreste, David V., The Development and Evaluation of the Cross-Lap Test Specimen and Apparatus for Testing Adhesives in Tension, Unpublished thesis, University of Michigan, 1950.
15. Hinken, Edward W., A New Method for Observing the Gap-Filling Properties of Wood Adhesives, Journal of the Forest Products Research Society, Vol. III, No. 3, September, 1953.
16. National Association of Furniture Manufacturers, NAFM Glue Testing Machine, Construction and Operation Manual, 1952.
17. Reinhart, F. W., Survey of Adhesion and Types of Bonds Involved, Symposium on Adhesion Case Institute of Technology, April, 1952.
18. U. S. Government Printing Office, Wood Aircraft Inspection and Fabrication, ANC-19 Bulletin, April, 1951.
19. Pryor, M. G. M., Ageing of Urea-Formaldehyde Adhesives, Royal Aircraft Establishment, Technical Note Mat-N-4-2051, April, 1944.
20. de Bruyne, The Strength of Glued Joints Aircraft Engineer, Vol. 16, 1944.
21. Volkersen, Olaf von, Die Nietkraftverteilung in zugbeanspruchten Nietverbindungen mit konstanten Laschenguerschnitten, Luftfahrtforschung 15(1938)41.
22. Goland, M., and Reissner, E., The Stresses in Cemented Joints, Journal of Applied Mechanics, 66(1944)A-17.
23. Koehn, George, Behavior of Adhesives in Strength Testing, Symposium on Adhesion, Case Institute of Technology, April, 1952.
24. Maxwell, John W., Shear Strength of Glue Joints as Affected by Wood Surfaces and Pressures, Technical Publication No. 64, New York State College of Forestry, Syracuse, N. Y., 1944.
25. Running, T. E., Emperical Formulas, John Wiley & Sons Inc., N. Y., 1917.
26. Peakes, G. L., Fundamentals of a Test Method, ASTM Bulletin, January, 1952.
27. Wernimont, Grant, Precision and Accuracy of Test Methods, Symposium on Application of Statistics, ASTM, Special Technical Publication No. 103, 1950.

28. Youden, W. J., and Cameron, J. M. . Use of Statistics to Determine Precision of Test Methods, Symposium on Application of Statistics, ASTM Special Technical Publication No. 103, 1950.
29. Brownlee, K. A., Industrial Experimentation, Chemical Publishing Co., Inc. N. Y., 1952.
30. Bennett, C. A. and Franklin, N. L. Statistical Analysis in Chemistry and the Chemical Industry, John Wiley and Sons Inc., 1954.
31. Snedecor, George W. Statistical Methods, Iowa State College Press, 1948.
32. ASTM Committee F-11, ASTM Manual on Quality Control of Materials, American Society for Testing Materials, Philadelphia, Pennsylvania, 1951.
34. ASTM Committee - D-14, Symposium on Adhesives American Society for Testing Materials, Philadelphia, Pa., 1946.
35. ASTM Committee D-14, Symposium on Testing Adhesives for Durability and Permanence, American Society for Testing Materials, Philadelphia, Pa., 1953.
36. Kitazama, George, A Study of Adhesion in the Glue Lines of Twenty-two Woods of the United States. New York State College of Forestry Technical Bulletin No. 66, 1946.
37. Rinker, R. C. and Kline, G. M. Survey of Adhesives and Adhesion, National Advisory Committee for Aeronautics Technical Note No. 989, 1945.
38. Federal Specification MMM-A-175, Adhesives; Methods of Testing U. S. Government Printing Office, April, 1951.
39. Eickner, H. W. The Gluing Characteristics of 15 Species of Wood with Cold Setting Urea-Resin Glues, U. S. Forest Products Laboratory Report No. 1342, April, 1950.
40. Olson, W. Z., Effect of Moisture Content of Wood on Joint Strength in Gluing Birch Veneer and Maple Lumber with Room-Temperature-Setting and Intermediate-Temperature-Setting Phenol, Resorcinol and Melamine Glues, U. S. Forest Products Laboratory Report No. R 1534, May, 1954.
41. Olson, W. Z., and Bruce, H. D., Strength of Joints in Hard Maple Blocks, Glued with Certain Resin Glues, after Various Open and Closed Assembly Periods, U. S. Forest Products Laboratory Report No. 1542, May, 1946.

42. Olson, W. Z., and Bruce, H. D. Variation in Maximum Allowable Assembly Time with Age in the Pot at Time of Spreading for Four Resin Glues. U.S. Forest Products Laboratory Report No. 1546, Sept., 1946.
43. Mylonas, C. Stress Distribution in Glue Joints International Congress of Applied Mechanics, London Proceedings VII Vol. 4.
44. Delmonte, John, The Technology of Adhesives Reinhold Publishing Corporation, N. Y., 1947.
45. Wakefield, E. M. The Tension Normal to the Glue Line Plywood Test, Canadian Forest Products Laboratory, 1943.
46. de Bruyne, N. A. Theory and Practice of Gluing with Synthetic Resins, Lang, Maxwell & Springer Ltd., 1954.
47. Jamieson, A. M. Adhesion in Theory and Practice Plastics Institute (London) Transactions 17 No. 30 (1949).
48. Kline, G. M. and Reinhart, F. W. Fundamentals of Adhesion Mechanical Engineering Vol. 72 (1940).
49. Farrow, Hamby and Smith, Glue Line Study, Industrial and Engineering Chemistry, Anal. Ed. 18(5)1946.
50. Gunthrop, S. Adhesion Engineering, Society of American Engineers Journal, 60: Jan., 1952.
51. de Bruyne, N. A. The Nature of Adhesion, Aircraft Engineer, Vol. 28, 1939.
52. Campbell, W. G., Chemical Factors Involved in the Gluing of Wood with Cold Setting Urea-Formaldehyde Glues. Department Scientific and Industrial Research, Forest Products Research Laboratory, Report B, 1943.
53. Moser, Frank, Approximating the Attractive Forces of Adhesion for Glass and Other Surfaces ASTM Bulletin October, 1950.