EFFECT OF RESIN IMPREGNATED CORE VENEER ON SHEAR STRENGTH OF DOUGLAS-FIR PLYWOOD

by

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ABSTRACT

The influence of lathe checks on shear strength of Douglas fir plywood was investigated by means of impregnating lathe checks of rotary-cut veneer to various depths using a phenol-formaldehyde resin.

Comparative tensile shear strength tests were conducted on a Table Model Instron machine and photographs taken at various stages of load application to illustrate the varied manner of failure.

Strength of rotary-cut veneer plywood was about 60 to 70% that of sawn veneer plywood, but after the lathe checks of core veneer were impregnated by resin there was no significant difference between them. The shear strength (Y) was found to be highly correlated with penetration depth of adhesive into lathe checks (X). The linear relationship between these factors was:

$$Y = 228.22 + 1.28052X \ (SE_E = 21.82;\ r = 0.893).$$

Per cent wood failure estimated by conventional methods failed to relate to shear strength. Rather, the per cent wood failure occurring within 10% of the initiation of an annual increment was found to be a better indicator of shear strength. Use of photography helped to explain more clearly stress distribution and wood failure in the specimens. It was found that the ultimate strength was reached in conventional plywood when the lathe checks were just opening.

Core-impregnated plywood was used in a test to compare the tensile shear resistance when tight-side and loose-side of veneer was next to the glue line. Neither strength nor wood failure were significantly different between the two. Tensile shear strength for plywood made of impregnated core veneer and untreated face veneer was two to three times as high as that of conventional plywood. The per cent wood failure in core veneer and shear strength varied inversely. Results obtained in this study indicated that it is feasible to develop a plywood which has shear strength as high as 500 psi while remaining economical to manufacture.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Many studies have been done during recent years to determine the factors influencing the tensile shear strength of plywoods. Of these factors, lathe checks are always regarded to be of the greatest importance. However, several fundamental questions concerning the influence of lathe checks have not been answered clearly. For example, how deeply does the glue migrate into lathe checks in proportion to their total depth? Will varying depths of glue migration influence the shear strength of plywood? How does the critical area of a shear specimen having lathe checks behave under the applied load, in comparison with that of a check-free (i.e. sawn veneer) specimen? If these questions could be satisfactorily answered, it is believed that the new knowledge could lead to better techniques that would improve strength properties of plywoods.

The value of wood failure as a criterion of plywood quality has been a subject on which many conflicting opinions have been expressed. This may be due to lack of understanding of the mechanism of wood failure in relation to shear strength.

It has long been recognized that veneer properties are affected by the peeling process. The loose- and tight-side of a veneer are expected to be different in strength properties. The tight-side might have been compressed beyond the proportional limit by the nose bar, and the tensile strength parallel to the grain of the loose-side might be reduced by lathe checks. A test of these variables on plywood specimens has not been done.

In view of the above, the first purpose of this study was to investigate how mechanical behaviour of plywood in tensile shear, perpendicular to the grain of the core plies, would be influenced (a) by presence of lathe checks and (b) by different depths of adhesive penetration into lathe checks. Shear strengths were determined with plywood in which the face plies were not treated.

The shear testing was done on an Instron machine which directly records the stress-strain curve on a chart. Close-up photographs of the samples, in different stages of load application, were also taken and used for analyses of stress and wood failure at known positions on the stress-strain curve.

The second purpose was to determine the contribution of the tight- and loose-side of veneer in the face plies to the tensile shear strength of plywood made with resin-impregnated core veneer, with failure forced by specimen design to occur in face ply.

Another objective was to examine the influence of the resin-impregnated core veneer on the shear strength of plywood in which the face plies were not treated, with failure forced to occur in core.

It is hoped that the results of this experiment will lead to the development of a plywood which has improved shear strength and still will remain economical to manufacture.

REVIEW OF LITERATURE

A. Lathe Checks

1. Formation

The influence of peeling technique on veneer quality has received considerable study in recent years (12, 23, 30, 34, 35, 39, 40, 42, 45, 46). Fleischer (23) obtained excellent close-up photographs of veneer cutting and showed that an increase in nose-bar pressure was effective in reducing both the severity of lathe checks and roughness of the veneer. Excessive compression in the case of some softwoods, however, resulted in shelling or slivering, due to a separation between earlywood and latewood. Variations in frequency and depth of checks, in veneer thickness and in surface quality in peeled veneers were observed by McMillin (46). He found that, as nose-bar pressure was increased stepwise so that compression of the veneer increased from zero to 15% of veneer thickness, the depth of lathe checks decreased, while their frequency (of checks) increased.

The mechanism of veneer formation at the cellular level was studied comprehensively by Leney (39, 40). When his study is combined with the explanation postulated by Koch (35), it is seen that stresses in the zone adjacent to the cutting edge of the knife can be classified simply into tension, shear and compression. These critical zones of stress concentration are presented diagrammatically in Fig. 1. Because of stresses, three types of rupture may occur, singly or in combination, as veneer is formed. Leney (39, 40) identified these types of rupture as tension checks, shear checks, and compression tearing.

> "Tension check is due to tension stresses resulting from combination of cantilever beam action, compression just behind the cutting edge, and shear stresses caused by the cutting edge resisting the movement of the wood. Shear checks from behind the cutting edge when high compressive stresses combined with resulting friction resist the movement of the chip up the knife. Compression tearing was attributed to a dull knife resisting the movement of the wood past the cutting edge." (39).

About the same time Collins (12) postulated that lathe checks in Douglas-fir veneer were produced by an unstable "snap action" in an area stressed under tension normal to the break. At first, the stress would be nearly normal to the cut, but would change rapidly to a direction nearly parallel to the cut.

ii. Influence on shear strength of plywood.

Tensile strength perpendicular to the grain in rotary-cut veneer has been studied by Kivimaa (34). He found that increase of nose-bar pressure increased the tensile strength of veneer but reduced the depth of lathe checks.

Curry (15) and Yavorsky and Cunningham (71) postulated that a large component of shear existed in the plane of the core veneer of three-ply specimens. Existence of lathe checks in the core veneer exerted a pronounced effect on the amount of shear strain in this region. A similar opinion was reported by Norris, Warren and McKinnon (48). They added that lathe checks reduced the effective area of each ply by reducing the cross-section area.

of wood subjected to stress and, furthermore, lathe checks introduce a zone of stress concentration that should further decrease the shear strength.

Practical investigations were also done by Bethel and Huffman (5), Feihl (22), and Palka (54). Bethel and Huffman found that, in plywood of poplar core and gum face, the orientation of lathe checks with respect to the sawn cuts in the test specimen could cause significant differences in the rolling shear strength. Strength was lower for specimens pulled open than for those pulled closed. A similar study was done by Feihl (22) who found that the influence of lathe checks on the strength of yellow birch plywood was of a very contradictory nature. This was explained as being caused mainly by major differences in the distribution of stresses in the specimens submitted to different tests. The bending shear test was found to be better than the tension shear test. He concluded that specimens with lathe checks pulled closed have higher strength than those with the checks pulled open. (Fig. 2).

Palka (54), investigated factors influencing several strength properties of Douglas-fir plywood. He concluded that the most important single factor was veneer type. The dominant role of this factor is attributed to the effect of lathe checks and surface quality. The average rolling shear strength of sawn veneer was about 1.5 times that of rotary-cut veneer blocks. However, he suggested that the reduction in rolling shear resistance attributable to the mechanical effect of lathe checks was comparatively small and/or partly countered by the adhesive penetrating into them. The latter was more pronounced for blocks prepared under high gluing pressure (350 psi).

B. Wood Failure

i. Importance

Tests of glue bonds are made in an attempt to predict the behaviour to be expected of the plywood in service. In most instances the criterion for acceptance or rejection is that the test specimen must have a glue bond strength at least equal to that of the wood in the specimen. This line of reasoning led to the use of percentage wood failure as the basis for evaluating bond strength (72).

In Canada per cent wood failure is accepted as a standard for estimating glue-bond quality (10) for testing exterior-type Douglas-fir plywood bonded with waterproof phenol-formaldehyde resin. According to Canadian specifications (10):

> "If the average wood failure of ten test specimens from a test piece is less than 60 per cent, or if more than one test specimen is less than 30 per cent, that test piece fails. If more than one test piece from a test panel fails, then that panel fails."

Importance of per cent wood failure, therefore, can be seen.

ii. Uncertainty of relationship between wood failure and shear strength

The importance of wood failure was not emphasized in earlier research in England or the U.S.A. (50, 66). Shear strength of plywood was based upon breaking loads obtained from mechanical tests of glue joints. Truax (65), in discussing results of his experiments, stated that under good gluing conditions the joint strength was not seriously influenced by the percentage of wood failure developed by the test. This was later confirmed by Northcott (49), who used Douglas-fir veneers bonded with phenol-formaldehyde resin.

By 1938 serious consideration was being given to the use of per cent wood failure as a criterion of bond quality for plywood specification purposes, if not for research purpose (50). The amount of wood failure was expected to be related to the service life of plywood (57).

A review of various data and reports from different sources, together with his experimental results, led Northcott (49, 50) to postulate that there was a poorer correlation between breaking load and service life than between per cent wood failure and service life. He further showed that strength values from mechanical tests gave more reliable estimates of bond strength than results obtained by the per cent wood failure method.

Shen (59) found that per cent wood failure in spruce plywood was not as accurate an indicator for estimating the glue-line quality as was the breaking load.

Palka (54), using Douglas-fir veneers, postulated that an increase of shear strength was associated with higher wood failure. The simple correlation coefficient between shear stress and wood failure percentage was 0.54 for sawn veneer panels and 0.76 for rotary-cut veneer panels.

In a recent report, Northcott and co-workers (52, 53) concluded that, within certain limits, the per cent wood failure was a potentially good estimate of plywood durability. They suggested that it was reasonable to accept per cent wood failure as a worthwhile predictor of bond durability with hot-pressed, phenolic-glue-bonded Douglas-fir plywood. The per cent wood failure was expected to be more sensitive to initial bond degradation than was the breaking load.

From the results and opinions above, it may be concluded that the relationship of per cent wood failure to breaking load in tension shear test has not been adequately defined. Certain variations in wood, glue, in gluing, or in test and measuring method, may cause the amount of wood failure of a glue joint to vary considerably (59). The density of wood (3), wood species (51), whether heartwood or sapwood (59), latewood percentage, veneer thickness, gluing pressure, moisture content of veneer (54), angle of grain in relation to the glue-line (4), thickness of glue-line (11) and kind of glue used (19), were factors found influencing the per cent wood failure of shear specimens.

iii. Relationship between wood failure and lathe checks

It had been observed (48) that the number of lathe checks within one lineal inch of veneer (from its cross-section) was independent of veneer thickness and that their depth, expressed as a proportion of the veneer thickness, increased with this thickness. Consequently, plywood panels made from thick veneers had a lower shear strength than panels of the same thickness made from thin veneers (15). Considering this effect, along with Palka's finding (54) that reduction in wood failure accompanied increasing veneer thickness, it is possible that increase of lathe check depth would cause reduction in per cent wood failure.

From results obtained by Bethel and Huffman (5), orientation of lathe checks with respect to the saw cut influenced the per cent wood failure, as well as shear strength (p.5). Regardless of whether specimens were tested after boiling or in dry condition, the average wood failure of specimens for which lathe checks were to be pulled open was lower than that of specimens for which lathe checks were to be pulled closed.

C. Relationship of Resin-penetration to Shear Strength of Plywood

i. Permeability of Douglas-fir wood

Erickson and co-workers (21) illustrated that permeability of sapwood in the longitudinal and radial anatomical direction was greater than that of heartwood. The superior permeability of latewood over earlywood was explained by Griffin (26) as due to the greater capillary forces in the lumina of latewood and the greater degree of aspiration in pits of earlywood than of latewood.

Krahmer and Côté (38) described three natural processes which modify the condition of bordered pit-pairs. One was pit aspiration, the second was pit occultation with extractives, and the third process was pit incrustation. Pit membranes of Douglas-fir studied were not heavily incrusted like those of western red-cedar, but pit aspiration was commonly found in the heartwood of both species.

Recently, Koran (37) showed that the presence of extraneous materials in the capillary structure was an important factor prohibiting penetration. The influence of origin of the material was reported by Miller (47). He found that heartwood of Douglas-fir from eastern Oregon was generally much less permeable than that from the western half of the State. Craig (14) reported that trees from high elevations had lowest permeability while trees from medium elevations had the highest variation in permeability.

The styrene impregnation technique applied in this study had been developed by Erickson and Balatinecz (20). They found that in radial impregnation the liquid moved mainly in the ray tracheids. Ray parenchyma cells were mostly impermeable. In tangential impregnation, the penetration was comparatively slow. Movement was through tracheid bordered pits and into and across ray tracheids to some extent. The higher permeability of sapwood over heartwood in Douglas-fir was also demonstrated.

ii. Resin properties

Impregnating veneer with a synthetic resin to stabilize the dimensions, and increase the strength of plywood made from it, can be effectively accomplished only when resin-forming constituents penetrate the cell wall structure and become bonded to the active groups in the wood upon formation of the resin (62). Hence, use of a high molecular weight or prepolymerized resin, or non-polar resin-forming constituents, is not desirable because deposition within the coarse capillary structure of wood renders it less efficient.

A comparison of commercial water soluble phenol-formaldehyde resinoids for wood impregnations has been made by Burr and Stamm (8). By using an alkaline catalyst, the degree of prepolymerization of the impregnant was sufficiently lowered so as to be soluble in water in all proportions. This system was superior to the raw mix, since the resin was less volatile and very small amounts were lost during drying prior to curing of resin (61). Another advantage of the phenol-formaldehyde system was that it swelled wood about 25% beyond the swelling in water, thus further opening up the structure. After cure of the resin, the retained volume of wood was close to the normal water-swollen volume of that wood. The application of urea-formaldehyde resin was found less successful (61), mainly because the lower polymer was only about 20% soluble in water and the resin-forming solid tended to precipitate in the coarse void structure of the wood as it was dried, rather than continuing to diffuse into the fiber walls. Also, the cured urea resin was far less water resistant than the phenol-formaldehyde resin.

Gap-filling properties of several wood adhesives was compared by Goto, Kawamura and Sakuno (25). They found that phenol-formaldehyde glue was the best, while resorcinol and polyvinyl acetate were next.

iii. Resin impregnation and shear strength

An interesting experiment examining the influence of adhesive on the strength of plywood has been done by Curry (16). Plywoods were made from veneers ranging in thickness from 1/10 inch to 1/50 inch, using phenol-formaldehyde resin and two other types of adhesive, and tested. It was found that when the veneer thickness was not less than 1/16 inch, the contribution of adhesive to the total strength of plywood was little. But for plywoods made from thinner veneers, the influence of adhesive became more significant. Neglect of adhesive influence could lead to considerable error when calculating strength values because of the structure of the wood being modified by the presence of adhesives. Though the penetration of adhesive had irregular and indefinite borders, ray tissue was deeply penetrated. A similar finding that the shear strength of wood was the deciding factor for shear strength of glue joint specimens was shown in a report by Marian and Stumbo (43).

Since wood is typically nonhomogeneous, whereas resin is strictly homogeneous, impregnating resin into it increased uniformity and thereby strength (61).

Strength properties of wood which had been resin impregnated, then compressed, were obtained by Stamm and

Seborg (63), and Dadswell and co-workers (17). The results showed that phenol-formaldehyde resin was effective in increasing the compressive and shear strengths, whereas toughness was decreased.

In Impreg (wood impregnated with resin but not compressed), treatment with synthetic resins was found to improve only the compressive strength properties parallel and perpendicular to the grain, and hardness, while ultimate tension parallel to grain, toughness and Izod impact strength were decreased. However, because of technical progress, and improved chemicals, greater toughness of treated wood has been obtained (27).

Solechnik and co-workers (60), on the other hand, found that bending resistance of wood impregnated with condensation products of phenol-formaldehyde resin was increased by 11-25%.

MATERIAL AND METHODS

A. Experimental Design

In this experiment, shear strength and per cent wood failure were evaluated in 12 treatments divided into three groups. Each treatment had 12 specimens randomly taken from 4 duplicate panels. The treatments were as follows:

GROUP A - Evaluation of shear strength for specimens having different depths of adhesive penetration into lathe checks in core veneers due to varying periods of adhesive impregnation.*

Treatment 1 - Conventional plywood made of rotary-cut veneers bonded by AMRES 2211 phenol-formaldehyde glue only.

Treatment 2 - Plywood made of rotary-cut veneer with 5-minute resin (No. 4880) impregnation of core veneer.

Treatment 3 - Plywood made of rotary-cut veneer with 10-minute resin impregnation of core veneer.

Treatment 4 - Plywood made of rotary-cut veneer with 30-minute resin impregnation of core veneers.

Treatment 5 - Plywood made of sawn veneer without resin impregnation, using AMRES 2211 glue only.

GROUP B - Evaluation of shear strength for specimens having resin-impregnated core veneer with failure forced by specimen design to occur in face ply.

Treatment 6 - Plywood made of rotary-cut veneer with tight-side of face ply being adjacent to fully resin-impregnated core veneer.

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* Hereafter, the word "resin" will refer to resin No. 4880. The term "glue" will refer to industrial use AMRES 2211. And "adhesive" will refer to either glue or resin according to the text.

Treatment 7 - Plywood made of rotary-cut veneer with loose-side of face ply being adjacent to fully resin-impregnated core veneer.

Treatment 8 - Plywood made of sawn veneer with fully resin-impregnated core veneer.

GROUP C - Evaluation of shear strength for specimens having resin-impregnated core veneer with failure forced to occur in core.

Treatment 9 - Plywood made of sawn veneer with core impregnated by methanol-resin mix, flattened and dried at 140°F. and bonded by glue.

Treatment 10- Plywood made of rotary-cut veneer with core impregnated by methanol-resin mix, and bonded directly into plywood.

Treatment 11- Plywood made of rotary-cut veneer with core impregnated by methanol-resin mix, flattened and dried at 140°F. and bonded by glue.

Treatment 12- plywood made of rotary-cut veneer with core impregnated by water-resin mix, flattened and dried at 140°F. and bonded by glue.

Analysis of variance and Duncan's multiple range test (41) were performed upon the data obtained.

B. Materials

1. Veneer collection

a. Log

A Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) log, 10.5 feet in length and about 23 inches in diameter, was chosen from the log-pond of the Pacific Veneer and Plywood Division, Canadian Forest Products Ltd., New Westminster. Its origin was Vancouver Island but the exact location was not known. A 6-inch long section was cut from one end of the log and later sawn into the tangential plane. The remaining 10-foot log was peeled on a commercial lathe.

B. Peeling and sawing

Before peeling, every tenth growth ring from the pith was clearly marked by india ink at each end of the log (Fig. 3). One quadrant of the 80- to 100-year part of the log was sprayed with blue paint to serve as a reference mark for subsequent sampling. Sawn and rotary-cut veneers were taken from this zone. Thus, the location and hopefully the properties of rotary-cut and sawn veneers were closely matched.

Peeling took place two hours and 15 minutes after the honing of the knife. According to the data available, the setting of the machine was as follows:

Peeling speed	170 fpm.
Knife angle	90 deg.
Horizontal gap	0.125 in.

The log was chucked at the pith. This enabled the longitudinal axis of veneer to be parallel to the grain direction. The resulting veneer was 1/7 inch in thickness.

Facilities of the Vancouver Forest Products Laboratory of the Canada Department of Forestry were used to saw the short log tangentially into sheets of 1/7-inch thickness and 4-by 6-inch surface dimension.

C. Selection and grouping of veneers

(1). Group A

Four 36-by 30-inch rotary-cut veneers taken from the end of the bolt adjacent to the log used for sawn veneer were sawn into strips of 6-by 24-inches along the grain (total of 6 strips). Four strips were randomly chosen to serve as core veneers. Each strip was sawn into four 6-by 6-inch veneers which were randomly assigned to four treatments. Hence, each treatment was applied to four veneers marked alphabetically. The other strips were also sawn into 6-by 6-inch veneers to be used later as face veneers.

Twelve 4-by 6-inch sawn veneers were randomly chosen. Four of them were used as core and eight as face plies. This assignment allowed each treatment to have 12 veneers to be made into 4 panels.

(2). Group B

Five consecutive parallel strips of 6-by 24-inch rotary-cut veneer were cut into 6-by 6-inch samples yielding a total of 20. Sixteen of these were randomly chosen and separated into two equal groups of 8 each. Both groups served as face plies, one to test the strength of tight-side of veneer, the other for test of loose-side. All 4-by-6-inch sawn veneers were chosen to be face veneers for test of shear strength of face ply. These three classes of material provided comparison with results of other treatments of rotary-cut veneers.

Eight 6-by 6-inch and four 4- by 6-inch samples of 1/10-inch thick sapwood veneers were taken from another tree to serve as cores of plywoods. In a preliminary test of this study these veneers had proved to be easily penetrated by the impregnating resin. This assignment allowed each treatment to have 12 veneers to be made into 4 panels, all of which would force failure upon stressing to occur in the face plies.

(3). Group C

Twelve 6-by 6-inch rotary-cut sapwood veneers from the long log were randomly selected from a pile of veneers which had been cut into consecutive parallel strips. They were separated into three equal groups of four veneers, and later used as core veneers for resin-impregnation.

Twenty-four rotary-cut veneers of the same dimensions as the core veneers were obtained from matched heartwood of the same log, and used as face plies. The above mentioned veneers were applied to Treatments 10, 11 and 12.

Samples for Treatment 9 were made of sawn veneers. Eight sawn sapwood veneers were taken and marked to indicate their position with respect to the cambium. They were then impregnated with resin. Four of them were selected for use as core veneers. The reason for this arrangement is described in sections iii and iv. Eight non-impregnated sawn veneers of heartwood were used as face plies. Again, this assignment allowed each treatment to have 12 veneers to be made into 4 panels.

ii. Staining

In order to render lathe checks easily observable, the peeled core veneers of Group A were submerged in about 0.5% by weight of Calcozine Rhodamin BPX solution (red) for 12 hours, then air-dried for two weeks.

Under microscopic observation, it was found that the dye penetrated to the tip of the lathe checks, but did not dispere into the wood surrounding the lathe checks. A preliminary test of this study showed that the presence of the dye had no effect on resin impregnation and gluing.

iii. Drying

After more than two weeks air-drying in the working room of the laboratory, the moisture content of veneer averaged 8.37%.

Veneers of all treatments were lightly sanded by hand to secure smooth surfaces which were then cleaned by a strong vacuum cleaner to remove fine wood particles that otherwise would hinder adhesion. Veneers were piled, supported by sticks between every tow veneers, and about 50 pounds of flat iron plates were placed on top of the pile to flatten them.

They were further dried in a small oven at 140°F for 6 hours. This temperature was used to minimize the degradation of wood strength which otherwise might result upon exposure to higher temperature. The consequent moisture content of veneer averaged 5.50% which was believed to be suitable for the resin impregnation process (61). A high moisture content might result in the moisture in the wood diffusing out of the veneer as the resin-forming material diffused in. As Stamm stated (61), this tends to dilute the resin. The volume of the resin increased so that eventually some had to be discarded.

The core veneers of Treatments 2, 3 and 4 in Group A, and of all treatments of Group B and Group C, were stored in a plastic bag and later dried with the core veneers soon after the latter were impregnated.

iv. Impregnation

Two phenol-formaldehyde resins, No. 4000 and No. 4880, obtained from Pacific Resins Ltd., New Westminster, B.C. were tested in a preliminary study to determine their feasibility for the purpose intended.

Resin specifications were as follows:

	Resin No. 4880	Resin No. 4000
Non-volatile fractions	63.3%	37.5%
Viscosity (Centistokes)	600	15
Specific gravity	1.202	1.135
pH	9.3	6.5-7.0

Resin No. 4000 was found to be more easily impregnated into the wood but, perhaps due to its short chain length, the resin did not hold the lathe checks strongly. Upon testing, the tension shear strength of treated plywood was found to be not significantly different from that of conventional, untreated plywood. Use of this resin was therefore abandoned.

Work was then concentrated on the use of resin No. 4880. Since the solids content of this resin was 63.3%, dilution was necessary. However, like most short chain phenol-formaldehyde resins (61), resin No. 4880 was not readily soluble in water at pH less than about 9. The resin was diluted by distilled water to 40% solids content. Three per cent of sodium hydroxide by weight was added to retain pH, 0.5% of Victoria blue dye by weight was added so that the cured resin could later be distinguished by stereomicroscope when within the lathe checks (lathe checks were indicated by red colour). The pH of the mixture, as indicated by a Beckman glass electrode pH meter, was 9.1, which proved adequate for the purpose of the experiment.

The core veneers of Treatments 2, 3 and 4 of Gromp A, all treatments of Group B, and Treatment 12 of Group C, were immersed into the resin one sheet at a time. Each veneer, suitably weighted, was placed vertically in the container. The container was then placed in a pressure cylinder and 90 psi air pressure was applied. Treatments 2,3 and 4 of Group A were kept in the cylinder for 5, 10 and 30 minutes, respectively.

This operation was expected to result in varying depths of resin penetration into lathe checks. Next, veneers were removed from the cylinder at the appropriate times and dried. Veneers of Group B and Treatment 12 of Group C remained in the cylinder and were impregnated for 20 hours. The per cent resin content of the veneers was determined on the oven-dry basis by comparison with three extra veneers which served as controls and which were checked visually by stereoscope at 20 X magnification. Resin contents after 20 hours impregnation were 29.0% to 31.5% of oven-dry weight of wood.* These per cent resin contents were considered sufficient to saturate the cell wall (61). Microscopic observation supported this.

In order to speed the time of impregnation and at the same time obtain a reasonable amount of resin in the wood, a better solvent was sought which could dilute the resin, allow its uniform distribution in wood substance, and dry fast. Methanol was found to be such a solvent. For colouring the resin, 0.5% by weight of Victoria blue dye was again added. The final solids content of the mixture was again made to 40%. Core veneers of Treatments 9, 10 and 11 were treated. Three hours was found to be long enough for impregnating sapwood veneers from the outer part of the stem. Ease of resin impregnation was observed to decrease with an increase in the distance of wood substance from the cambium.

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* (Weight of impregnated veneer after drying - oven-dry weight of veneer)/ oven-dry weight of veneer X 100

In order to completely impregnate all the veneers, time of impregnation was prolonged to 5 hours. This enabled the veneer to have a resin content of 20-22% of its oven-dry weight. Again, this was confirmed by microscopic observation.

Together with core veneers of the other treatments and all face veneers, the impregnated veneers, with the exception of Treatment 10, were placed in the oven and dried at 140°F. for 36 hours. This temperature and time for drying was chosen firstly because the boiling point of methanol is 148°F. (64.5°C.). If the drying temperature were higher than 148°F. the boiling of the solvent would expel the resin from the cell walls. Secondly, final setting of the resin was expected to be done in a hot press at a temperature of 300°F. Thirdly, 36 hours drying at this temperature would not degrade the strength of Douglas-fir wood (58). Two parallel sticks were placed between the veneers as they were stacked. Several heavy iron plates were placed on the top to flatten the veneers.

After drying, the moisture content of both impregnated and non-impregnated veneers averaged 2.02%.

C. Plywood Panel Construction

AMRES 2211 phenol-formaldehyde glue was used in the major part of the experiment for bonding panels. The adhesive was mixed and applied according to the manufacturer's specification. Except for core veneers of Treatment 10, which were not oven-dried, all the oven-dried impregnated veneers were lightly sanded a second time to provide a smooth surface, and cleaned by a strong vacuum cleaner.

The glue was uniformly spread on all veneers, with the exception of core veneers of Treatment 10, to ensure a spread of 50 pounds per thousand square feet per double glue line. Veneers of alternating grain directions were carefully arranged so that face plies were exactly perpendicular to their respective centre ply.

Use of methanol as solvent for resin might directly enable assembling impregnated veneers into plywood without the drying process prior to the application of heat and pressure. An attempt was made to determine the feasibility of this hypothesis. Impregnated veneers of Treatment 10 were exposed to room temperature for 30 minutes before application of the AMRES 2211 glue. At the same time, the face veneers were spread with the glue on their loose-side and allowed to stand for 10 minutes. Results of this preliminary experiment proved that veneers could be strongly glued using a pressing time the same as that of conventional plywood, which is normally 5 minutes.

Treatment 6 was designed to test shear strength parallel to grain in plywood where the tight-side of face veneer was arranged to be in contact with the core veneer. The assembled veneers were pressed at 150 psi and 300^{o}F. Temperature at the glue-line was measured by a portable potentiometer and time recorded when constant temperature was reached. It was found that 5 minutes was sufficient for plywood of core-dried veneer, and five and one-half minutes for cores of Treatment 10, where the sudden boiling of methanol in the centre ply was clearly visible.

Immediately upon leaving the hot press the panels were stacked in a thermostatically controlled oven (212°F.) for one hour, then placed in another oven at 140°F. for 24 hours. The purpose of this "hot stack" was to cool the plywood gradually and to allow complete curing of glue-lines. The panels were then kept in the laboratory for two weeks before sampling.

D. Preparation and Test of Specimens

i. Sample size

Since tests of tension shear were conducted on a Table Model Instron Tester, it was necessary to consider the maximum loading capacity of the machine (50 Kg) in determining sample size. In a preliminary study, different sizes of samples were tested to find a suitable one. A width of about 0.2 inch was chosen, with the length between two notches depending on treatments. For Groups A and B, length was about one inch, and for Group C about 0.5 inch. If specimens of Group C were not trimmed to 0.5 inch in length (between two notches), failure in the core for samples of Treatments 9 and 12 was impossible to obtain because of the resin-strengthened core veneer.

ii. Trimming of samples and measurements

Four panels of each treatment were cut into sample of sizes described above. The depth of notch was two-thirds of the core veneer thickness with the arrangement of lathe checks to be pulled open (5, 22), as shown in Fig. 2. This is believed to be the most sensitive method to test rolling shear of plywood. Twenty-four samples were randomly chosen. Half were used for test when specimens were dry and the other half for test after boiling. The procedure for preparation of the latter was according to the CSA standard 0121-1961 (10).

> "Shear specimens ...shall be boiled in water for 4 hours, then dried for 20 hours at a temperature of 145 ± 5°F. They shall be boiled again for a period of 4 hours and tested while wet."

iii. Measurements of lathe checks, adhesive penetration depth and angle of lathe checks

The end sections of each sample were lightly sanded using a belt sander. This enabled the stained part of wood to be observed and provided higher accuracy in measurement of dimensions.

The linear dimensions of samples were taken to an accuracy of 0.001 inch using a micrometer caliper.

A stereomicroscope (5 X magnification) was used to measure veneer thicknesses, depth of lathe checks, depth of glue penetration (Treatment 1) and resin penetration (Treatments 2, 3 and 4) and to estimate per cent wood failure. The depth of lathe checks and of the penetrations were measured perpendicularly from the deepest point of lathe check and that of the penetrations to the glue-line (48). As mentioned above, lathe checks had been stained by Calcozine Rhodamine BPX (red), resin was coloured by Victoria blue and the colour of glue was black (Fig. 13). Therefore, depth of checks and that of the penetrations were easily identified.

In Group A, depth of each lathe check between the notches was "read" to give average depth. Veneer thickness was obtained by averaging three readings of core veneer thickness in each sample. In order to relate the depth to veneer thickness, the average depth of lathe check was divided by vener thickness to give a per cent depth of lathe check. The depth of adhesive penetration was divided by the depth of lathe check to give per cent depth of adhesive penetration (Table V).

Inclination of lathe check was obtained by measuring with a transparent protractor the angle of the three longest lathe checks to the glue-line. The recorded values were averaged to represent the lathe check inclination of the sample and are shown in Table V.

iv. Testing

All tests were performed with the same Table Model Instron Testing instrument. For accuracy, the test pieces were carefully aligned parallel to the axis of loading. The grips holding the sample were uniformly tightened by means of a torque-wrench set for 60 foot-pounds for dry samples and 35 foot-pounds for wet samples, which prevented the crushing of specimens before and during testing.

Load was applied with a continuous motion of the moveable crosshead at a rate of 0.02 inch per minute. Load was recorded automatically throughout the test on a chart. The ultimate load, load to unit strain within the proportional limit, and ultimate strain are available from this record (Fig. 4).

v. Estimation of wood failure and position of failure

The per cent wood failure of broken specimens was evaluated by two methods: (1) the conventional way, which is defined as being an estimate of the amount of wood fibre adhering to the surfaces of a fractured glue joint, expressed as a percentage of the total joint area, and (2) in measuring the position within an annual increment, in relation to its initiation, at which failure occurred, recorded as a per cent of the width. Amount of wood failure in this position was also estimated and expressed as a percentage of the total joint area. The estimation was done under a stereomicroscope at a magnification of 20 X.

E. Photographic Technique

In order to take photographs of the development of failure in plywood during loading, a SAS Asahi Pentax camera was placed in front of the loading side of the Instron machine. An extensible bellows unit was attached to the camera to magnify the object, with the lens focused on the critical shear area of the sample (Fig. 4). For the purpose of observing the whole critical area, the distance between the two notches was shortened to about 0.4 inch. When the sample was placed in the machine and before application of load, the first photograph was taken for reference. As soon as the machine started, the effect of tension stress and strain on the sample was observed through the viewer. When a slight change was observed, the pen of the recording chart and the movement of loading arms were stopped. This avoided the vibration of the machine influencing the camera. The photograph was then taken and a number was marked on the stress-strain curve as a reference point of the photograph being taken (Fig. 5 to 12). A sequence of photographs was taken until the sample failed.

A preliminary study was done to observe the effect of stopping the machine during test, since such action permitted stress relaxation and a possible alteration in the ultimate point of failure. The study showed that the stress-strain curves and shear strengths obtained in tests during which the machine was stopped for about 5 seconds were similar to results obtained in an uninterrupted test, hence the effect of these interruptions was ignored in this study.

RESULTS

A. Shear Strength

The shear strengths of various groups and treatments were found to be significantly different (Tables I, II). Since the results of Group C gave data that varied greatly between treatments, a direct comparison of the strength of groups is not considered reasonable. Instead, the strength of specimens made of lathe-check-free sawn veneer from each group (i.e., Treatment 5 from Group A, Treatment 8 from Group B and Treatment 9 from Group C) were compared (Tables III, IV). The analyses of variance showed that the average strength of Treatment 5, Group A was significantly lower than that of Treatments 8 and 9 from the two other groups, whereas that of Treatment 9, Group C was not significantly different from Treatment 8, Group B, in the dry condition.

The variations between treatments of each group are as follows:

i. Group A

The differences of depth of resin penetration into lathe checks in Treatments 1 - 4 and differences of shear strength in all treatments were found to be highly significant (Tables VI, VII and VIII).

As shown in Table V, average depths of adhesive penetration into lathe checks were 16, 47, 88 and 97% for Treatments 1, 2, 3 and 4 respectively. Average shear strengths were 252, 280, 343, 356 and 343 psi for Treatments 1, 2, 3, 4 and 5 respectively.

Regardless of the fact that the lathe checks of Treatment 1 were penetrated by glue only and those of Treatments 2, 3 and 4 were penetrated by resin, a mathematical relationship between penetration depth and shear strength of specimens was computed. This was done because it is believed that since either the glue or the resin can hold lathe checks strongly during load, their relationship to the strength of specimen is the same. This relationship was found to be highly correlated as shown by the linear equation for the dry condition (Fig. 5).

$$Y = 228.22 + 1.28052\ X \quad (SE_E = 21.82;\ r = 0.893)$$

where Y = shear strength and

X = penetration depth as per cent of depth of lathe check.

The average strength values obtained from tests of wet specimens followed the same pattern as those of dry specimens; they were 133, 175, 236, 226 and 229 psi, respectively, for Treatments 1, 2, 3, 4 and 5 (Table VIII).

ii. Group B

As previously stated, this group was designed to test the shear strength parallel to the grain in untreated face plies and for evaluating the possibility of developing a strong resin-impregnated core plywood, The results indicated that the average shear strengths of Treatments 6, 7 and 8 were 557, 506 and 544 psi in dry test, and 370, 347 and 382 psi in the boil test, respectively. Analyses of variance showed that there were no significant differences between the treatments in either test (Table IX and X).

For dry tests, the shear strengths of this group were significantly higher than those of any treatment of Group A. Average strengths of Group B are about two to three times as high as those for Treatments 1 and 2, and 1.5 times as high as Treatments 3, 4 and 5.

iii. Group C

This Group differed from Group A and Group B in that two different solvents were used to impregnate resin into the core veneer in order to obtain a strong resin-wood complex. Also, the samples were designed to fail in the core veneer.

The average shear strengths of the specimens of Treatments 9, 10, 11 and 12 were 589,156,376 and 530 psi, respectively, in dry test. The analyses of variance showed that there were highly significant differences between treatments (Table XI). Treatment 9 was significantly higher than Treatments 10 and 11 at the 1% level, and Treatment 12 at the 5% level.

Average wet strengths of Treatments 9, 10, 11 and 12 were 291,125,187 and 267 psi, respectively. Treatments 9 and 12 were not significantly different but were higher than Treatments 10 and 11 at the 1% level. Treatment 11 was higher than Treatment 10 at the 5% level (Table XII).

B. Per Cent Wood Failure

i. Group A

Average per cent wood failures estimated by the conventional method did not show significant differences (Table XIII). They were 94, 96, 89, 94 and 96%, respectively, for Treatments 1 to 5. Positions of failure within an annual increment were found to be 7, 5, 6 and 7% for Treatments 2 to 5 respectively. Their differences were not significant (Table XIV).

The average per cent wood failures occurring in these positions were 63, 75, 80 and 95% for Treatments 2 to 5, respectively. The analysis of variance showed that Treatment 5 (sawn veneer plywood) was significantly higher in per cent wood failure at the 1% level than Treatment 2, and Treatment 3 at the 5% level, but not significantly different from Treatment 4 (Table XV).

ii. Group B

The position of failure within an annual increment was found to be inconsistent from sample to sample. Average per cent wood failures estimated by the conventional method were 84, 79 and 80% for Treatments 6, 7 and 8, respectively. Their differences were not significant (Table XVI).

iii. Group C

The per cent wood failure in this group was found to be significantly different between treatments. The order of magnitude of the data were 97, 95, 76 and 62% for Treatments 10, 11, 12 and 9, respectively (Table XVII).

C. Photographic Evidence

Photographs of plywood samples made of sawn veneers, rotary-cut veneers with lathe checks fully penetrated by resin, and non-impregnated rotary-cut veneers were satisfactory. The setting of camera and testing apparatus are shown in Fig. 4. The stress-strain curves and the points at which the photographs were taken are shown in Fig. 6, 7, 8, 10, 11 and 12. The photographs of all test specimens after failure are shown in Fig. 13.

DISCUSSION

The study of Group A was designed to compare the shear strength of rotary-cut veneer specimens having lathe checks in core veneer partially or fully penetrated by adhesive, with the specimens made of sawn veneer. Consequently, tensile shear strengths of Group A specimens depend mainly on the shear resistance perpendicular to the grain of wood. Group B was designed to evaluate shear resistance of specimens with the core veneer fully impregnated by resin and where failure was forced to occur in a face ply. Therefore, the strengths of specimens in Group B depended on shear resistance parallel to the grain of wood. On the other hand, Group C was designed for evaluation of shear strength of specimens having resin impregnated core veneer, with failure forced to occur in the core, so that strengths of this group depended solely on the combination of resin and wood.

Hence, the order of magnitude of shear strength as shown by Table III is considered reasonable. From this, it is clear that the hypothesis of this thesis is sound. That is, plywood made of resin impregnated core veneer and untreated face veneers can be a product having shear strengths about 1.5 times as high as that of sawn-veneer plywood, and two to three times as high as that of conventional plywood made of rotary-cut veneer.

Further discussion of variations within groups is included below.

A. Influence of Lathe Checks on Shear Strength

The assumption which leads to the theoretical analysis of failure in lap joints was given by Volkersen in 1938 (18). According to him, the distribution of shear stresses in the adhesive layer arises solely from differential straining in the lap joint. This hypothesis was modified by Goland and Reissner in 1944 (24). They stated that tearing stresses, which were ignored by Volkersen, should be taken into account. Baud (72) employed an isotropic model of plywood test specimen which traced the stress distribution by photoelastic means. Thereby, he confirmed that tearing or tensile stresses exist normal to the plane of the glue joint in the vicinity of the notch. In this region, shear components occur in the plane of the glue joint. However, the main portion of the test section is subjected only to tensile and compressive stresses. Consequently, the plane of the glue joint is free of shear stress. Similar results were reported by Ishihara and co-workers (33).

Further application of a strain-indicating brittle lacquer to wood and wood-glue combinations were investigated by Yavorsky and Cunningham (71). They found that a large component of shear existed in the plane of the core veneer of three-ply specimens. The presence of stress concentrations at the notches was demonstrated by the formation of initial cracks in these areas at low loads, whereas the central region was free of cracks until considerable load had been applied.

Any imperfection in veneers will therefore cause a reduction of tensile shear resistance in plywood. This can be seen from the photograph of sawn veneer plywood in this experiment.

In Fig. 6, photograph 2, the first crack occurred in the upper notch. The stress-strain curve (Fig. 6) indicated that the sample was stressed just over the proportional limit at that point. Instead of the crack opening, a defect between the notches was pulled open by continuous loading (photograph 3). Soon after, the ultimate strength was reached and the sample failed suddenly in the zone located within 10% from the initiation of an annual increment. Later, the defect noted above was observed under stereomicroscope, on the end surface, and identified as ray tissue. It is known that ray is the weakest tissue of wood when load is applied in the direction perpendicular to grain in the radial face (68). The defect might be due to the separation between rays and prosenchyma in drying, where latewood prosenchyma of high potential shrinkage is in contact with rays of relatively small radial shrinkage potential (28.56).

The occurrence of wood failure in earlywood was found in shear (43), transverse compression (7) and bending (36) tests. But this is the first report of shear failure occurring within an annual increment in the zone located within 10% of its initiation. This was reported as that region having maximum lignin content in an annual increment of Douglas-fir (70).

Results for the plywood made from normal rotary-cut veneer (Fig. 7 and Fig. 8) were completely different from those of sawn veneer plywood (Fig. 6). The fine black declined lines in the core veneers of these figures are the red lathe checks in samples 7 to 9 of Fig. 13. Photographs 2 of Fig. 7 and Fig. 8

showed no cracks in the face veneers in vicinity of the notches, but the lathe checks had opened slightly. When this occurred, the final rupture stress was reached. Photograph 3 showed that the real wood failure started at that point. All this evidence indicates that lathe checks definitely reduce shear strength of plywood.

A comparison between the stress-strain curves of plywood from sawn and rotary-cut veneers (Fig. 9), showed that the former failed abruptly soon after maximum stress was reached whereas the latter had a long elongation in the specimen. This might be caused by the opening of lathe checks which divided the critical area and resulted in the formation of several flows of stress in this area (1).

The extent to which lathe checks influence failure was demonstrated by the results of Group A. Analyses of variance showed that differences in shear strength between treatments of Group A were highly significant (Tables V, VII and VIII). Treatment 1 (conventional plywood) gave significantly lower results than did any other treatment; whereas differences between Treatments 3, 4 and 5 were not significant, they were significantly higher than Treatment 2 (Table VII). This could be explained as being due to the varying penetration depths of adhesive into lathe checks in the core veneers. It was observed that the penetration depth of glue into lathe checks of conventional plywood (Treatment 1) was 16% (Tables V and VI) of the average depth of lathe checks. This indicated that the load area was decreased by about 55%* so that other 45% of the area was subjected to full load.

The penetration of adhesive into lathe checks of Douglas-fir heartwood was difficult. Even when using a short chain resin, and impregnating under 90 psi air pressure for 5 minutes, as in Treatment 2, the penetration depth of resin was less than half the lathe check depth. This is explained in the following way:

(i) Nature of veneer. The curved nature of lathe checks, and the shear type of lathe checks (Fig. 1) which were concealed deep in the veneer and therefore non-accessible to adhesive, should be considered.

(ii) Effect of pH of wood. The pH of mixed commercial phenol-formaldehyde is about 12, but that of Douglas-fir heartwood is only 3 to 4.5. It was found (13) that the pH of both film and liquid phenolic resin decreased with increasing assembly time. High veneer moisture contents accentuated the decrease.

According to stamm (61),the decrease of pH causes reduced solubility and glue transfer. It is understandable that, since pH of Douglas-fir is so low, when the glue is spread its pH will rapidly decrease. This is provided that the rough surfaces at the entrances of lathe checks may absorb some amount of glue (6) and the excessive depth of lathe checks can alter the proportion between the amount of glue and the surface area of lathe checks. Consequently, the buffering

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* $\frac{\text{\% depth of lathe checks}}{100}(100 - \text{\% depth of adhesive penetration})$

potential of wood is sufficiently great to overpower the pH of glue (44). The viscosity of glue greatly increases and no further penetration occurs.

(iii) Influence of extractives. The effect of extractives on glue bonds has been explained by Huffman (32), who stated:

> "The extractives may act as deterrents to adequate penetration of the fluid adhesive, they may retard the dissipation of water or other solvents from the glue line, and their chemical composition may act as a barrier to proper wetting or to the formation of molecular bonds". "kiln drying resulted in concentrating the extractives in the outer layers".

Hancock (29) found that in the case of Douglas-fir veneer treated at high temperature, fatty acids concentrated at the surface, reducing the wettability of veneer. This chemical barrier will no doubt slow the penetration rate and depth of glue.

These influences, and the effect of high temperature of the hot press, accelerated the loss of water and polymerization of glue. The possibility of glue further penetrating into lathe checks is thus greatly reduced.

As mentioned above, there is a highly significant linear relationship between the depth of adhesive penetration into the lathe checks (X) and the shear strength (Y), such that:

$$Y = 228.22 + 1.28052\ X.$$

The depth of resin penetration and shear strength in Treatment 2 were significantly higher than those of Treatment 1. Similarly for Treatments 3 and 4, which had similar strengths, the depth was about two times higher than Treatment 2, and five to six times higher than that of Treatment 1. It is interesting to note that shear strength of Treatments 3 and 4 were not significantly different (Tables VII and VIII), but the penetration depth of the latter was significantly higher than that of the former (Table VI). This could be interpreted as follows: When the penetration depth was beyond 80% the shear strength of plywood made of rotary-cut veneer remained unchanged and no different from that of plywood made of sawn veneers (Tables VII and VIII).

The relationship between penetration depth and shear strength can also be observed from the photographic results. Figure 10 shows that the lathe checks were completely held by resin, so that failure occurred in the face ply. From photograph 3 of the same Figure it may be implied that the face failure may have been due to the resin strengthening the center ply, by the slight angle between the load axis and the sample causing misalignment of sample (2), or by defect in the face ply. Figure 11 demonstrated that when a crack occurred in the vicinity of the notches (photograph 3), the specimen was already over the proportional limit. When the shear lathe check* was slightly opened, the maximum stress was reached. The sample then failed suddenly in the critical area through the earlywood and the broken shear lathe check.

Figure 12 shows the response of sample to the load when the lathe checks and other defects were completely held by resin. A small crack was shown near to the upper notch in

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* Shown by red color in NO. 5 sample of Fig. 13, its position in photograph A, NO. 5 is indicated by an arrow, while in photograph B, the red color is visible.

the face ply (Fig. 12, photograph 2) at which stage the specimen was stressed over the proportional limit. Complete failure occurred at the initiation of one annual increment. The resin was so strong that the course of breaking had passed or deviated around the tip of glue. As a result the stress-strain curves of plywood made from sawn veneers, and rotary-cut veneers with lathe checks fully impregnated by resin, were similar.

B. Influence of Lathe Checks on Wood Failure

Differences in average per cent wood failure in various treatments of Group A as estimated by the conventional method were not significant (Table XIII). However, the character and position of the failure in Treatment 1 (conventional plywood made of rotary-cut veneer) varied greatly from that of Treatments 3, 4 and 5 (plywood made of veneer with lathe checks completely impregnated by resin and plywood made of sawn veneer). In Treatment 1, the wood broke between the tips of the lathe checks in core veneer. The wood gradually rolled open after the ultimate strength was reached. But in Treatments 3, 4 and 5, failure occurred suddenly in the beginning of earlywood.

From this it can be seen that the per cent wood failure of plywood made of rotary-cut veneer was not intimately related to the ultimate strength. Instead, the per cent wood failure occurring within one or more annual increments in the zone located within 10% from its initiation gave a better indication of ultimate strength. This position in the annual ring was found to have the lowest tensile strength (69) and compression strength (31) in Douglas-fir. Analysis of variance showed that average per cent wood failure of sawn veneer plywood (Treatment 5) in this region was significantly higher than in Treatment 2 and Treatment 3, but not significantly different from Treatment 4 (Table XV). This result clearly indicated that wood with no lathe checks and wood with lathe checks highly impregnated by resin resulted in higher per cent wood failure.

C. Influence of Rotary-cutting on Shear Strength and Wood Failure in Tight-side and Loose-side of Veneer

A statistical analysis of results showed that there were no significant differences either in shear strength or wood failure among all treatments of Group B. This finding indicated that at the normal industrial lathe settings, veneer is not stressed beyond the proportional limit. However, the position of wood failure within the annual ring was no longer in the beginning of earlywood, which was varied from specimen to specimen.

The shear strength of Group B samples averaged over 500 psi in dry test (Table 1). This is much lower than comparable data from various sources (9,67). According to Stamm and Seborg (63), and Stieda (64), shear values are highly dependent upon the method of testing. Data, therefore, are not comparable unless the method used and size of specimens are identical.

Results of this experiment indicate a new finding: that even if the specimens do not fail in core veneer, tension shear strength of plywood made from resin impregnated core veneer and non-impregnated face veneers, will be two to three times as high as that of conventional plywood made of comparable rotary-cut veneers.

D. Influence of Resin Impregnation on Shear Strength and Per Cent Failure of Core Veneer

Two things have now become clear. First, the area of wood within an annual ring least able to resist stresses is in the zone located within 10% from its initiation. Second, the shear strength of latewood of Douglas-fir is greater than, or at least equal to, that of phenol-formaldehyde glue-line. Therefore, as shown by this experiment, there is no doubt that the application of resin to strengthen earlywood, as in Treatments 9 and 12, will increase shear strength of the wood. Average strength in dry test of Treatments 9 and 12 were 588 and 530 psi, respectively. These figures were not significantly different from the average strengths of Group B, but were significantly higher than results for Treatments 10 and 11, and Treatment 5 (plywood made of sawn veneer without resin-impregnated core veneer).

The per cent core veneer failure, however, was higher in Treatments 10 and 11 than in 9 and 12 (Table XVII).

A question arises in that, since resin should remedy the lathe defect, why were there significant differences in shear strengths between Treatments 9, 10, 11 and 12? An explanation is given below:

(i). The highest strength in Treatment 9 was due, firstly, to the methanol-mixed resin being uniformly distributed in the wood tissue and, secondly, to the sawn veneer having minimum defects. Therefore, failure in the core veneer was only 62% by standard wood failure estimation procedures.

(ii). Samples of Treatment 12 were made from rotary-cut veneers, and hence contained many lathe checks. Through microscopic observation, it was found that lathe checks were firmly held, but the distribution of resin in the wood was not as even as in the samples of Treatment 9. These factors were believed to account for the strength values of Treatment 12 being lower than those of Treatment 9.

(iii). It is interesting to note that the specimens of Treatment 10 have the lowest shear strengths but highest wood failure values. This experiment indicated that direct assembly was possible. Because the boiling point of solvent was too low (145°F.) in comparison with the hot press temperature (300°F), pressing time was shortened to that used in making conventional plywood. Even so, rapid boiling of methanol expelled resin from the wood and also pushed the lathe checks open. This resulted in core-impregnated plywood being weaker than untreated plywood (Treatment 1).

The cyclic boiling process (10, 55) could also have caused weakening of the wood. After samples were exposed to the first cycle of boiling and drying at 145°F.for 20 hours, most of the lathe checks in Treatment 1 were opened wide. Continuous boiling and drying subjected the samples to the stresses of shrinking and swelling, consequently the lathe checks were enlarged, resulting in further decrease of loaded area. In Table 1 it is shown that the shear strength of boiled samples of Treatment 1 was similar to that of Treatment 10. Here, lathe checks had been already opened by methanol when the plywood was made.

(iv). The strength of samples from Treatment 11 in dry test was equal to, or higher than, that of Treatments 3, 4 and 5 of Group A, but lower than that of Treatments 9 and 12. From observation of the manner and per cent wood failure, this was believed due to several lathe checks in specimens not being strongly held when the plywood was made. It is also possible that the setting of the oven-temperature was too high (140° F.) for drying the methanol-resin mix. If this is so, the fast evaporation or boiling of methanol from wood would cause the larger lathe checks to open. Another reason might be that the viscosity of methanol-diluted resin was rather low, and did not hold the larger defects.

The order of magnitude of shear strength in the boil test in treatments of every group was similar to that of the dry test. Unexpectedly, the values of Treatments 9 and 12, which were highest in dry test, were much lower than the average of Group B, and Treatments 3, 4 and 5 of Group A. These results are of doubtful value. The relatively degraded strength was thought due to the critical area in the samples of Group C being trimmed to one-half that of Group B. During boiling, the dimension of impregnated core veneer was almost constant, but the untreated face veneers tended to swell. This mutual action between core and face plies weakened the wood and glue transition zone (43). Consequently, in tension shear specimens which were alternately dried and wetted, the smaller the critical area the higher the stress concentration in this area will be . This is proved when examining the tested specimens of treatment 9, which showed that failure occurred in the wood and glue transitions.

It is highly possible that methanol can be used as a solvent for resin impregnation of sawn veneer. For rotary-cut veneer, if a method of fast drying the solvent at low temperature can be developed, a strong product can be obtained by direct assembly. This offers considerable commercial possibilities. Otherwise impregnation as in Group B would be required.

CONCLUSIONS

1. The presence of lathe checks caused the tension shear strength of plywood made of rotary-cut veneers to be lower than that made of sawn veneers. Shear strength of conventional plywood with an average of 16% depth of glue penetration into lathe checks was only about 70% that of plywood made of sawn veneers in dry, and about 60% in wet, condition.

2. In plywood made of sawn veneer, cracking occurred in the vicinity of one notch, indicating that the specimen was stressed beyond the proportional limit. Ultimate strength

was reached when sudden failure occurred in earlywood of an annual ring.

3. During loading, cracking did not occur in the vicinity of the notch, but opening of lathe checks in the critical areas was observed in conventional plywood made of rotary-cut veneer. Ultimate strength was reached when lathe checks were just opening.

4. When all lathe checks were completely impregnated with resin, shear strength and manner of failure of plywood were not different from that of plywood made of sawn veneer. Shear strength increased about 40% as a result of this treatment.

5. Shear strength was highly influenced by depth of adhesive penetration into lathe checks. Relationship between these two factors is linear. When core veneer was fully impregnated by resin, shear strength of sawn-veneer plywood was about 1.5 times as high as that of untreated plywood.

6. There was no significant difference in the per cent wood failure as estimated by conventional method, for plywood made from rotary-cut and from sawn veneer. Use of photography illustrates that relating per cent wood failure to shear strength is more meaningful in plywood made of sawn than that of rotary-cut veneers.

7. The weakest plane to resist shear stress in sawn veneer was found to be in the zone within 10% of initiation of an annual increment. Application of per cent wood failure occurring in this area, for evaluating the strength of plywood, is considered a more sensitive means than use of conventional methods of estimation; i.e., an estimate of the amount of wood fibers adhering to surfaces of a fractured glue joint regardless of position of failure in an annual increment.

8. It was found highly feasible to employ medium chain length phenol-formaldehyde resin, with methanol as solvent, to strengthen the earlywood portion of veneers. Advantages of this process are:

(i) a product with high strength properties results, and

(ii) veneers can be directly assembled into plywood with the same hot press period as that of conventional plywood.

However, it must be noted that the influence of lathe checks limits the application of this technique to plywood of rotary-cut veneer. If a method of fast drying of methanol from impregnated wood at low temperature could be obtained, a strong product could be produced by direct assembly.

9. Shear strength parallel to grain of the tight-side and loose-side of rotary-cut veneer, obtained by test of standard tension shear specimens, showed no significant difference.

This result indicated that plywood made of resin impregnated core veneer, and untreated face veneers, can be a product having shear strengths two to three times higher than that of conventional plywood.

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Table I. Summation of average shear strengths and per cent wood failures

Group	Treatment	Number of specimens	Shear strength dry test psi	dry test S.D.	boil test psi	boil test S.D.	Conventional Wood failure* %	Remarks
A	1	12	252	20	133	14	94	* Dry test only
A	2	12	280	17	175	14	96	
A	3	12	343	23	236	24	89	S.D. Standard
A	4	12	356	21	226	18	94	deviation
A	5	12	343	34	229	26	96	
B	6	12	557	82	370	34	84	
B	7	12	506	78	347	47	79	
B	8	12	544	83	382	45	80	
C	9	12	589	65	291	38	62	
C	10	12	156	46	125	49	97	
C	11	12	376	65	187	33	95	
C	12	12	530	56	267	31	76	

56

Table II. Analysis of variance: Average shear strengths in Groups A, B and C (dry test).

Source	Degrees of freedom	Sum of squares	Mean square	F	
Groups	2	1108500	554250	183.74	**
Treatments	9	1458400	162050	53.72	**
Error	132	398170	3017		
Total	143	2965070			

** Significant at the 1% level

Table III A. Analysis of variance: Average shear strengths in Treatments 5, 8 and 9 of Groups A, B and C, respectively (dry test).

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatments	2	411157	205578	50.34 **
Error	33	134744	4083	
Total	35	545901		

** Significant at the 1% level

Table III B. Duncan's multiple range test: Average shear strengths in Treatments 5, 8 and 9 of Groups A, B and C, respectively (dry test).

Groups	A	B	C
Treatments	5.	8.	9.
Means (psi)	343	544	589

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table IV A. Analysis of variance: Average shear strengths in Treatments 5, 8 and 9 of Groups A, B and C, respectively (boil test).

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	2	141668	70834	7.32	**
Error	33	319458	9681		
Total	35	461126			

** Significant at the 1% level

Table IV B. Duncan's multiple range test: Average shear strengths in Treatments 5, 8 and 9 of Groups A, B and C, respectively (boil test).

Groups	A	C	B
Treatments	5.	9.	8.
Means (psi)	229	291	382

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table V. Summation of averaged data of Group A

Treatment	Lathe Checks			Penetration depth[1]		Shear strength		Wood failure			
	Number (per in.)	Angle (deg.)	Depth (%)	(%)	S.D.	Dry test (psi)	Boil test (psi)	A[2] (%)	B[3] (%)	C[4] (%)	D[5] (%)
1	14	56	66	16*	9	252	133	94			
2	13	54	65	47**	8	280	175	96	63	7	1.9
3	15	55	64	88**	7	343	236	89	75	5	1.5
4	14	55	66	97**	3	356	226	94	80	6	2.4
5						343	229	96	95	7	3.0

1. Penetration depth of adhesive into lathe checks.

   * by AMRES glue only ** by resin No. 4880 only S.D. Standard deviation

2. Conventional wood failure

3. Wood failure occurring in C (see page 28)

4. Position of wood failure in an annual increment from its initiation

5. Standard deviation of C

Table VI A. Analysis of variance: Average penetration depths of adhesive into lathe checks in Treatments 1 to 4, Group A.

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	3	50078.0	16693.0	301.7	**
Error	44	2434.3	55.3		
Total	47	52512.0			

** Significant at the 1% level

Table VI B. Duncan's multiple range test: Average penetration depths of adhesive into lathe checks in Treatments 1 to 4, Group A.

Treatments	1.	2.	3.	4.
Means (%)	16	47	88	97

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table VII A. Analysis of variance: Average shear strengths in Treatments 1 to 5, Group A (dry test).

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatments	4	101540	25384	44.84 **
Error	55	31136	566	
Total	59	132670		

** Significant at the 1% level

Table VII B. Duncan's multiple range test: Average shear strengths in Treatments 1 to 5, Group A (dry test).

Treatments	1.	2.	5.	3.	4.
Means (psi)	252	280	343	343	356

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table VIII A. Analysis of variance: Average shear strengths in Treatments 1 to 5, Group A (boil test).

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatments	4	95204	23801.0	59.96 **
Error	55	21831	396.9	
Total	59	117035		

** Significant at the 1% level

Table VIII B. Duncan's multiple range test: Average shear strengths in Treatments 1 to 5, Group A (boil test).

Treatments	1.	2.	4.	5.	3.
Means (psi)	133	175	226	229	236

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table IX. Analysis of variance: Average shear strengths in Treatments 6 to 8, Group B (dry test).

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	2	16459	8229.7	1.26	NS
Error	33	216070	6547.6		
Total	35	232529			

Table X. Analysis of variance: Average shear strengths in Treatments 6 to 8, Group B (boil test).

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	2	7475	3737.6	2.08	NS
Error	33	59288	1796.9		
Total	35	66763			

NS Non-significant

Table XI A. Analysis of variance: Average shear strengths in Treatments 9 to 12, Group C (dry test).

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	3	1340400	446810	130.22	**
Error	44	150970	3431		
Total	47	1491400			

** Significant at the 1% level

Table XI B. Duncan's multiple range test: Average shear strengths in Treatments 9 to 12, Group C (dry test).

Treatments	10.	11.	12.	9.
Means (psi)	156	376	530	589

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table XII A. Analysis of variance: Average shear strengths in Treatments 9 to 12, Group C (boil test).

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatments	3	208210	69403	46.99 **
Error	44	64981	1477	
Total	47	273190		

** Significant at the 1% level

Table XII B. Duncan's multiple range test: Average shear strengths in Treatments 9 to 12, Group C (boil test).

Treatments	10.	11.	12.	9.
Means (psi)	125	187	267	291

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table XIII. Analysis of variance: Average per cent wood failure by conventional methods in Treatments 1 to 5, Group A.

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	4	386.1	96.53	1.62	NS
Error	55	3279.8	59.63		
Total	59	3665.9			

Table XIV. Analysis of variance: Average position of wood failure in an annual increment from its initiation in Treatments 2 to 5, Group A.

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	3	37.06	12.354	2.42	NS
Error	44	224.75	5.108		
Total	47	261.81			

NS Non-significant

Table XV A. Analysis of variance: Average per cent wood failures occurring in earlywood* in Treatments 2 to 5, Group A.

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	3	6254.1	2084.7	5.05	**
Error	44	18147.0	412.4		
Total	47	24401.0			

** Significant at the 1% level

Table XV B. Duncan's multiple range test: Average per cent wood failures occurring in earlywood* in Treatments 2 to 5, Group A.

Treatments	2.	3.	4.	5.
Means (%)	63	75	80	95

* Within 10% of an annual increment from its initiation.
Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Table XVI. Analysis of variance: Average per cent wood failures by conventional methods in Treatments 6 to 8, Group B (These are all of Group B).

Source	Degrees of freedom	Sum of squares	Mean square	F	
Treatments	2	145.5	72.75	0.48	NS
Error	33	4999.5	151.50		
Total	35	5145.0			

NS Non-significant

Table XVII A. Analysis of variance: Average per cent wood failures by conventional methods in Treatments 9 to 12, Group C.

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatments	3	10114.0	3371.2	17.98 **
Error	44	8250.1	187.5	
Total	47	18364.0		

** Significant at the 1% level

Table XVII B. Duncan's multiple range test: Average per cent wood failures by conventional methods in Treatments 9 to 12, Group C.

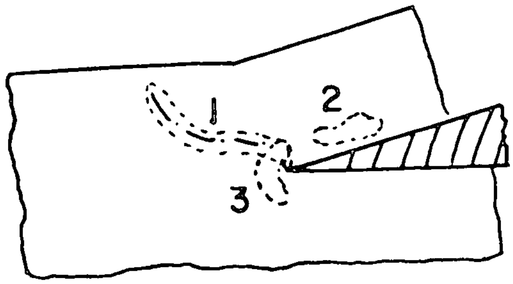
Treatments	9.	12.	11.	10.
Means (%)	62	76	95	97

Any two means not underscored by the same line are significantly different. Any two means underscored by the same line are not significantly different.

Zone 1. Tension

Zone 2. Shear

Zone 3. Compression tearing

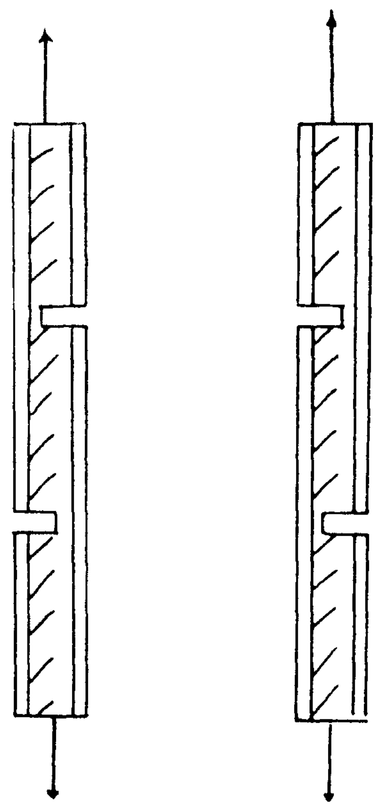


(From Koch, P. 1964. Wood machining processes. The Ronald Press Co., New York. p. 445.)

Fig. 1. Critical zones of stress in veneer cutting without a nosebar.

A Specimen cut to pull open.

B Specimen cut to pull closed.



A B

Fig. 2. Lathe check orientation in plywood shear test specimens.

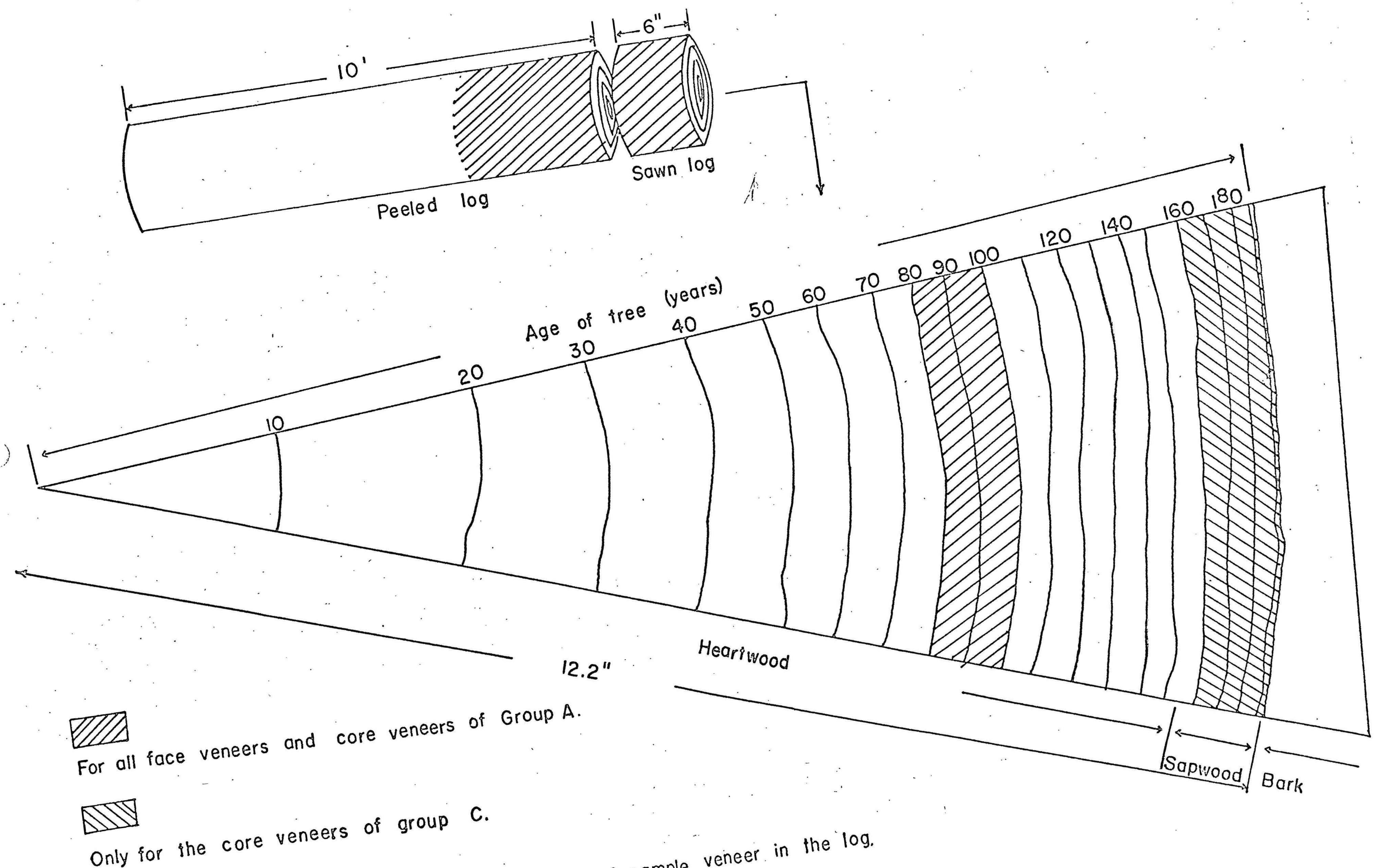


Fig. 3. Position of sample veneer in the log.

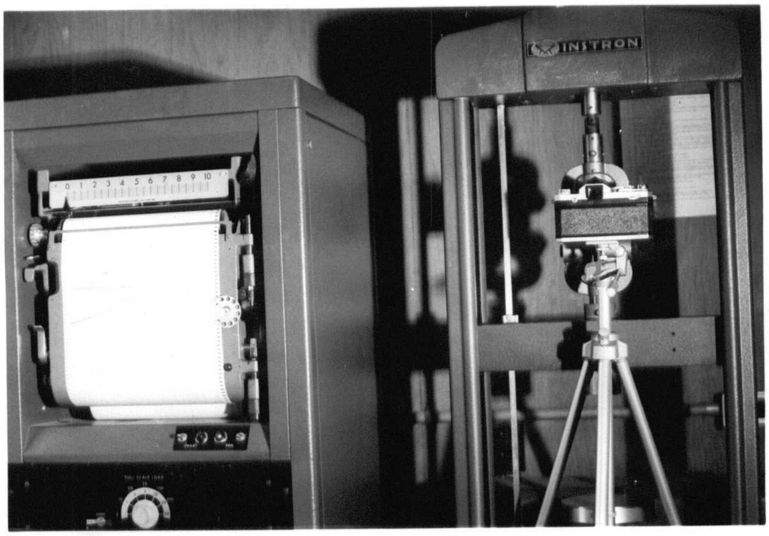


Fig. 4. Camera setup and testing apparatus

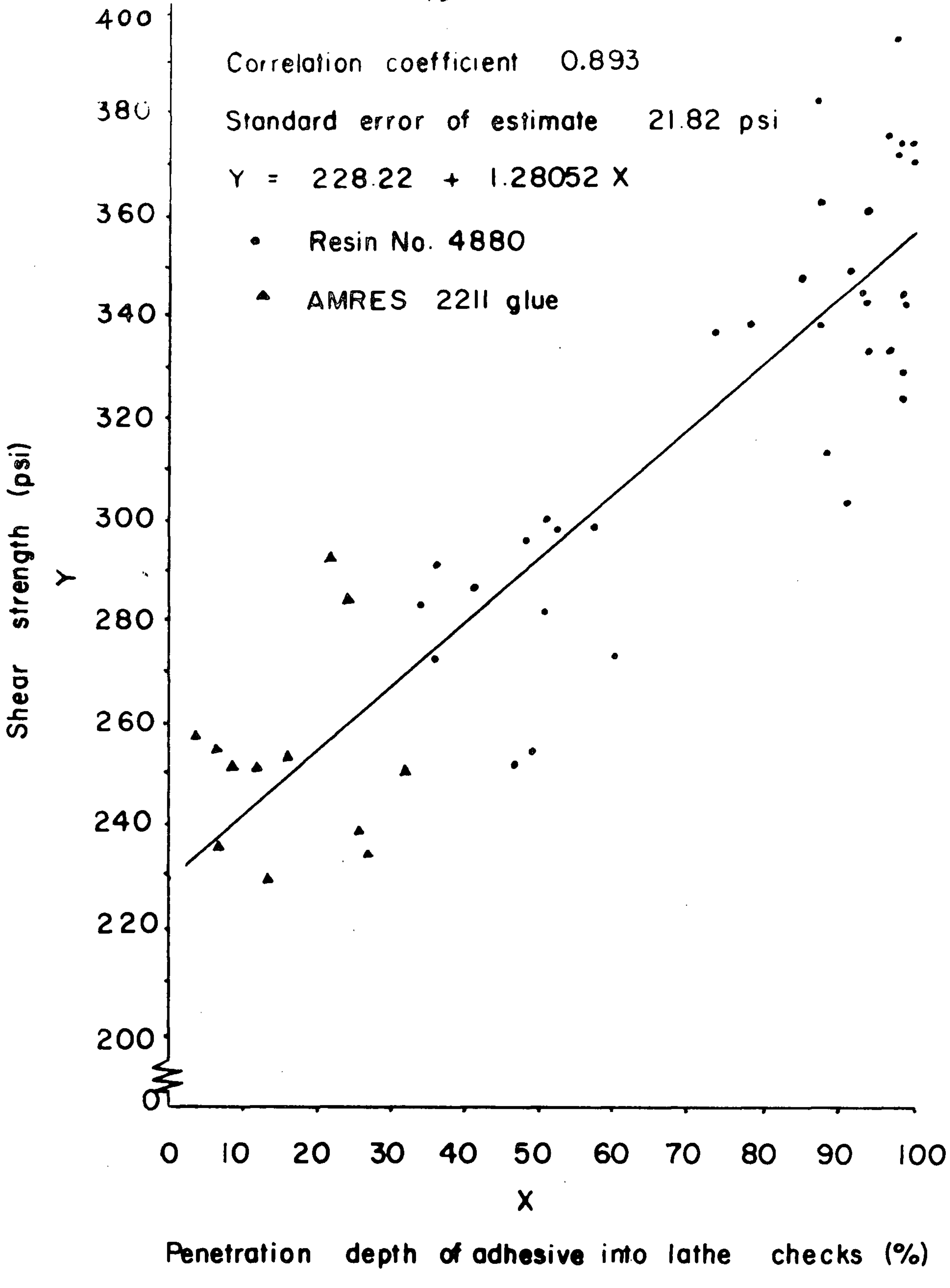


Fig. 5. Relationship between shear strength of plywood and penetration depth of adhesive into lathe checks.

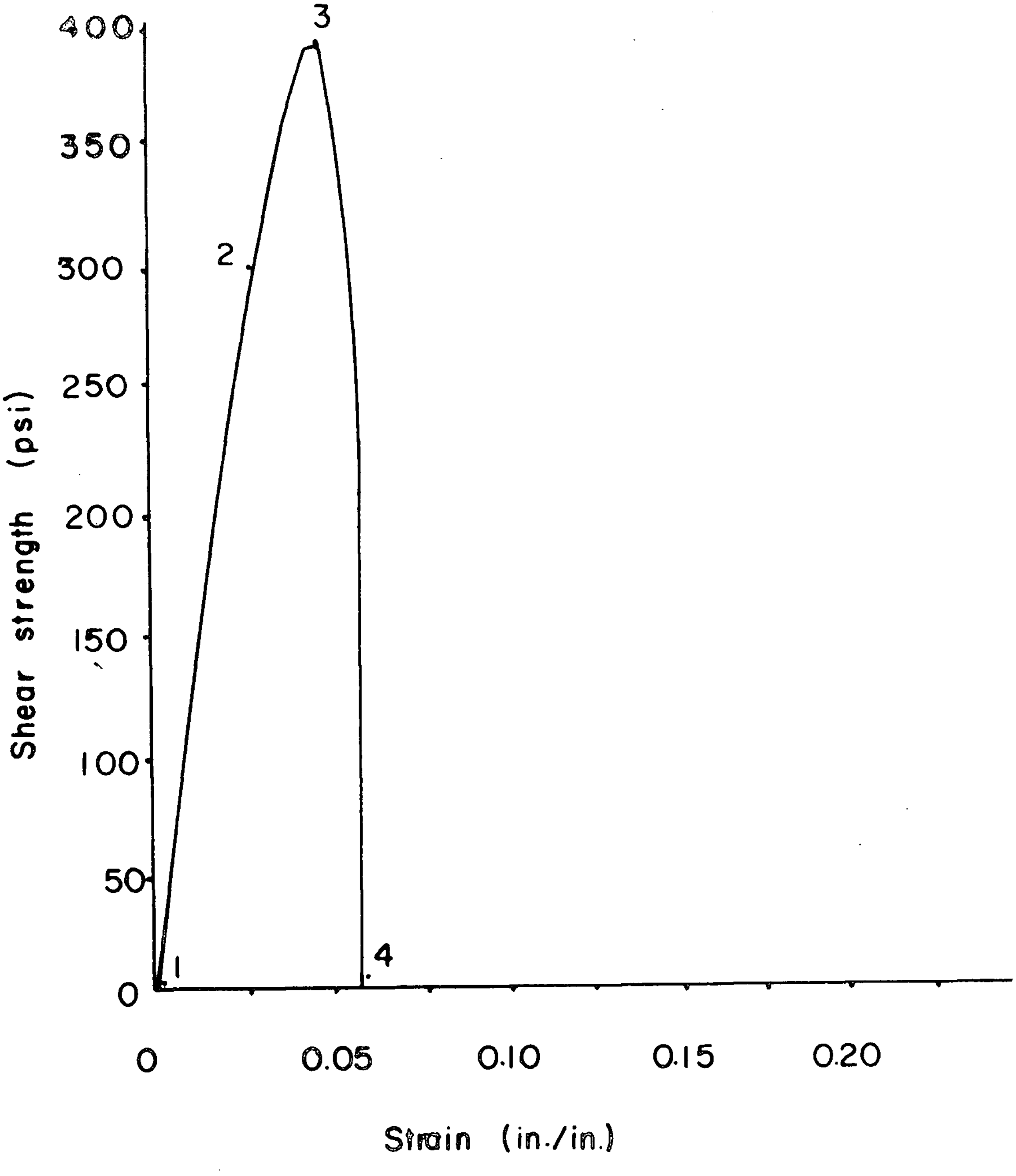


Fig. 6. Stress-strain curve for plywood made of sawn veneer, with accompanying photographs at the positions noted --Treatment 5.

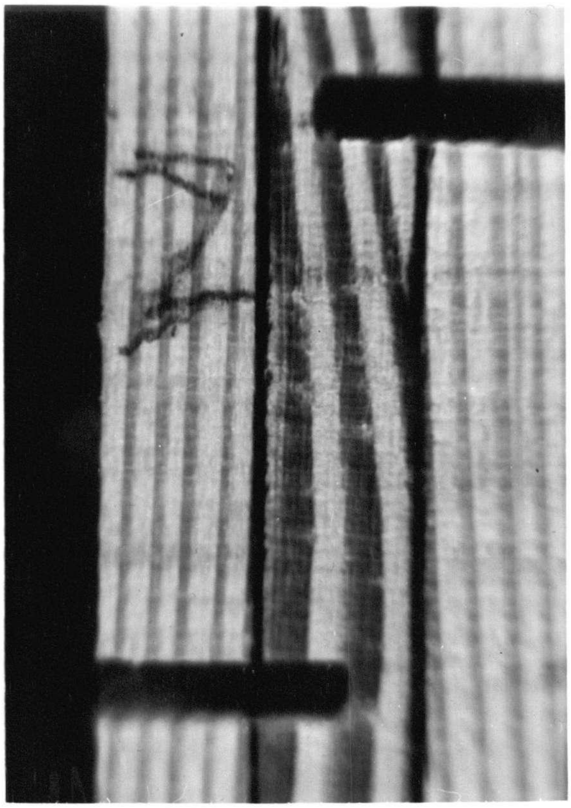


Fig. 6 - Photograph 1

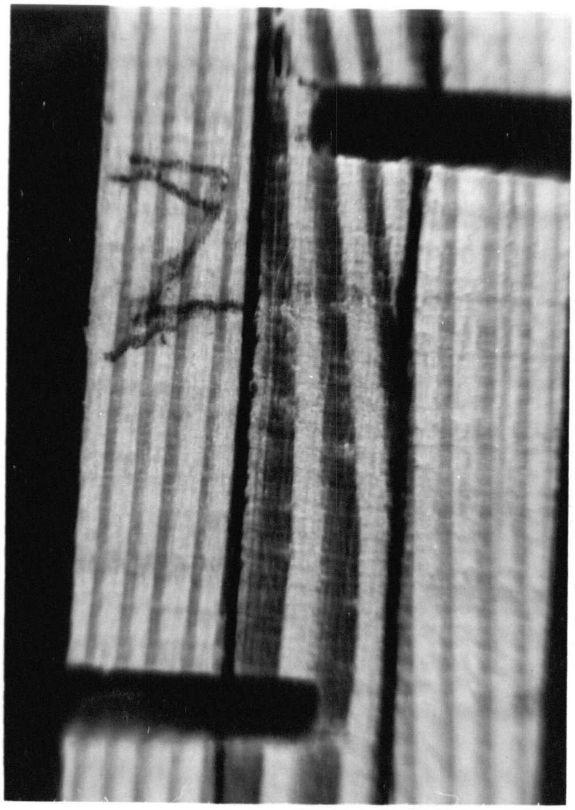


Fig. 6 - Photograph 2

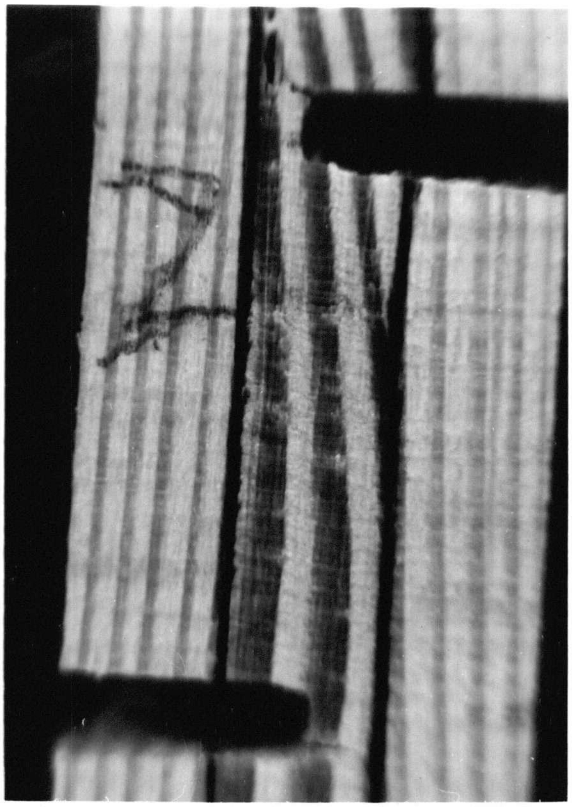


Fig. 6 - Photograph 3

Fig. 6 - Photograph 4

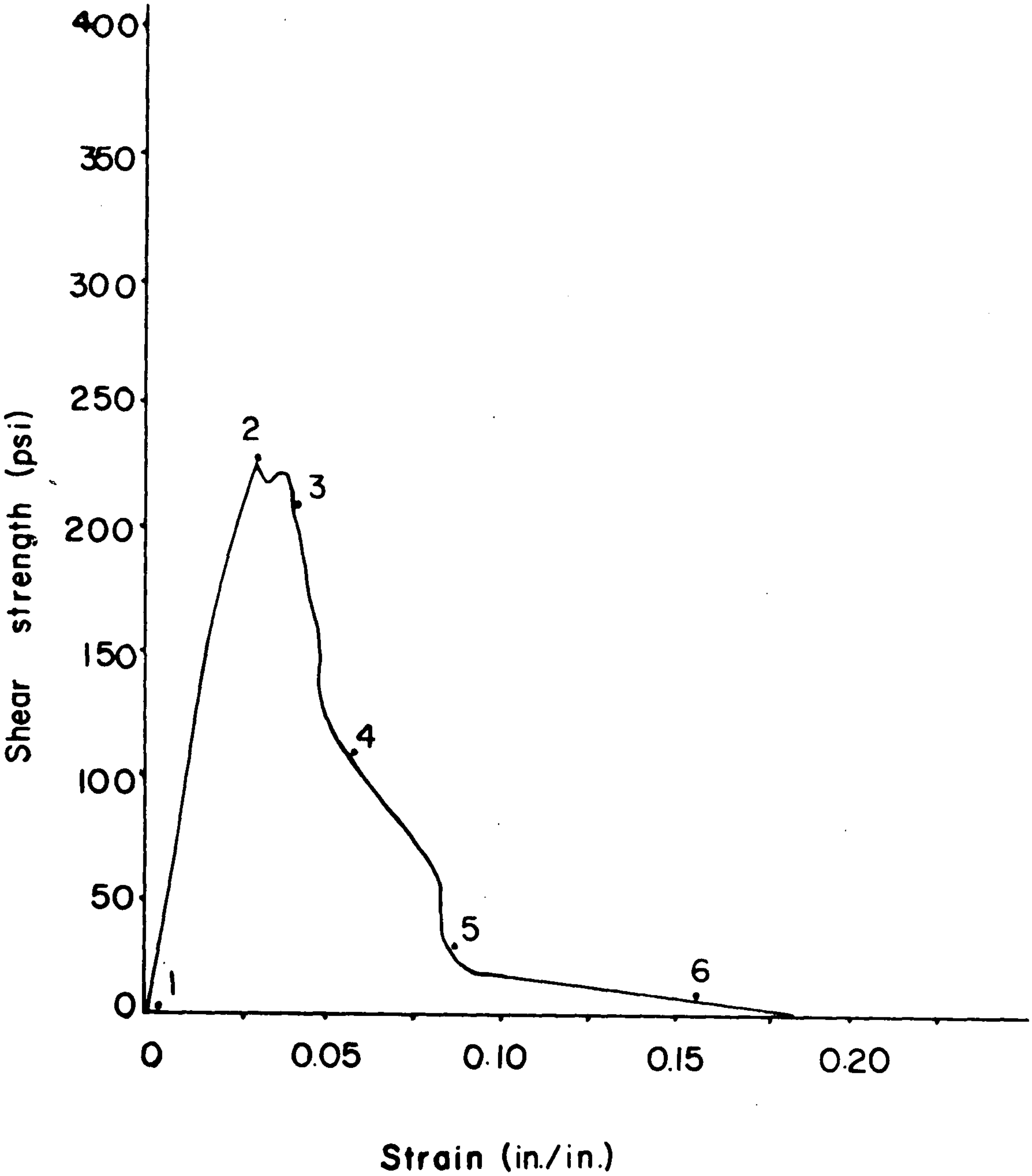


Fig. 7. Stress-strain curve for plywood made of rotary-cut veneer, with accompanying photographs at the positions noted (Sample 1). --Treatment 1.

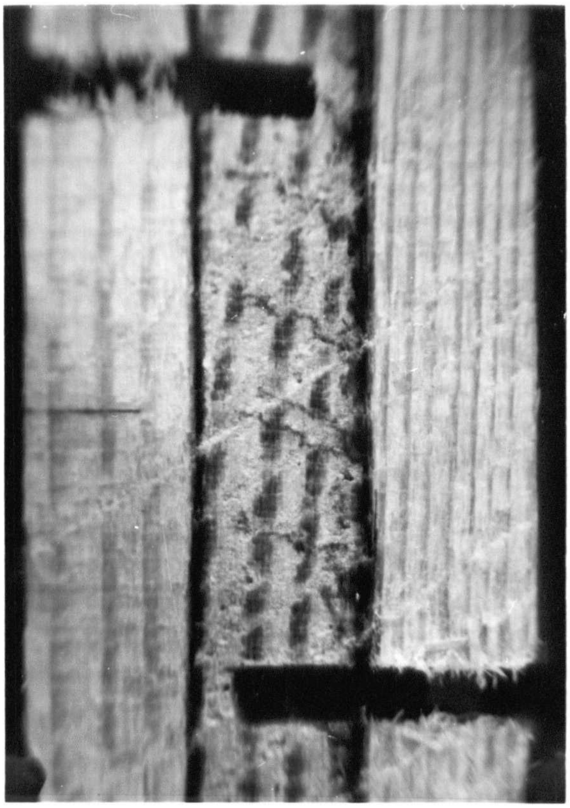


Fig. 7 - Photograph 1

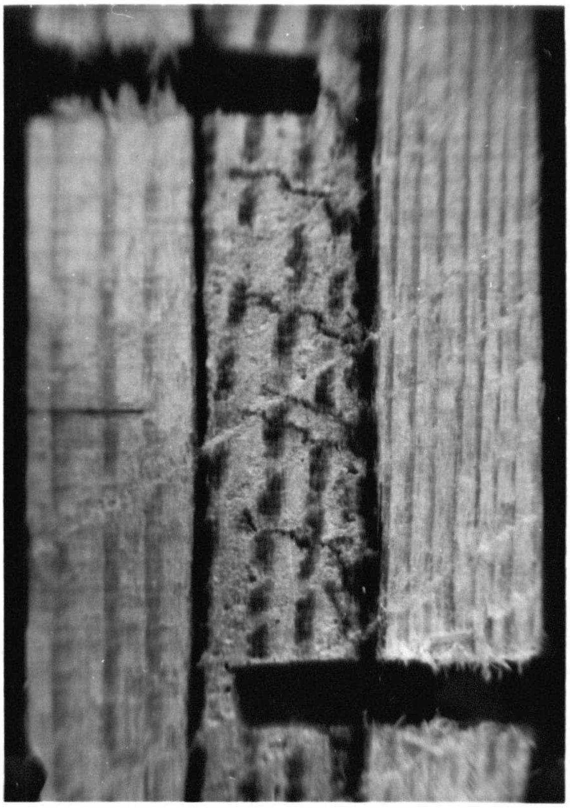


Fig. 7 - Photograph 2

Fig. 7 - Photograph 3

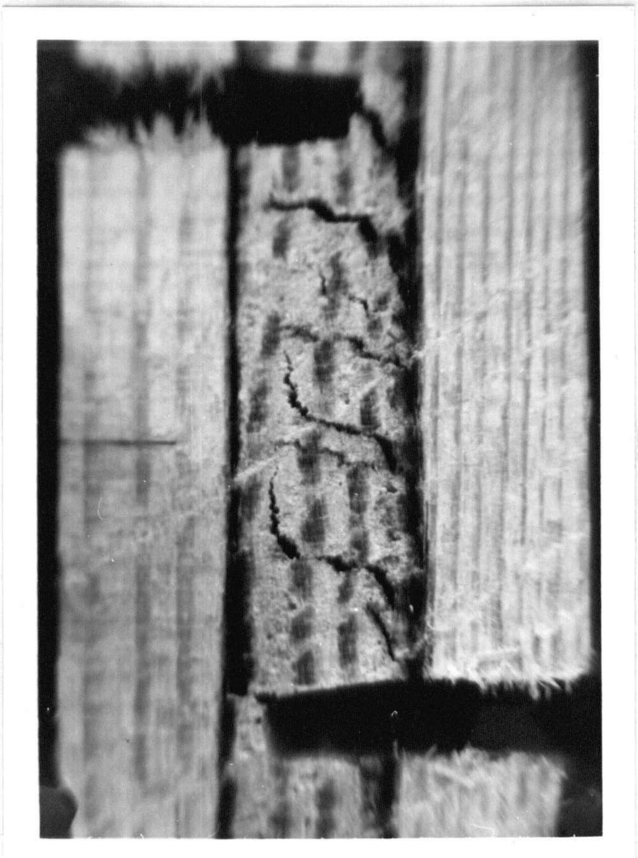


Fig. 7 - Photograph 4

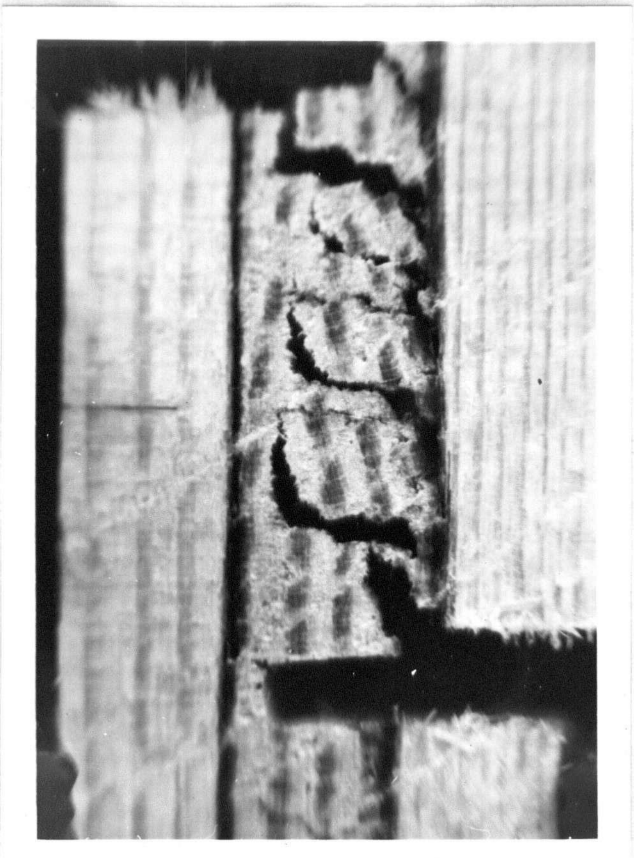


Fig. 7 - Photograph 5

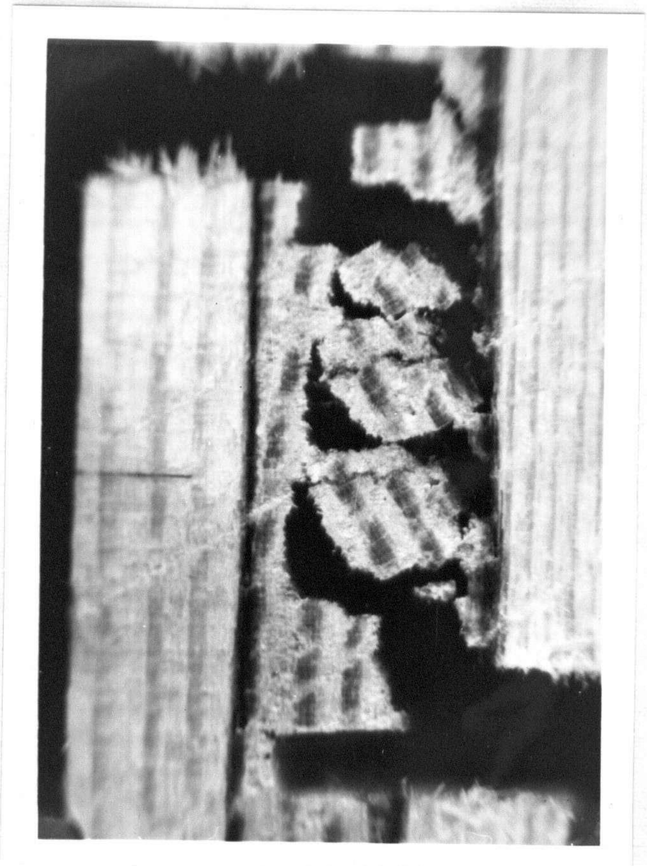


Fig. 7 - Photograph 6

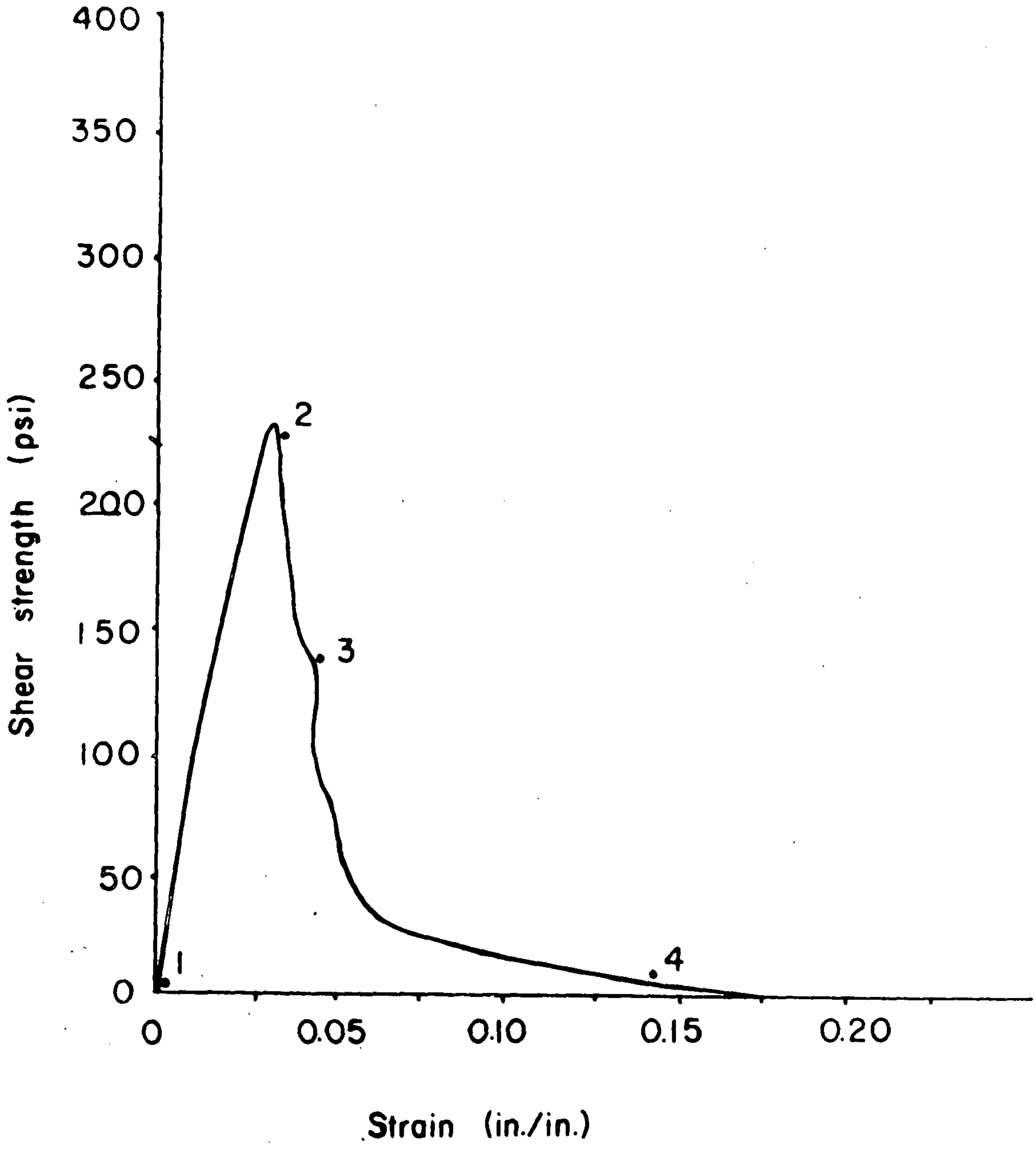


Fig. 8. Stress-strain curve for plywood made of rotary-cut veneer, with accompanying photographs at the positions noted (Sample 2). --Treatment 1.

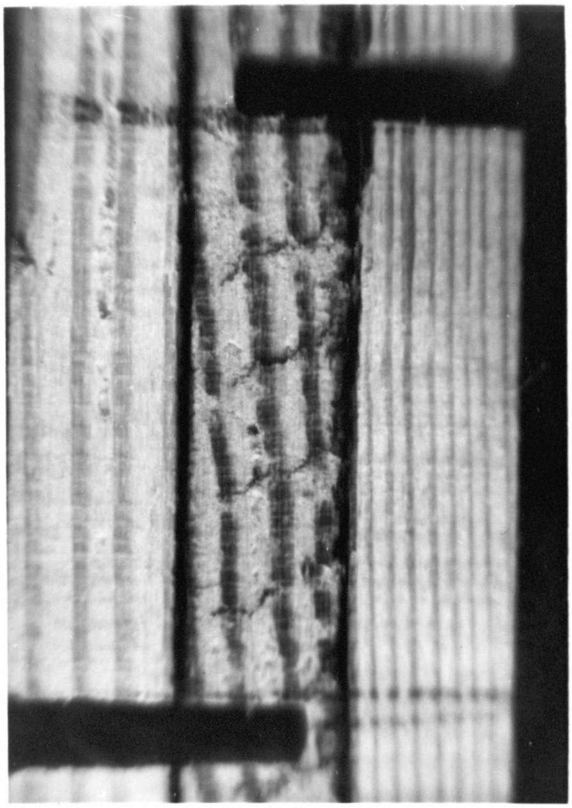


Fig. 8 - Photograph 1

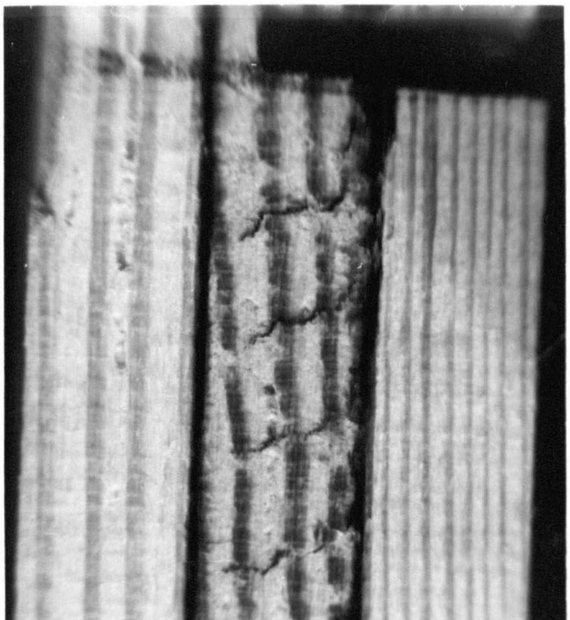


Fig. 8 - Photograph 2

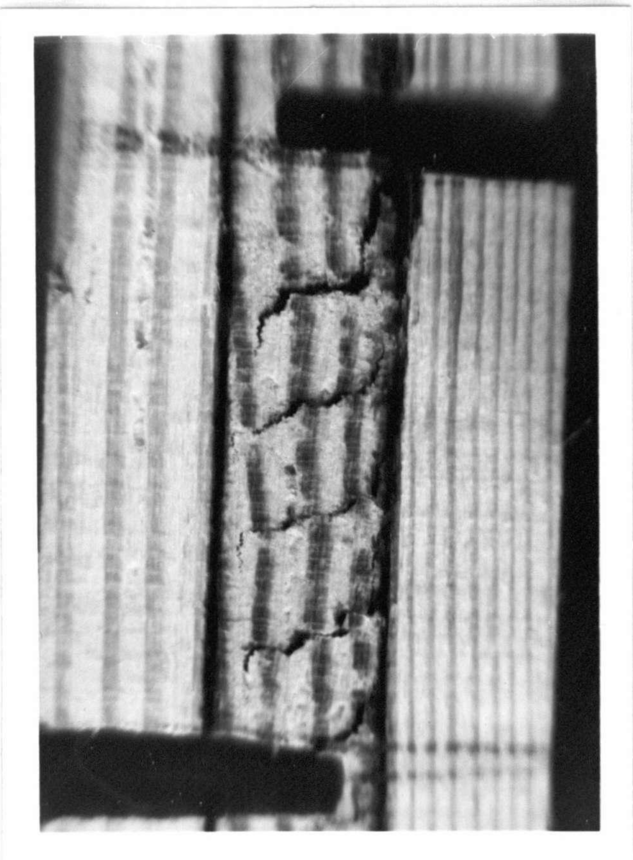


Fig. 8 - Photograph 3

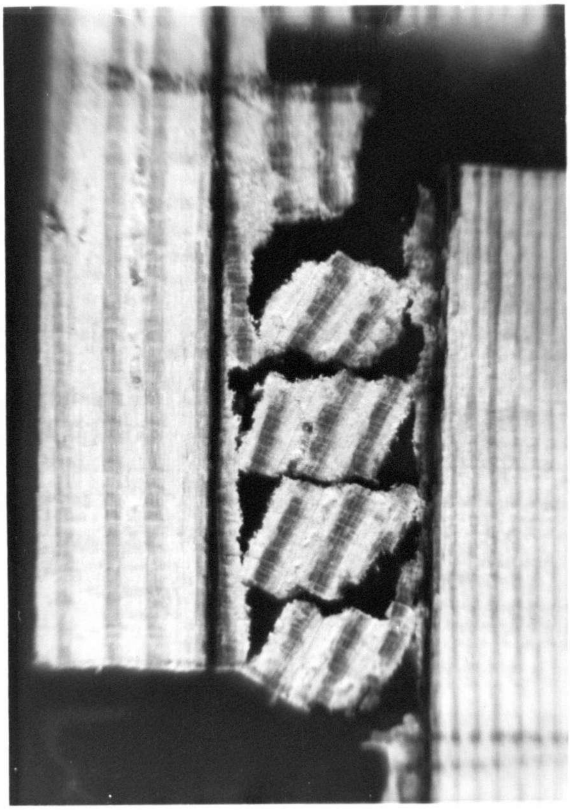


Fig. 8 - Photograph 4

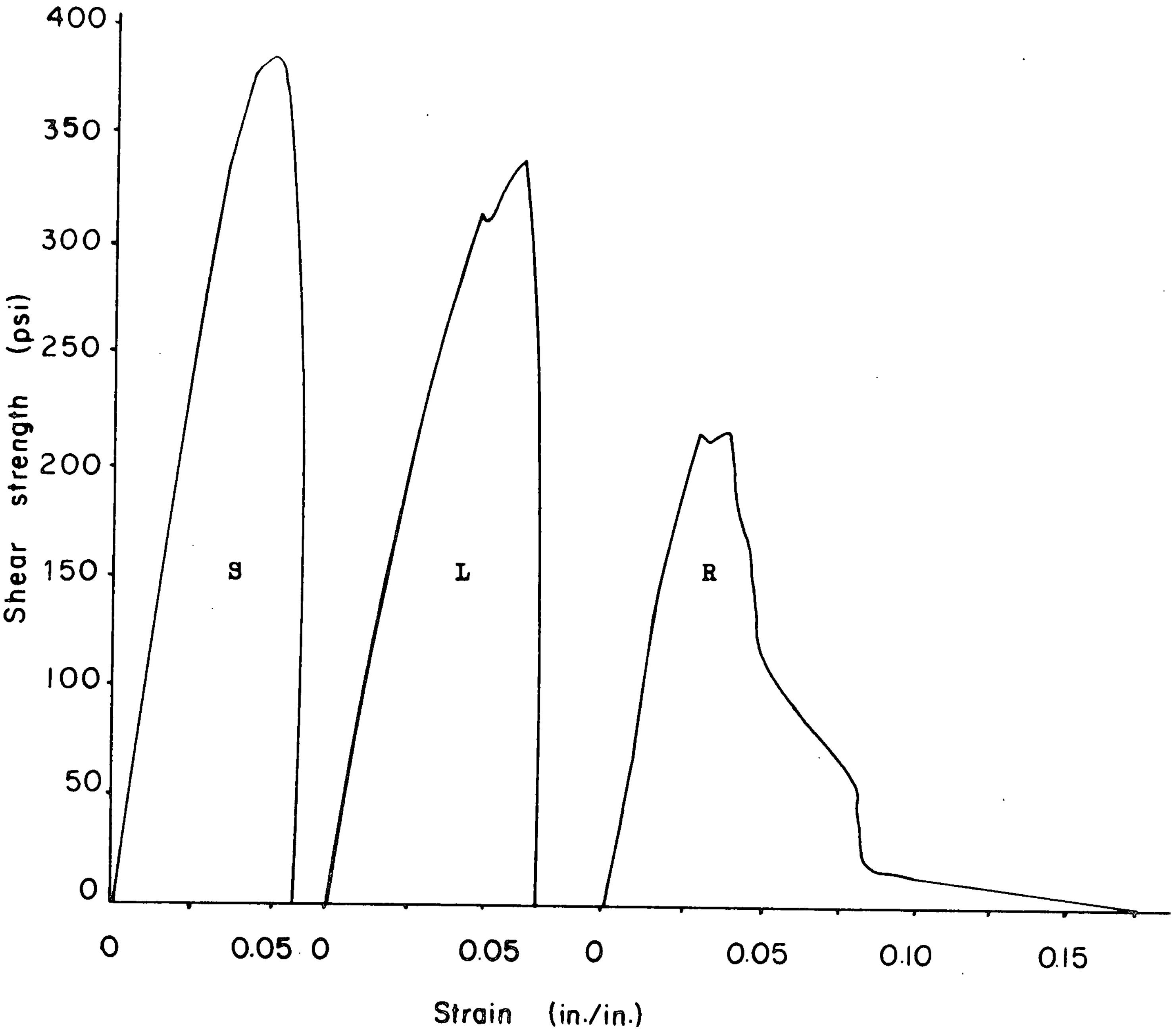


Fig. 9. Comparison of stress-strain curves for plywoods made of sawn veneer (S), rotary-cut veneer with lathe checks fully impregnated by resin (L), and rotary-cut veneer (R).

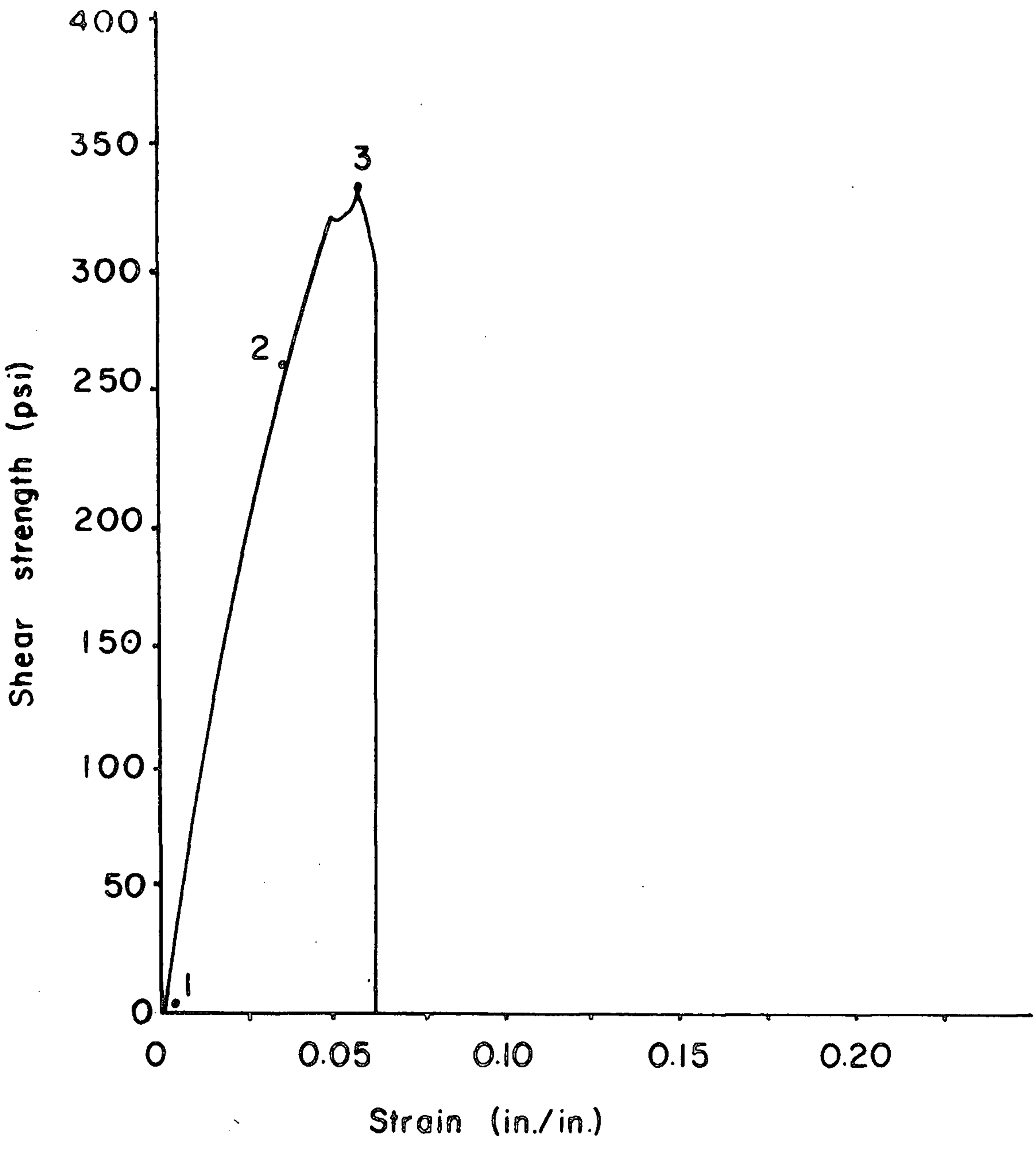


Fig. 10. Stress-strain curve for plywood made of rotary-cut veneer, with lathe checks fully impregnated by resin, with accompanying photographs at the positions noted (Sample I). --Treatment 4.

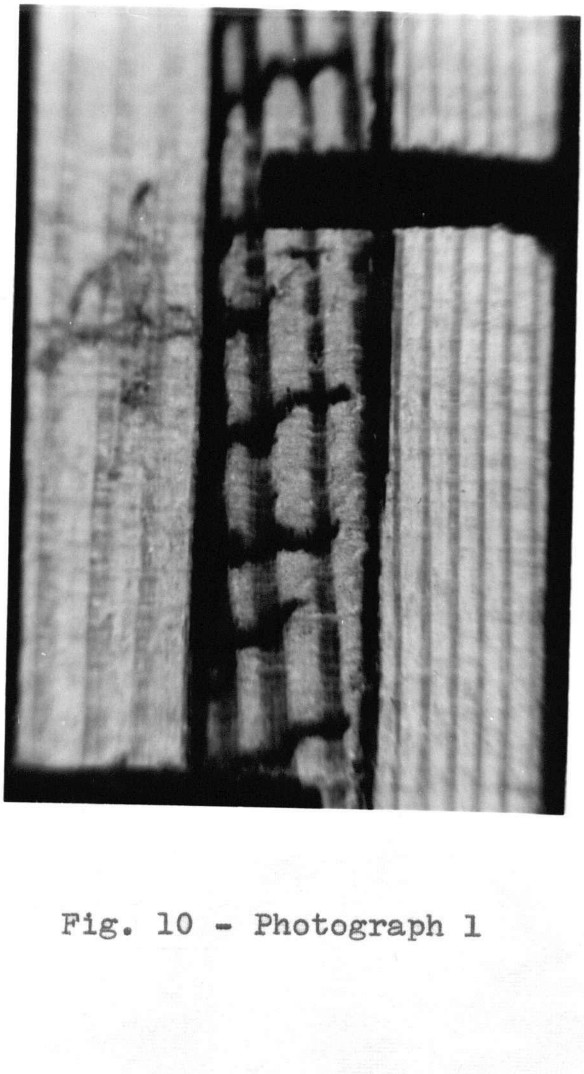


Fig. 10 - Photograph 1

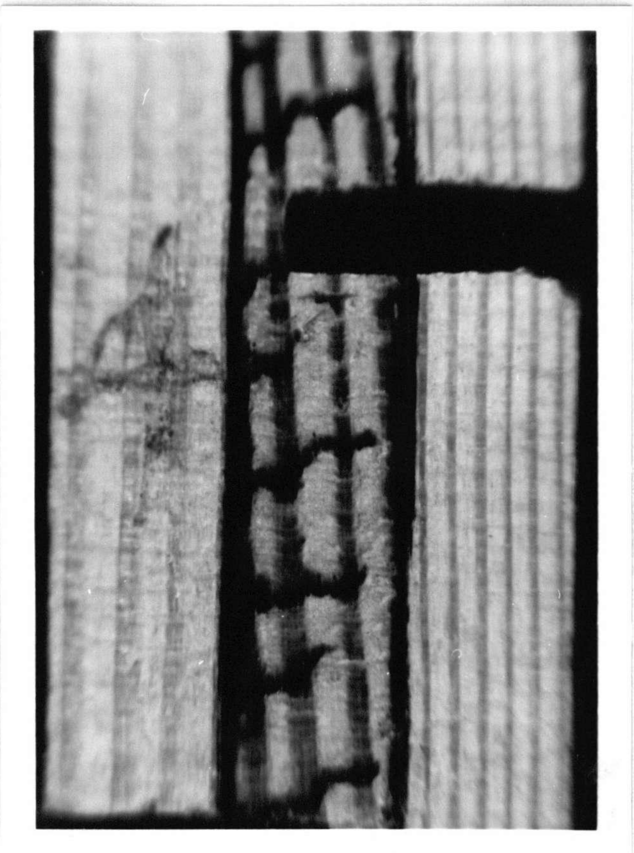


Fig. 10 - Photograph 2

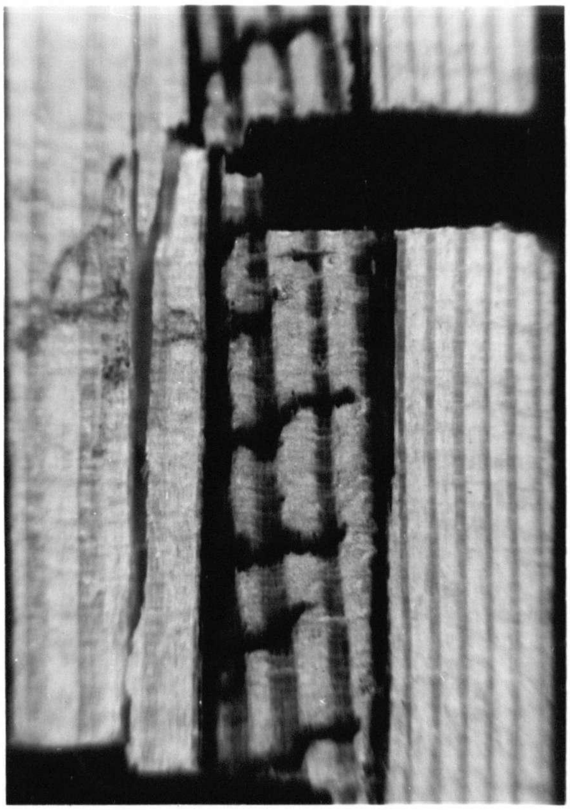


Fig. 10 - Photograph 3

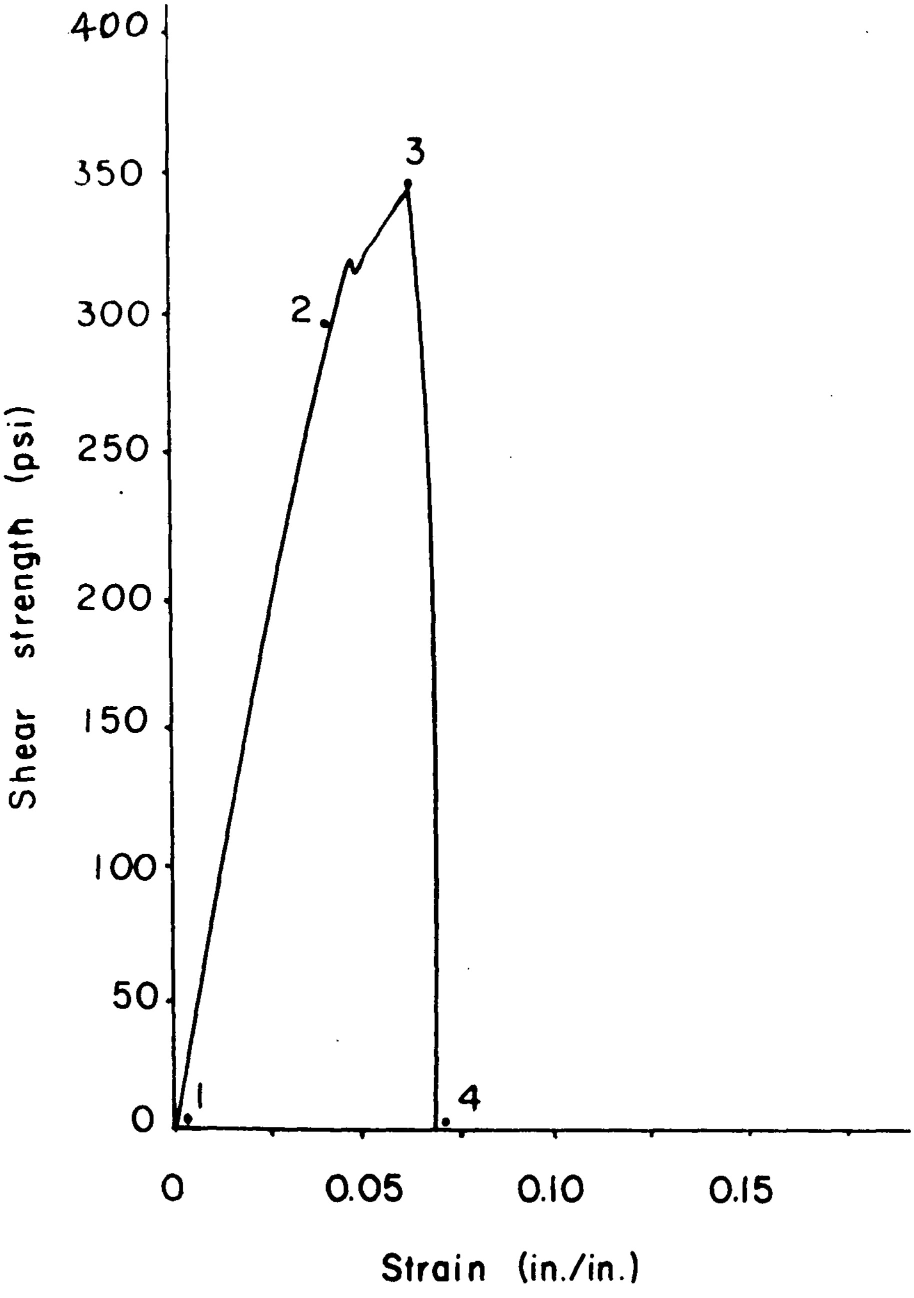


Fig. 11. Stress-strain curve for plywood made of rotary-cut veneer with lathe checks fully impregnated by resin, with accompanying photographs at the positions noted (Sample-2). --Treatment 4.

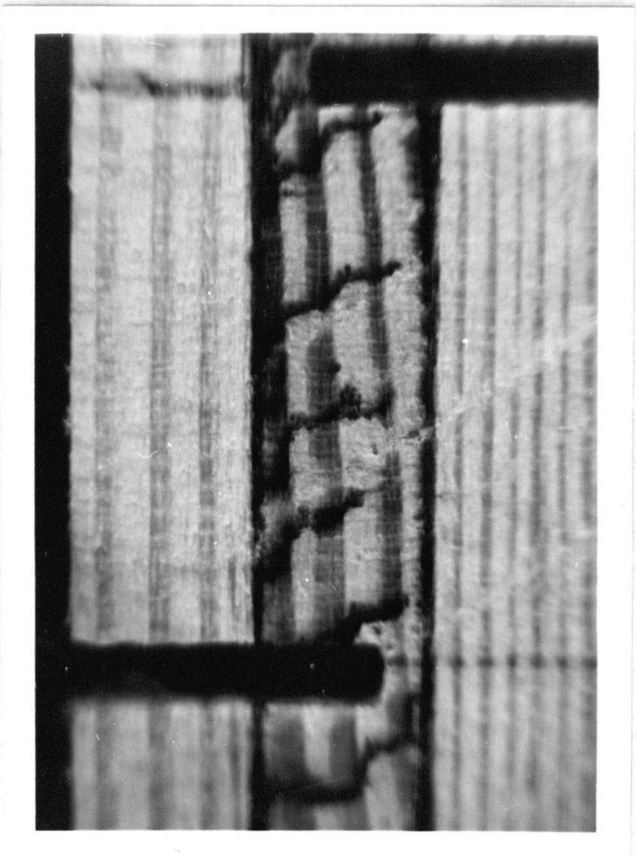


Fig. 11 - Photograph 1

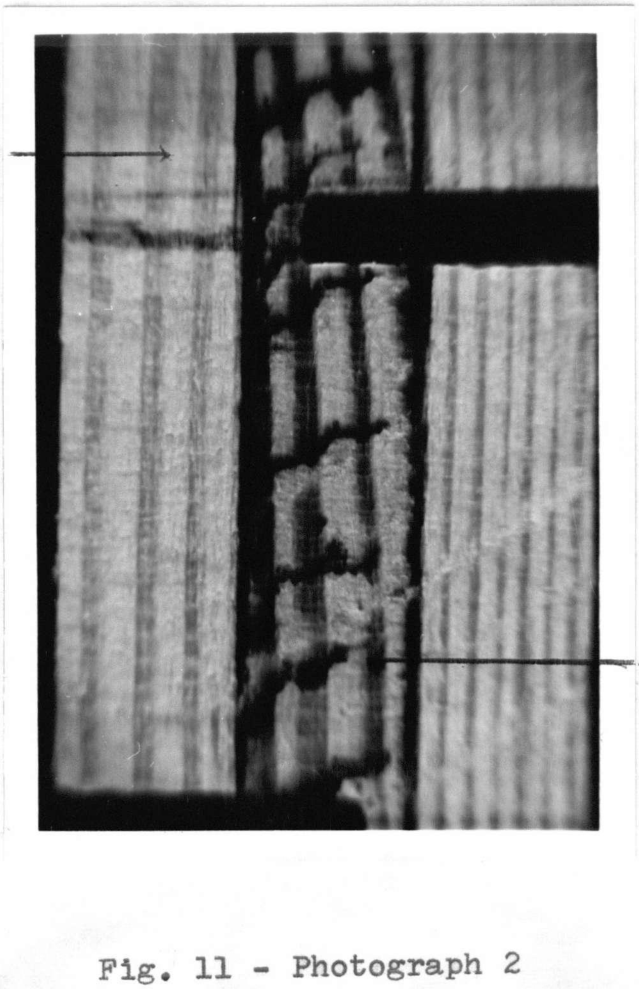


Fig. 11 - Photograph 2

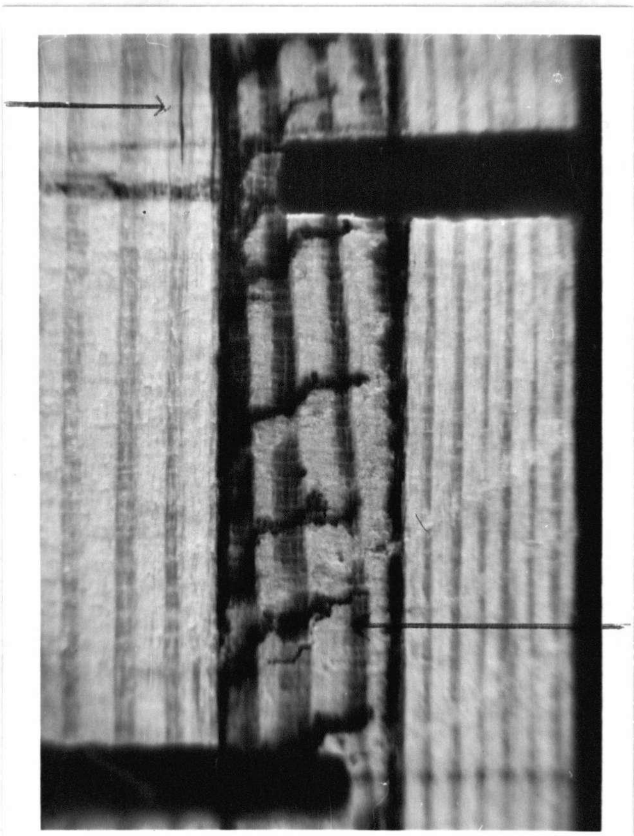


Fig. 11 - Photograph 3

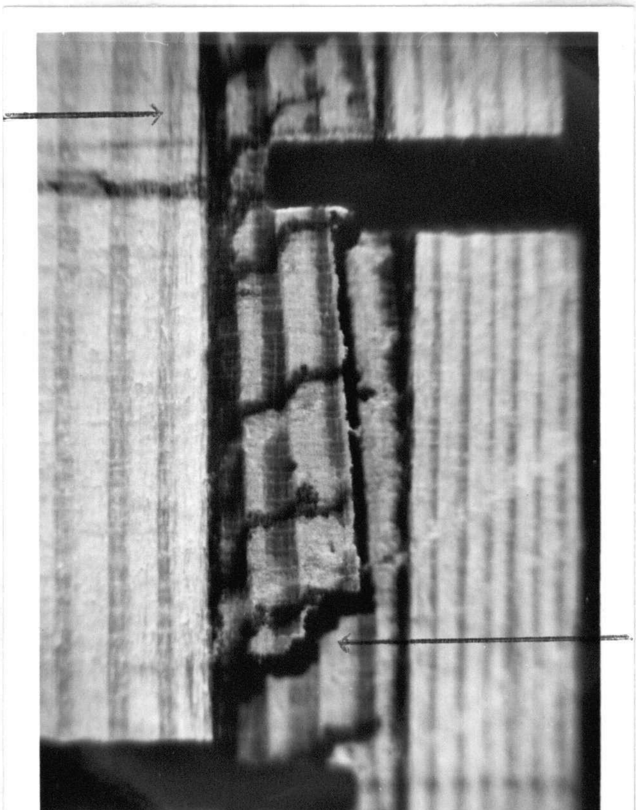


Fig. 11 - Photograph 4

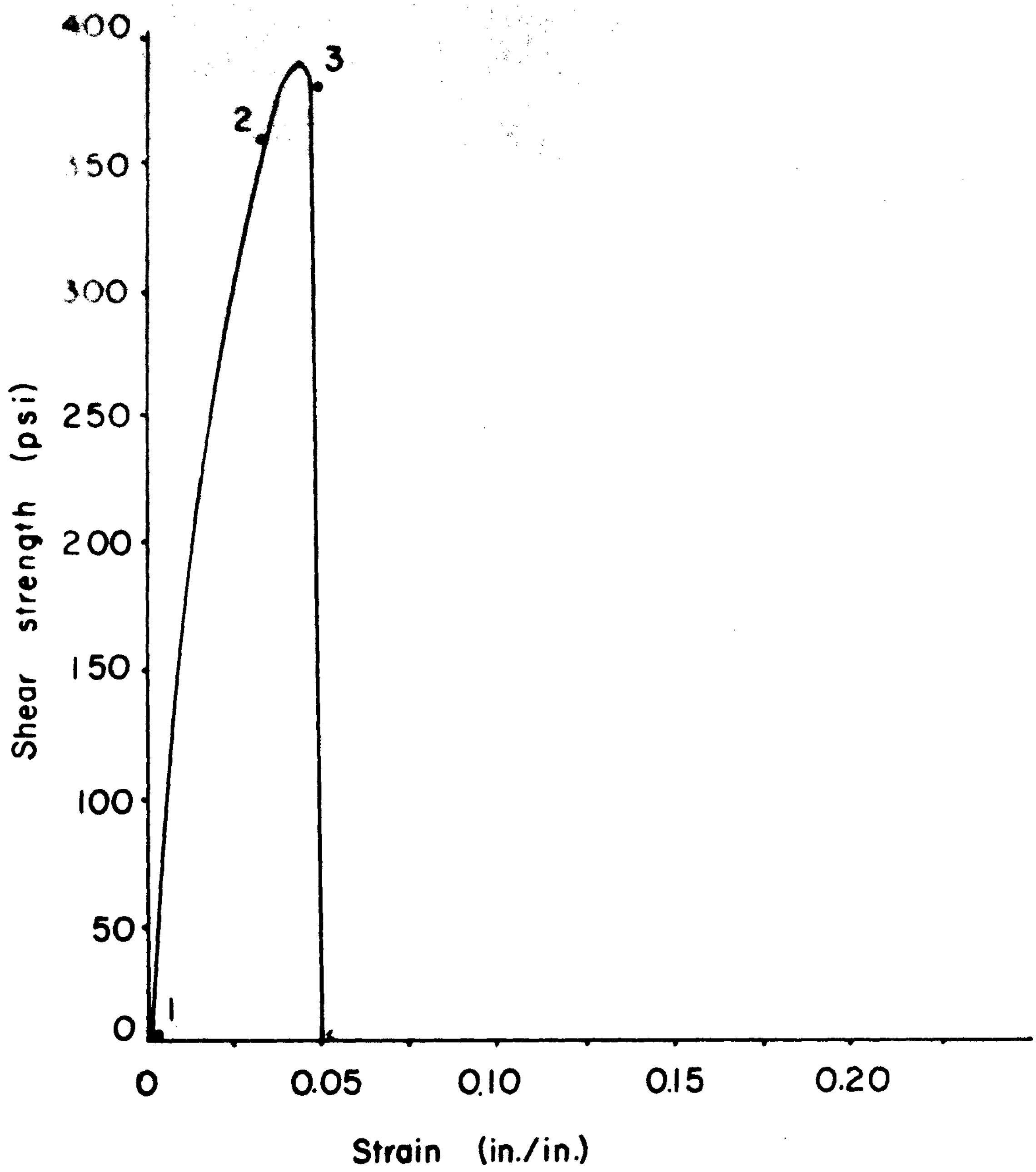


Fig. 12. Stress-strain curve for plywood made of rotary-cut veneer with lathe checks fully impregnated by resin, with accompanying photographs at the positions noted (Sample 3). --Treatment 4

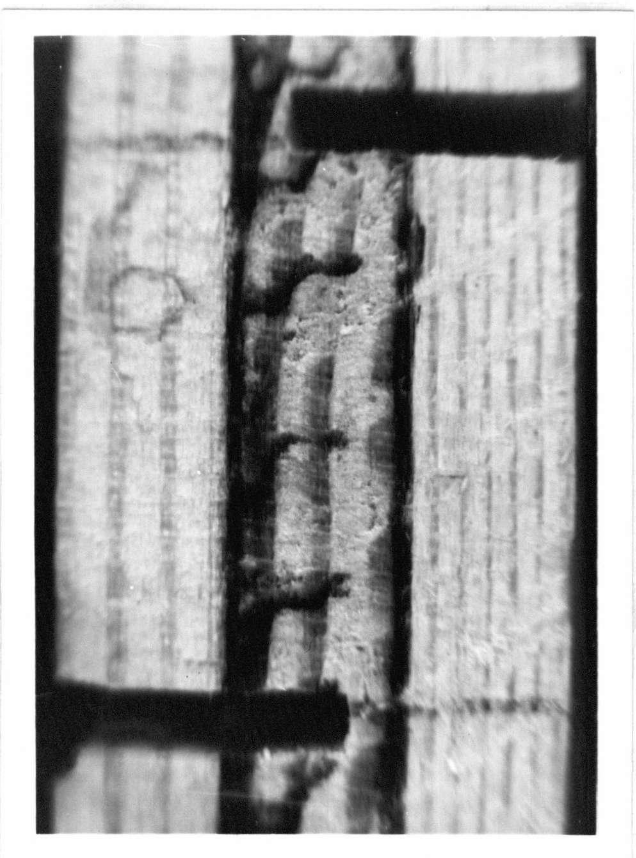


Fig. 12 - Photograph 1

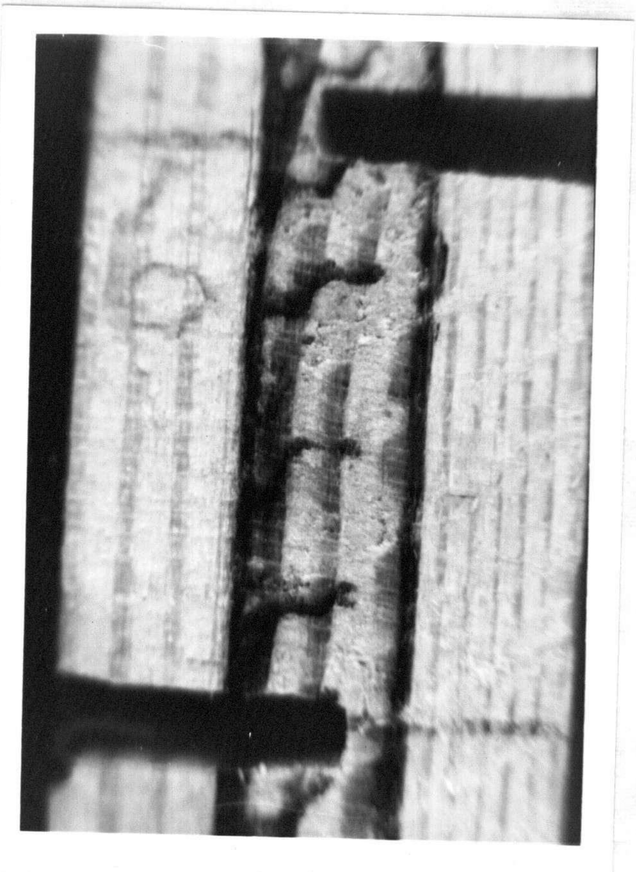


Fig. 12 - Photograph 2

Fig. 12 - Photograph 3

No. 1, 2 and 3. Plywood made of sawn veneer

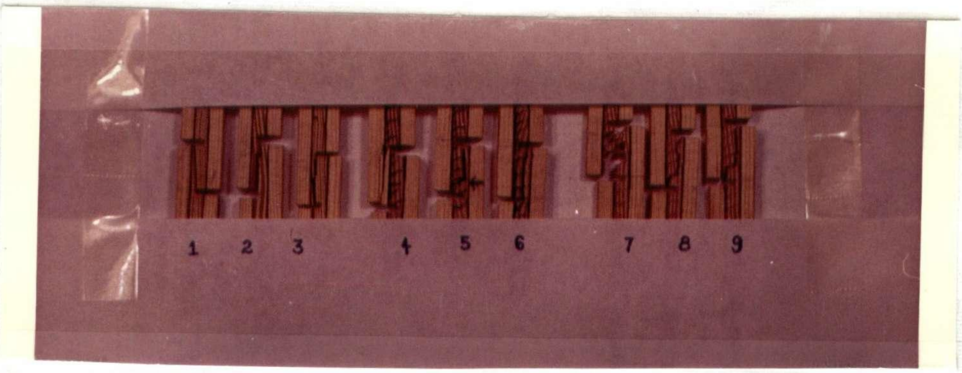
(No. 2 is the sample for Fig. 6)

No. 4, 5 and 6. Plywood made of rotary-cut veneer with lathe checks impregnated by resin

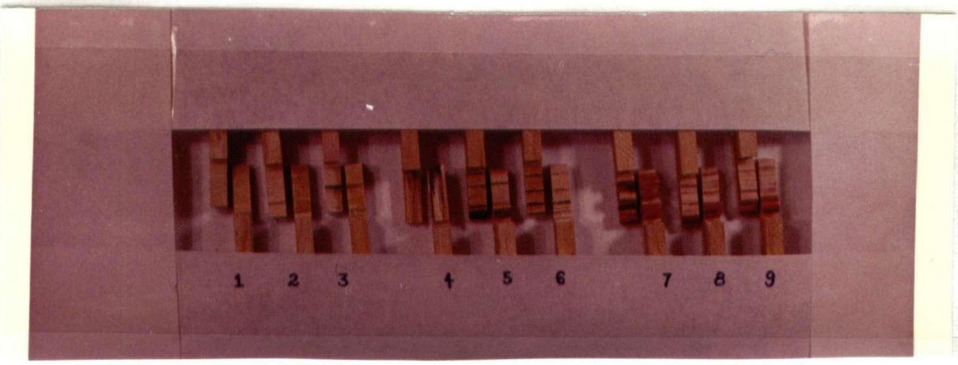
(No. 5 and No. 6 are the samples for Fig. 11 and 12)

No. 7, 8 and 9. Plywood made of untreated rotary-cut veneer

(No. 7 and No. 9 are the samples for Fig. 7 and 8)



A



B

Fig. 13. Test specimens after failure