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DEVELOPMENT OF NON-DESTRUCTIVE TESTS FOR LAMINATED GUNSTOCK BLANKS

Progeess Report No.7
June 10 to August 1, 1954

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Development of Non-destructive Tests for Laminated Gunstock Blanks. Progress Report No. 7 for the period June 10 to August 1, 1954

Introduction

This is the seventh of a series of progress reports on work undertaken at the Yale School of Forestry to develop a practical method of testing laminated gunstock blanks with respect to the integrity of the glue bonds. The study is sponsored by the Springfield Ordnance District of the Department of the Army under Contract No. SAR/DA-19-059-ORD-1329.

The study anticipates the development of an appropriate non-destructive test that can be used to evaluate the integrity of glue bonds of laminated gunstock blanks fabricated under production conditions in a commercial laminating plant. Work began on June 1, 1953, with a review of the literature pertaining to the subject. The first progress report of this series included a description of exploratory testing with x-ray absorption and high frequency sound transmission, in addition to the literature review mentioned above. The second and third progress reports dealt primarily with the exploration and evaluation of an ultrasonic energy transmission technique. The fourth and fifth progress reports and the technical interim report, which covered the work performed during the entire first year of the contract period, were concerned primarily with the destructive testing of 200 laminated gunstock blanks. The objective of this destructive testing was to determine the feasibility of using a destructively tested end sample from each gunstock blank as an index of the quality of the entire blank. The test results of the end sampling technique were presented in the technical interim report in the form of a statistical analysis accompanied by a discussion of its application.

In addition to the destructive test data the results of exploratory non-destructive testing by a vibrational technique were presented in the two preceding reports. A description of the apparatus for conducting the vibrational tests was presented in the fifth progress report and results of vibrational testing of both solid and laminated wood were presented in the technical interim report.

From the results of all three non-destructive tests conducted on experimental material (x-ray absorption, ultrasonic energy transmission, and resonant frequency vibration) it has become evident that the vibrational test holds the greatest promise as a test of both solid and laminated wood. The vibrational characteristics of the gunstock blanks did not provide a satisfactory indication of the glue bond quality of the blanks. It has been suggested that this may have been due to differences in the vibrational characteristics of the laminae of the gunstock blanks. As a result it has been proposed that additional non-destructive testing be restricted to a thorough study of the vibrational test conducted on solid wood and small laminates in which the extent and character of defective glue line areas is precisely controlled.

The major part of this progress report has been allocated to a working plan for the evaluation of the non-destructive vibrational test. Both solid and laminated Black Walnut will be studied. In addition a brief description of new and improved test apparatus for measuring the vibrational characteristics of both wood and laminated wood specimens is also included in this progress report.

Working Plan
for
THE VIBRATIONAL PROPERTIES OF WOOD AND LAMINATED WOOD AS RELATED TO NON-DESTRUCTIVE TESTING

Introduction

Three non-destructive tests have been evaluated with particular reference to laminated wood during the past year. Both x-ray absorption and transmission of ultrasonic energy have shown definite shortcomings. A vibrational technique which evaluates two vibrational properties of wood non-destructively has shown the greatest degree of promise. It has been shown in a previous progress report [1] that not only the quality of laminated wood but also that of solid wood can be evaluated by the vibrational technique. Furthermore, the test can be performed in a rapid accurate manner with conventional apparatus.

The purpose of this study is to expand the information thus far accumulated by both non-destructive and destructive tests of a group of solid wood specimens having a wide range of strength properties and a group of laminated wood specimens embodying non-defective laminates and laminates incorporating different glue line defect types.

Only one species, Black Walnut, will be employed for both solid and laminated wood testing. For the study of solid wood, small clear heartwood specimens representing a wide range of wood quality will be employed. The data derived from the non-destructive and destructive tests of such material will be correlated in an effort to determine the best relationship between the two test methods. For the study of laminated

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[1] Technical Interim Report. <u>Development of Non-destructive Tests for Laminated Gunstock Blanks</u>. June 1 1953 to June 10, 1954.

wood, both the vibrational properties of the individual laminations prior to laminating and the final laminated product will be evaluated. Laminates will be assembled with and without defective areas, vibrationally tested, and destructively tested. Results of both the non-destructive and destructive tests will be statistically analyzed in an effort to correlate the vibrational characteristics of laminates with the quality of their glue bonds.

Experimental Procedure

Vibrational Properties of Solid Wood

As indicated previously, this phase of the study will be confined to testing small clear heartwood specimens of Black Walnut (*Juglans nigra*).

The test material will be selected from clear, straight-grained heartwood in the form of quarter-sawn, 8/4 stock that has been air seasoned to a moisture content of approximately 25 percent. The test material to be used in the solid wood phase of the study will be selected from material representing a range of specific gravities of approximately 0.40 to 0.70 (oven-dry weight and oven-dry volume). The material to be used for the laminated wood phase of the study will be within the specific gravity range of 0.53 to 0.59.[2] Previously kiln-dried material of uncertain history is not acceptable for this study since the exposure of the material to high drying

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[2] These indicated specific gravity ranges based on oven-dry weight and oven-dry volume are only tentative and will necessarily be dependent on the range available.

temperatures could conceivably alter both the vibrational and static strength properties of the wood. After air seasoning, the material will be kiln-dried at a dry-bulb temperature not in excess of 140° F.

The following kiln schedule will be employed for drying the material to be used in both the solid and laminated wood phases of this study. This schedule is based on the assumption that the material has previously been air-dried to a moisture content of approximately 25 percent.[3]

	Moisture Content		Dry-bulb Temp.	Wet-bulb Temp,	Relative Humidity
Step Number	From	To	°F	°F	%
1	25	20	110	105	84
2	20	15	120	105	60
3	15	Final	130	100	35

Four kiln samples will be employed to follow the changing moisture content of the kiln load. When the driest of the four samples reaches a moisture content of 8 percent in the final stages of drying temperature and humidity conditions will be set to a 140° F dry-bulb and 120° F wet-bulb temperature. This corresponds to an equilibrium moisture content of 8 percent. When the wettest sample has reached a moisture content of 10 percent, conditions will be changed to a dry-bulb temperature of 140° F with a wet-bulb temperature of 132° F. This corresponds to an equilibrium moisture content of 13.5

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[3] The drying schedule presented is one adapted from <u>Schedules for the Kiln Drying of Wood</u>. FPL Report No. D1791. U.S. Dept. Agr. For. Serv., For. Prod. Lab., Madison, Wisconsin.

percent. This condition will be maintained for a period of 48 hours and will serve to equalize moisture distribution within the boards in the load and also relieve any case-hardening that may have occurred during the course of drying.

Material previously selected for the solid wood phase of the study will be divided into the following eight groups based on specific gravity: .40-.42, .44-.46, .48-.50, .52-.54, .56-.58, .60-.62, .64-.66, and .68-.70. From each group five specimens will be selected preferably from five different boards. In the event that this cannot be accomplished no more than two specimens will be taken from the same board. The two specimens will be taken from opposite extremities of a board and in no case will be end-matched.

The five specimens selected from each density class will be initially sawed to the dimensions 0.8 x 1.0 x 24in. Growth ring placement will be normal to the 1.0-in. face. The specimens will be entirely heartwood, straight grained,[4] and entirely free of any visible defects. Immediately after sawing, a specimen 1 in. along the grain will be cut from the test piece for a shell and core moisture content determination. Immediately adjacent to the moisture content section, a wafer 1/4 in. along the grain will be taken for a specific gravity determination. This determination will be made with a mercury volume-meter and will have as its basis oven-dry weight

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[4] In no case will slope of grain in any specimen of either the solid or laminated wood phase of the study exceed 1 in. in 50 in.

and oven-dry volume. The specific gravity determination will be used as a check to insure that the density of the specimen falls within the specified class limits. These sections for moisture content and specific gravity determinations will be taken from the end of the test specimen nearest the center of the original plank.

The test specimens in the original dimensions will be end-coated with Angier log sealer [5] and subjected to a conditioning treatment of 140° F dry-bulb temperature and a 126° F wet-bulb temperature. This corresponds to a 10 percent equilibrium moisture content. It is recognized that the original drying may not bring the material to the desired moisture content of 10 percent and also provide a uniform moisture distribution through all the specimens. Therefore, the additional treatment should accomplish this objective while maintaining comparable treatment conditions for all specimens. Care will be exercised during all drying and conditioning processes to prevent the temperature from exceeding 140° F. During glue line curing no temperature in excess of 150° F will be employed.

The moisture content of the test specimens will be determined on a weight basis using data collected from the shell and core sample of each specimen. The weight change of eight different specimens representing the entire range of specific gravities will be closely observed to determine when the test

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5. Angier log sealer No. SB-525. This is a sealing compound manufactured by Angier Products Inc., Cambridge, Mass.

specimens have attained the desired moisture content.

Immediately after conditioning, the specimens will be planed to the final dimensions 0.6 x 0.8 x 18 in. Growth ring placement will be normal to the 0.8-in. face in all specimens.

After machining to final dimensions the test specimens will be kept in double vinyl-plastic bags to inhibit moisture content change. The specimens will be kept in these bags prior to and immediately following both the non-destructive vibrational and the destructive testing. During periods between testing these bags will be kept in a room in which the relative humidity conditions are such that approximately a 10 percent moisture content is developed in wood. Room conditions in which both non-destructive and destructive testing are performed will also be controlled to the extent possible in such a manner as to minimize moisture content changes in the test specimens.

Vibrational testing will be carried out with each specimen freely supported at two nodal points for each particular mode of vibration employed. Support will be obtained by loops of fine silk threads positioned at the nodal points. The specimens will be excited by air coupling between the diaphragm of an electrical speaker driver unit and the wood specimen. All measurements will be made with electronic equipment. Two vibrational properties will be measured on each specimen: resonant frequency and logarithmic decrement.[6] Each specimen will be vibrated at its

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[6] The method used and the equipment employed for the determination of the vibrational characteristics of wood specimens is outlined in Progress Report No. 5 Development of Non-destructive Tests for Laminated Gunstock Blanks. February 1 to March 31, 1954.

1st, 2nd, 3rd, 4th, and 5th harmonic modes of vibration and resonant frequency and the logarithmic decrement determined at each mode. Three separate determinations will be made of the vibrational properties at each mode and the final value employed for correlation purposes will be the mean of the three values obtained. Vibrational characteristics at the higher harmonics will be evaluated in order to ascertain at which mode the vibrational characteristics are most accurate in predicting the static strength properties of the test specimens. Immediately following the initial vibrational test, each specimen will be measured to the nearest .001 in. in cross sectional dimensions, to the nearest .01 in. in length, and weighed to the nearest .01 gm. Weights of the specimens will be determined at intervals during subsequent vibrational testing in order to correct data for any uncontrolled moisture loss or absorption.

After completion of vibrational testing, each specimen will be subjected to a static-bending test employing a third-point loading system. The approximate load at proportional limit will be calculated for each specimen from laboratory test data.[7] Each specimen will be loaded to one-half this computed value. The tests will be performed on a Baldwin hydraulic testing machine. The specimens will be loaded on a radial face over a 16 in. span at a platen speed of .091 in. per minute. Deflections will be read to the nearest .0001 in. at mid-span as well as under one load at a sufficient number of load intervals that

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[7] Markwardt, L. J., and T.R.C. Wilson. *Strength and Related Properties of Woods Grown in the United States.* U. S. Dept. Agr. Tech. Bul. 479. 1935. Table 1.

stress-strain relationships below the proportional limit can be accurately plotted for each test specimen.

Following completion of third-point loading, each specimen will be returned to the plastic bag for at least four days to permit complete recovery from pre-stressing and then tested to destruction in static bending by center loading. Again testing will be performed on a Baldwin hydraulic machine. The specimens will be loaded in a tangential direction over a 16-in. span at a platen speed of .082 in. per minute. Deflections will be read to the nearest .0001 in. at a sufficient number of load intervals to provide an accurate curve of the load-deflection relationship of each test specimen.

From the load-deflection data of the third-point loading test of each specimen, Young's modulus free of shearing deformation[8] will be computed from the following formula.

$$E' = \frac{Pl^3}{36\ bd^3\Delta}$$

where E' = pure Young's modulus, pounds per square inch

Δ = difference in deflection between mid-span and a point under load[9] at the proportional limit, inches

P = load at proportional limit, pounds

and b, d, l = breadth, depth, and span of specimen, inches

From the load-deflection data of the center-load static-bending test of each specimen the following strength properties will be calculated: fiber stress at proportional limit, modulus

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[8] In the following discussion Young's modulus free of shearing deformation will be referred to as pure Young's modulus.

[9] The point at which deflections are read under the load can be either of the two loading points one-third the span from the points of support of the specimen.

of rupture, apparent Young's modulus, work to proportional limit, and work to maximum load. These data will be calculated from the following formulas:

$$fspl = \frac{1.5\ Pl}{bd^2} \qquad WPL = \frac{P\Delta'}{2bdl}$$

$$MR = \frac{1.5\ P'l}{bd^2} \qquad WML = \frac{\text{area under load-deflection curve to maximum load, inch-lbs.}}{bdl}$$

$$E = \frac{Pl^3}{4\ bd^3\Delta'}$$

where

$fspl$ = fiber stress at proportional limit, pounds per square inch

P = load at proportional limit, pounds

P' = maximum load, pounds

Δ' = mid-span deflection at proportional limit, inches

MR = modulus of rupture, pounds or square inch

E = apparent modulus of elasticity, pounds per square inch

WPL = work to proportional limit, inch-pounds per cubic inch

WML = work to maximum load, inch-pounds per cubic inch

and bdl = breadth, depth, and span of specimen, inches.

From pure Young's modulus (E') and apparent Young's modulus (E) the modulus of rigidity will be computed from the following formula:

$$G = \frac{0.3d^2\ EE'}{(\frac{1}{2}\ l)^2\ (E'-E)}$$

where G = modulus of rigidity, pounds per square inch

E' = pure modulus of elasticity, pounds per square inch.

E = apparent modulus of elasticity, pounds per square inch.

and d,l = depth and span of specimen, inches.

After computation of all static strength data, an attempt will be made to correlate them with the non-destructive test data including resonant frequency, logarithmic decrement, weight, and dimensions. An outline of the statistical procedure to be employed is presented in the latter part of this working plan.

If a vibrational test proves applicable for estimating the quality of both solid and laminated wood it would seem desirable to know the effect of moisture content on the vibrational properties since wood will be subject to moisture content changes during both machining and fabrication into laminated billets. Therefore, an additional phase of this study, dealing with solid wood, will be concerned with the effect of moisture content on the vibrational characteristics of wood.

For this phase of the study 10 specimens of Black Walnut within a specific gravity range of 0.53 to 0.59 will be selected from clear straight-grained heartwood, free of any visible defects. The ten specimens will be randomly selected from ten sticks which were dried in the original kiln run. The specimens will be initially sawn to the rough dimensions 0.30 x 0.65 x 14 in. Growth ring placement will be normal to the 0.65-in. face in all specimens. After sawing to rough dimensions each specimen will be planed to a final thickness of 0.20 in., trimmed to a 10-in. length, and end coated with Angier log sealer.[10]

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[10] See footnote No. 5.

Essentially this phase of the study will involve conditioning the specimens as a group in a closed atmosphere over five different saturated salt solutions. When the specimens have reached equilibrium moisture conditions over each salt solution they will be removed, weighed, and immediately vibrationally tested. It is essential that these specimens be tested as rapidly as possible before any marked change in moisture content can occur. The data collected will be used to correlate the logarithmic decrement with moisture content.

Initially the oven-dry weight and weight at 35 percent moisture content of each of the ten specimens will be computed, using as a basis the original moisture content of the material. The ten specimens will then be placed in an autoclave and subjected to a gage pressure of 20 lbs. while immersed in water. At five minute intervals the specimens will be removed and weighed. When weight changes show that the specimens have attained an overall moisture content of 35 percent they will be placed over water in a desiccator and allowed to dry until they have reached constant weight and have developed a uniform moisture distribution. A uniform moisture distribution at or slightly above the fiber saturation point will be determined by shell and core moisture content sections 1 in. in length along the grain taken 1 in. from the end of each specimen.

When the specimens have developed a uniform moisture distribution each will be vibrationally tested in a manner previously described/[11] and both resonant frequency and the logarithmic decrement recorded at the fundamental resonant frequency.

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[11] See footnote No. 6.

The specimens as a group will then be successively conditioned over the saturated salt solutions indicated below.

Salt	Temperature °F	Relative Humidity %	Approx. Equilibrium Moisture Content
1. Sodium sulphate (Na_2SO_4)	90	85	18
2. Sodium nitrite ($NaNO_2$)	90	65	12
3. Magnesium chloride ($MgCl_2$)	90	30	6
4. Potassium acetate ($KC_2H_3O_2$)	90	20	4
5. Lithium chloride ($LiCl$)	90	10	2.5

The specimens will be placed on a wire screen immediately above the salt solution in a desiccator. The desiccator will be provided with a motor-driven fan to provide air circulation around the conditioning wood specimens. A temperature of 90° F. will be maintained around the desiccators at all times.

When the specimens have reached constant weight over a particular saturated salt solution they will be removed, weighed, and vibrationally tested. After drying over the fifth salt solution, the specimens will be placed over powdered phosphorus pentoxide (P_2O_5) until they have reached constant weight and then again vibrationally tested.

The last treatment should reduce the moisture content as low as possible without resorting to oven-drying. This procedure is followed to eliminate exposure of the test specimens to high drying temperatures.

After final conditioning and vibrational testing the specimens will be dried to constant weight in an oven operating at 212-220° F in order to verify the moisture content at which each vibrational test was performed.

The statistical prodecure to be employed for the analysis of the data collected in this portion of the study is outlined in the latter part of this working plan.

Vibrational Properties of Laminated Wood

The second phase of this study will be directed toward an evaluation of the non-destructive vibrational test as an indication of glue bond quality. Both defective and non-defective specimens will be studied with respect to the adhesive bond integrity. Several types of glue line defects with respect to location, type, and extent of defect will be investigated. The material used in this phase of the study will be restricted to Black Walnut. It will be derived from 8/4 quarter-sawn stock which had been dried in the original kiln charge with the material employed in the solid wood phase of the study. Only material in the specific gravity range of 0.53 to 0.59 with 12 to 20 growth rings per inch [12] will be employed. The individual laminations will be clear, straight grained, and free of any visible defects.

The study will be concerned with an evaluation of the vibrational test as a detector of faulty glue bonds occurring as a result of glue line voids, waxed areas, thick glue line areas, and areas in which the glue line has been allowed to exceed the

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[12] See footnote No. 2.

maximum assembly time. For this phase of the study 28 matched sets of laminates will be employed. Each matched set will be composed of 6 laminates longitudinally- and radially-matched as shown in Fig. 1. The material for each set of laminates will be derived from one quarter-sawn 8/4 plank (2 x 8 x 78 in.) Each plank must not have a grain deviation greater than 1 in. in 26 in. in order that a piece 5-in. wide may be cut from it.

The 2 x 5 x 78-in. defect-free piece will be sawn into six 2 x 2.4 x 24-in. units. Each unit will then be band-sawn into to laminations .95 x 2.4 x 24 in. Later, after further machining, each pair of tangentially-matched laminations will be assembled into either a defective or non-defective laminate. The longitudinal and radial matching of each set of six laminates is shown diagrammatically in Fig. 1.

Prior to final machining the laminations will be end-coated with Angier log sealer and will receive a final conditioning treatment at a dry-bulb temperature of 140° F and wet-bulb depression of 14° F to develop a uniform moisture content of 10 percent. This treatment will be carried out until no weight change is observed in any one of 8 individual laminations distributed throughout the charge. At the end of the conditioning treatment a shell and core moisture content section 1-in. in length along the grain and a 1/4-in. section for a final specific gravity determination (oven-dry weight and oven-dry volume) will be taken from each lamination. No specimen deviating outside the moisture content range of 9 to 11 percent or the specific gravity range of 0.53 to 0.59 will be employed for testing.

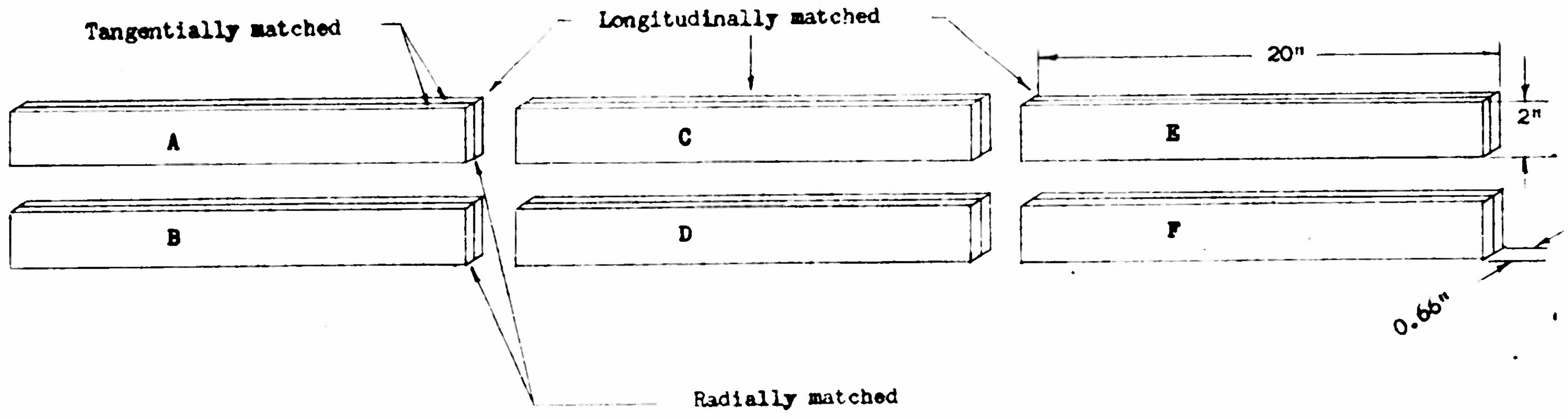

Fig. 1 A typical set of six matched laminates produced from a single quarter-sawn plank.

After final conditioning the laminations will be machined to the final dimensions 0.33 x 2.4 x 20.5 in. At all times prior to and after laminating the material will be kept in double vinyl-plastic bags in a manner similar to that employed with the specimens used in the solid wood phase of the study. The material will be kept in the same room under the same relative humidity conditions as the solid wood specimens. During both non-destructive and destructive testing of the laminates, relative humidity conditions in the room will be controlled to the extent possible in a manner to minimize moisture content changes of the specimens while under test.

The method of non-destructive testing will be essentially the same as the method employed in the solid wood phase of the study. Both logarithmic decrement and resonant frequency will be recorded. Immediately following the vibrational test each laminate will be measured to the nearest .001 in. in cross sectional dimensions, to the nearest .01 in. in length, and weighed to the nearest .01 gm. The individual laminations of specimens A and F (Fig. 1) will be resonated at the 1st, 2nd, 3rd, 4th, and 5th harmonic frequencies, and the logarithmic decrement and resonant frequency recorded at each mode of vibration. Each remaining lamination of each group will be resonated at only its fundamental resonant frequency. This procedure is proposed since it is felt that the study of static testing material and the laminations of the non-defective laminates at higher frequencies should supply adequate information to observe the relationship between logarithmic decrement and frequency. Three separate determinations will be made at each mode of vibration employed and the final value used will be the mean of the three recorded values. The object of the longitudinal and radial matching of laminations is to provide similar vibrational properties in a set of six laminates. This is extremely important in order to evaluate the test as a detector of defective glue lines. Any lamination exhibiting a logarithmic decrement outside a range of ± 5 percent of the mean value of the 12 laminations of any group will be replaced by a lamination having a logarithmic decrement which falls within the specified range.

After initial vibrational testing the tangentially-matched laminations will be assembled into the six specimens of each group. Specimen B will contain a glue line void. Specimen C will contain a defective area in the form of a heavily waxed spot applied in the same position on both laminations. Specimen D will contain a defective area in the form of a heavy glue line. This defect will be developed by sanding the gluing surfaces of both laminations with a small drum sander to provide an indentation in the laminate where the defective area is desired. The depth of the indentation in each lamination will be .01 in. Specimen E will be assembled with a glue line defect in the form of an area in which the maximum open assembly time of the adhesive has been exceeded. This open assembly time will be 2 ½ hours. As previously indicated, specimens A and F will be non-defective with respect to the glue bond quality.

Bonding will be accomplished with Penacolite G-1260, a phenol-resorcinol adhesive. A ten minute open assembly and 15 minute closed assembly will be observed for non-defective glue line areas. Bonding pressure will be delivered with bar clamps spaced on both sides of an assembly at sufficiently frequent intervals to provide a bonding pressure of at least 150 p.s.i. Oak cauls 3-in. thick will be used on both sides of each assembly.

The final machining of the individual laminations will be carried out not more than four days before assembly. These laminations will also be kept in bulk piles between the time of final machining and assembly.

A curing temperature of 150° F for a period of six hours will be employed. The time required for the entire glue line of a laminate to reach this temperature will be determined by means of a thermocouple placed at the center of a sample laminate. This procedure will be carried out for the first three gluing periods to determine the length of the heating period. All subsequent heating periods will employ this time as a base. During the glue line heating, curing, and cooling, relative humidity conditions will be maintained at such a level as to prevent moisture content chahge of the laminates.

After glue line curing the laminates will be machined to the final dimensions.66 x 2.0 x 20 in. All laminates will then be resonated at the 1st, 2nd, 3rd, 4th, and 5th, harmonic frequencies and logarithmic decrement and resonant frequency recorded at each mode of vibration. The purpose of resonating the laminates at different modes of vibration is to attempt to detect and locate the defective glue line areas.

Four different types of defective glue lines as well as two well bonded control laminates will be studied in each set. The extent and location of these defects will be the same in the four defective specimens of each set. A total of 26 sets of laminates will be assembled. The glue line defects in the different sets will vary in magnitude and location as shown by a representative specimen of each set in Fig. 2.

Specimen nos. 1 through 6 will contain glue line defects of the magnitude and location shown in Fig. 2. A previous study has shown that a glue line void had its greatest effect on the logarithmic decrement when a mode of vibration was employed which resulted in a nodal point occurring within the boundaries of the defective area. [13] Laminate nos. 1 through 6 will be resonated at all the harmonics previously indicated. However, vibrational characteristics recorded for the 2nd and 4th harmonic modes will be of particular interest since both modes result in the location of a nodal point at the center of the laminate. This procedure should provide an accurate evaluation of the magnitude of glue line defects which can be detected. The defective areas of laminate nos. 1 through 6 will extend completely across the width of the laminate. The defective areas in laminate nos. 7 through 12, which are of the same length and location as the glue line defects in specimen nos. 1 through 6, will be limited to the center 3/4 of the specimen width. With a laminate 2-in. wide this will result in a defect width of 1 1/2 in. with

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13. See footnote No. 1.

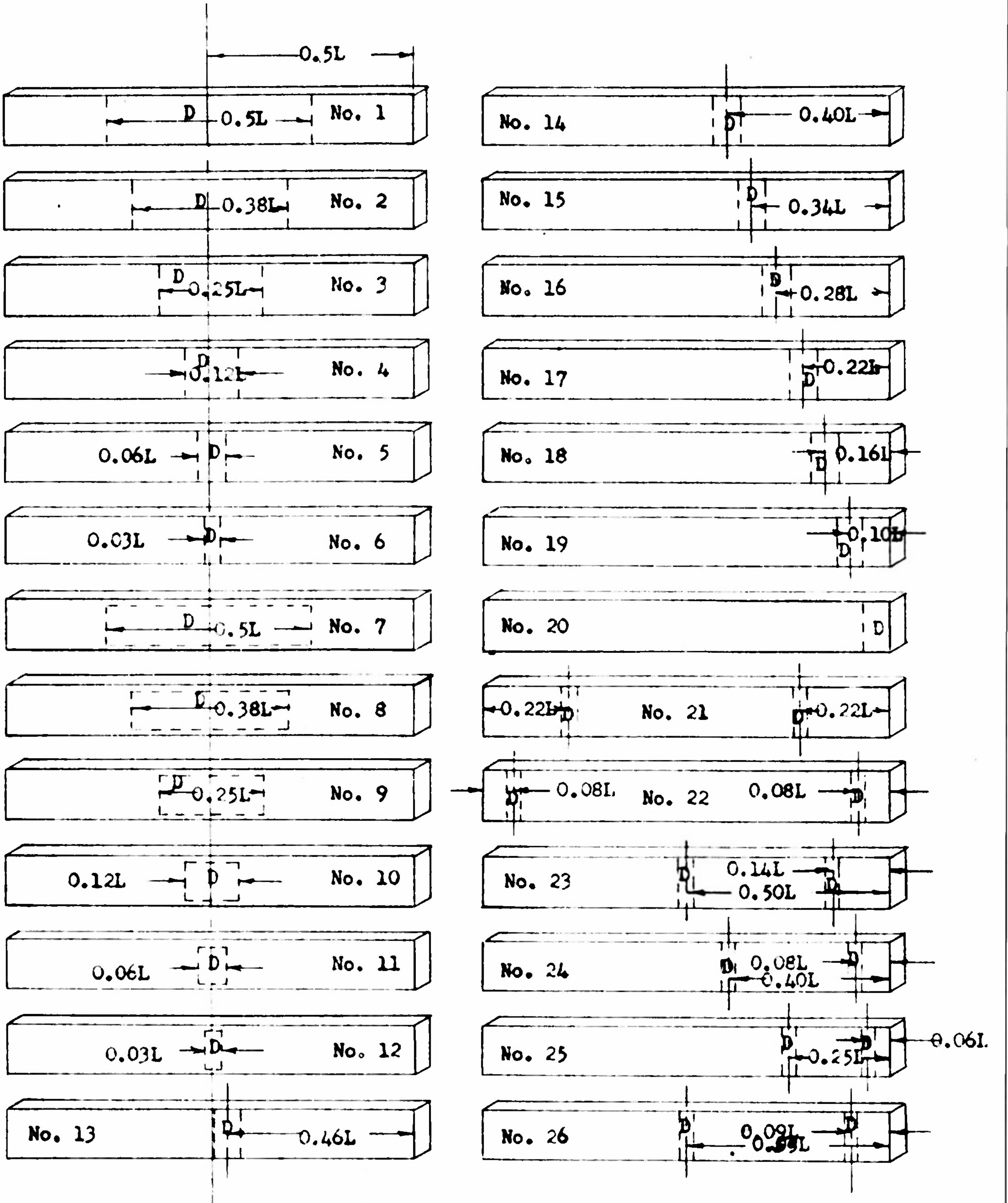

Fig. 2 Location and size of defective glue line areas in one laminate of each group of six specimens. The letter D designates a defective area. The numbers indicate the length and position of the defective areas where L = length.

a bonded margin 1/4-in. wide on each side of the defect. This procedure will essentially provide a replication of experimental procedure designed to reveal the magnitude of a glue line defect which can be detected by the vibration method. It will also indicate the type of glue line defect, whether open at the glue joint edge or enclosed in the laminate, that can be detected by this test method.

The width of glue line defects incorporated in the remaining 16 specimens will be dependent on the results obtained on the first 12 specimens tested. Should a glueline defect which is not exposed at the edges of a laminate prove to be detectable this type of defect will be employed in the remainder of the study. However, should it prove impossible to detect this type of glue line defect then defects exposed at the edges of a laminate will be utilized in the remainder of the study.

The first section of the study dealing with laminated wood will provide information relative to the magnitude of defect that can be detected. The smallest defective area that can be consistently detected will be employed in laminate nos. 13 through 20. These laminates (Fig. 2.) will be used to locate this smallest defect in eight different positions from the center to the end of the specimens. The laminates will be resonated at all the harmonic modes previously indicated to determine which mode is the most effective in locating a particular defect. Laminate nos 21 through 26 will employ two glue line defects. Each defect will have an area one-half the magnitude of the defective areas incorporated in laminate nos. 13 through 20. The location of the defects in these specimens has been selected in such a manner that every mode of vibration up to the 5th harmonic can be utilized in the evaluation of the test method.

After completion of non-destructive vibrational testing, each specimen will be cut into a series of shear specimens 1 in. in length along the grain. The specimens will be provided with 1/8-in. steps (Fig.3) and will be tested on a Baldwin hydraulic testing machine at a platen speed of 0.015 in. per minute. A total of 15 shear test specimens will be cut from each laminate in such a manner that small defects will occur in the center of any one test specimen. The use of 1/8-in. steps will provide tests over the maximum possible area of the laminates. The purpose of these shear tests is to verify the location and character of the included glueline defects. At all times during this destructive testing relative humidity conditions in the room will be controlled as accurately as possible to minimize moisture content change of the test specimens.

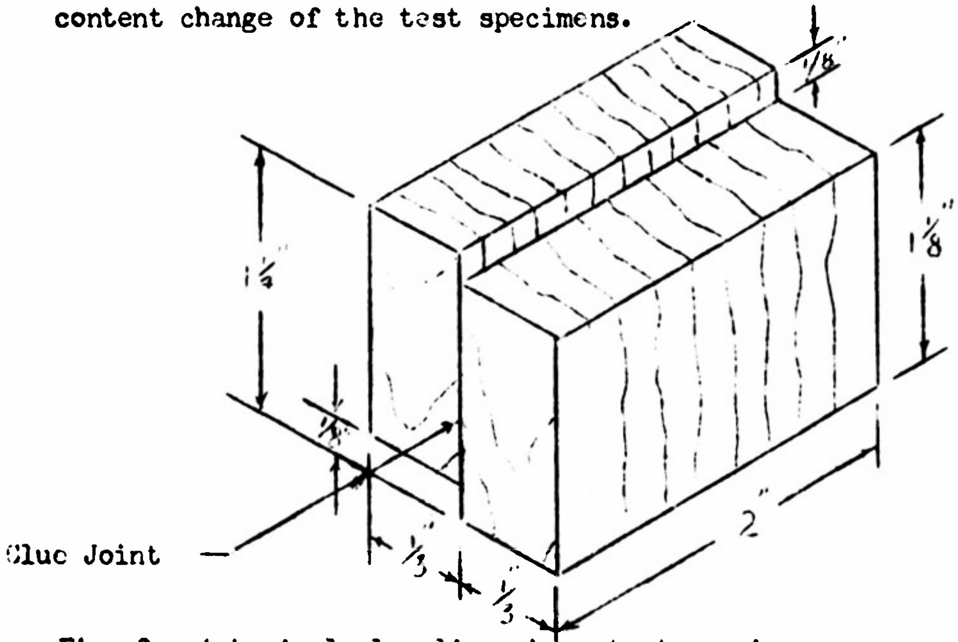

Fig. 3 A typical glue line shear test specimen.

The results of both non-destructive and destructive testing will be analyzed statistically to evaluate the vibrational test as a non-destructive test method. The design of this analysis is presented in the following section.

This experiment has been designed to investigate initially non-destructive vibrational testing of solid Black Walnut. The ultimate objective of this first phase of the study is to develop a non-destructive test for the evaluation of wood strength properties other than stiffness. The latter part of the study is devoted exclusively to an investigation of laminated wood. This section has been designed to include the major glue line defect types which occur in laminated material and to include various sizes and locations of these defects within a laminate in order that the vibrational test can be critically evaluated. As designed, the study should provide an accurate estimate of the feasibility of a vibrational test as an indication of the quality of both solid and laminated wood.

Design of the Statistical Analysis

Vibrational Properties of Solid Wood

The non-destructive testing of solid wood will provide four physical measurments of each test specimen: resonant frequency, logarithmic decrement, weight, and dimensions (breadth, depth, and length). The purpose of this phase of the study is to correlate these properties with the static strength properties of the test specimens: fiber stress at proportional limit, modulus of rupture, work to proportional limit, work to maximum load, and modulus of rigidity.

A procedure outlined by Fisher [14] involves the regression of a dependent measurement, on several independent variates (x_1, x_2, x_3, etc.). In this study the dependent measurement will be one of the five static strength properties indicated above. Six independent variates will be employed (resonant frequency, logarithmic decrement, weight, breadth, depth, and length). The method will employ six equations each including seven terms which will be solved by the use of matrices. In order to determine the most accurate relationships between the dependent and independent measurements the data will be analyzed in both a non-transformed and transformed condition. The data of all five dependent measurements (static strength properties) will be analyzed in a similar manner.

Dynamic and static modulus of elasticity values will be correlated by means of a simple regression. The static modulus will be used as the dependent variable and the dynamic modulus as the independent variable. The data accumulated in the study of the effect of moisture content on the logarithmic decrement will be analyzed in a similar manner. Logarithmic decrement will be designated as the dependent measurement with moisture content as the independent measurement. An equation of the relationship will be derived, the significance of either a linear or curvilinear relationship will be determined, and confidence limits will be fit about the regression line. The degree of correlation will be indicated by the correlation coefficient.

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14. Fisher, R.A. Statistical Methods for Research Workers Eleventh Edition. pp. 156-166. Hafner Publishing Co. New York, 1950.

Vibrational Properties of Laminated Wood

Initially a regression of logarithmic decrement on frequency of the individual laminations of the non-defective specimens will be calculated. The slope of a second regression of the logarithmic decrement on frequency of the non-defective laminates will be compared with the first by means of an F - test in order to observe the effect of a non-defective glue line on the logarithmic decrement.

The data from the phase of the study involving the testing of laminates with glue line defects of different magnitudes will also be analyzed by a simple regression. The symbol δ will be employed as the logarithmic decrement of either a defective or a non-defective specimen at any one chosen harmonic frequency and δ_1 will signify the lower logarithmic decrement of the two control laminates of each group taken at the same harmonic mode of vibration. A regression of $(\delta - \delta_1)$ on the area of the glue line defect will then be plotted for specimens with the same glue line defect type. The independent variate of the control specimens of each group will be zero or slightly greater. However, it is anticipated that the independent variates of the defective specimens will be larger and a correlation will exist between $(\delta - \delta_1)$ and the area of the glue line defects. The slopes of the regressions for the different types of glue line defects will be compared by means of an F-test. Confidence limits will be set on both sides of each regression. The lower confidence limit will indicate the smallest glue line defect of any type that can be detected with any desired risk.

The non-destructive test data obtained from the laminates, each with a single small glue line defect located at some position between the center and end of the laminate, and the laminates containing two glue line defects will be subjected to an analysis of variance.[15] The purpose of this analysis will be to determine the significance of differences between logarithmic decrements of grain matched defective and non-defective specimens when vibrated at the same mode.

Test Apparatus

A description of the essential components of the electronic apparatus employed for measuring the resonant frequency response curve of a wood specimen has been given ~~described~~ in a previous progress report.[16]

In order to compute the logarithmic decrement of a wood specimen it is necessary to know the width of the frequency response curve at some pre-determined point and the resonant frequency at which the logarithmic decrement is measured. Sufficiently accurate calculations of the logarithmic decrement can be determined by reading resonant frequency directly from the frequency scale of the driving audio oscillator. However, the measurement of the width of the response curve in cycles per second requires considerable more accuracy since it is an extremely low frequency. Previously this measurement has been carried out by setting one audio oscillator at a frequency corresponding to

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15. The procedures to be followed for the regressions and analysis of variance are outlined by Bliss, C.I. and D.W. Calhoun. An Outline of Biometry. pp. 81-152. Mimeographed copy. Yale University, 1954.

16. See footnote no. 6.

some pre-determined fraction of resonance amplitude on one side of the response curve and setting a second audio oscillator at a comparable position on the opposite side of the response curve. When the two signals were applied to the horizontal and vertical deflection plates of a cathode-ray oscilloscope, they produced a migrating Lissajous pattern whose frequency of migration was equal to the frequency difference of the two oscillators. Since the two oscillators were set at opposite equal amplitude points on the response curve their frequency difference was equal to the width of the curve at the pre-determined point. This frequency difference was determined by timing the migration of the Lissajous pattern.

It has been proposed in the preceding working plan to vibrate specimens at frequencies as high as the fifth harmonic. Since the width of the response curve may attain a magnitude of 200 cycles per second at the fifth harmonic it has become necessary to develop an alternate method for measuring the response curve width.

A special mixing circuit has been designed and assembled which will mix the frequencies of the two audio oscillators, filter the high frequencies, and pass the low difference frequency. This unknown difference frequency will then be measured by comparing it with a secondary frequency standard on the screen of the oscilloscope. An accurately calibrated low frequency oscillator will be employed as the secondary frequency standard.

A special lamp has been constructed for excitation of the photo-electric cell. The lamp consists of a small Sylvania Type A-2 bulb which emits light primarily in the ultraviolet spectrum and a lens system for focusing the light to a small uniform spot. Since the photo-electric cell is considerably more sensitive to ultraviolet light than the remainder of the light spectrum a greater voltage output from the cell should be obtained than has been previously realized when white light excitation was employed.

In addition to the instrumentation improvements described above a special vibration-free work bench has been constructed. The bench consists of a wood top constructed of laminated Douglas fir which is supported from a heavy wood frame by means of coil springs. The mass of the top and the stiffness of the springs provide the system with a resonant frequency of approximately 2 cycles per second. The top has a work area of approximately nine square feet and a thickness of 5 in. It was designed with a combination of mass, dimensions, and modulus of elasticity to provide it with a fundamental resonant frequency of approximately 250 cycles per second. This frequency does not occur in the vicinity of any of the resonant frequencies of the test specimen and therefore, will not interfere with the vibrational testing. Specimen supports, the photo-electric cell transducer, and light source will be placed on the bench top. The speaker driver used for exciting the test specimens to resonance will be supported above the bench top and will be rigidly coupled to the work bench frame. The improvements in test apparatus described in the preceding paragraphs should permit accurate calculation of the vibrational characteristics of the wood specimens.

Plans for Future Work

Inquiries relative to the availability of plank material from which test material can be selected have been placed with several manufacturers of Black Walnut lumber. It is anticipated that this material will be procured in the immediate future in order that testing may be under way before delivery of the next progress report.

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