THE EFFECT OF FATIGUE STRESS ON SHEAR IN WOOD

Thesis for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

John Dennis Sullivan

1958

This is to certify that the

thesis entitled

THE EFFECT OF FATIGUE STRESS ON SHEAR IN WOOD

presented by

John Dennis Sullivan

has been accepted towards fulfillment
of the requirements for

Ph. D. degree in Forest Products

Major professor

Date October 31, 1958

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THE EFFECT OF FATIGUE STRESS ON SHEAR IN WOOD

By

John Dennis Sullivan

AN ABSTRACT

Submitted to the School of Graduate Studies of Michigan
State University of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Forest Products

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ABSTRACT

The research reported here was conducted primarily to study the effect of fatigue loads on wood in shear parallel to the grain on a tangential plane. To the best of the author's knowledge, this research is the first of its kind. Samples of white fir, western hemlock, and Douglas-fir were tested under static loads and under fatigue loads in shear parallel to the grain. Moisture content was held constant and the specific gravity of the wood directly adjacent to the plane of failure was measured. Data were recorded and analysis was accomplished with the use of acceptable statistical systems. The results of the research are summarized in the following list:

1. Wood can be made to fail by fatigue loading in shear parallel to the grain on a tangential plane.
2. There is a linear relationship between shear stress and specific gravity at the line of failure for samples tested in static shear parallel to the grain on a tangential plane.

3. There is a significant regression of stress level and specific gravity at the line of failure on the number of cycles to failure in shear parallel to the grain on a tangential plane.
4. A linear relationship exists between shear stress and specific gravity at the line of failure in wood tested by fatigue loading in shear parallel to the grain on a tangential plane.
5. The early springwood offers the least resistance to loading in shear parallel to the grain on a tangential plane.
6. The stress level at failure for fatigue shear samples is less than for samples of the same species, with comparable specific gravity values, tested under static loads.

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ACKNOWLEDGEMENTS

The writer desires to express his appreciation to Dr. A. J. Panshin for his guidance and criticism in the preparation of this report. The guidance offered by Dr. R. Swenson, Dr. W. Baten, Dr. O. Suchsland, Dr. P. Koch, and Dr. J. Creighton is also deeply appreciated.

The author wishes to acknowledgment his indebtedness to Dr. C. O. Harris for the use of testing equipment and to Mr. B. Radcliffe for the photographic work.

TABLE OF CONTENTS

Table of Contents.- Continued.

LIST OF TABLES

LIST OF ILLUSTRATIONS

List of Illustrations.-Continued.

THE EFFECT OF FATIGUE STRESS ON SHEAR IN WOOD

INTRODUCTION

HISTORICAL NOTES

The fatigue strength or the endurance limit of a material has been defined as the maximum stress that can be applied repeatedly for a specified number of stress cycles without producing rupture of the material (24). Actual testing to induce a fatigue type failure was conducted in Germany in 1829 on mine-hoist chains (15). The first-recorded, fatigue research was followed initially by workers in France, Germany, and England to the end of the nineteenth century when the research in fatigue spread all over the world. From the early interest in metals, fatigue analysis was extended to plastics, glass, rubber, flax, and wood.

The normal method of fatigue testing involves the application of a cyclic load on the material in question. Depending upon the type of analysis being conducted, the stress may vary from zero to maximum in one direction or it can involve complete reversal of stresses. The end result of fatigue research is usually expressed graphically to show the relationship of stress level to number of cycles to failure. Throughout the remainder of this paper this curve will be called the S-N curve. Fatigue research in metals revealed a scattering of data along the S-N curve. This variation induced the use of statistical analysis to establish values of fatigue strength at certain levels of probability (31)(11). The stress levels used in such testing were based on a percent of the static load at failure for the same material. This design system produced admirable results for isotropic materials. For anisotropic materials, however, the same design has led to extreme variation of data about the S-N curve. The reason for the variation lies in the numerous factors that influence all the strength properties of wood regardless of the loading method.

Research into the fatigue properties of wood has been somewhat limited to compression and bending for plywood and for solid wood specimens (20)(19)(21)(8)(18)(22). An intensive search of the literature revealed only one investigator who worked directly on fatigue failure in shear parallel to the grain (23). This research was conducted on glued-shear specimens. The failure occurred primarily in the wood adjacent to the glue line; however, the number of samples so tested was considered inadequate by that investigator.

Previous studies of fatigue in wood have had widely varying results. The S-N curves were approximately the same shape in these studies, but they varied considerably in their height on the stress scale for identical species. All the workers appeared to have their results limited by an insufficient number of samples and by a large amount of variation from the S-N curve. Another factor common to these investigations was the complete absence of statistical significance in the results. This factor led the author of this paper to the assumption that perhaps these previous researchers had not taken some fundamental sources of error under consideration. These sources of error could be occasioned by such variables as specific gravity, moisture content, temperature, residual stresses, and damping capacity.

STATEMENT OF THE PROBLEM

The primary object of this research was to study the effect of fatigue loading on wood in shear parallel to the grain. This would obviously be possible only if a testing method could be developed that would induce failure in wood subjected to fatigue loading. The secondary object of the problem was to obtain an S-N curve with a minimum amount of variance. It was the author's opinion that a large source of error could be eliminated if specific gravity could either be accurately measured or held as a constant. Since it is virtually impossible to hold specific gravity of wood constant from one sample to another, the only remaining alternative was to measure specific gravity as accurately as possible. Since failure was to be related to specific gravity, it seemed natural to assume that the specific gravity at the exact point of failure would be a better measure than would be the average specific gravity of an entire sample.

This assumption immediately posed two questions: In which strength property of wood can the line of failure be exactly located, and how is the specific gravity at the point of failure to be measured accurately? Shear strength was selected because it is simple to locate the failure line in shear and because no previous fatigue research had been conducted on solid wood specimens in shear fatigue.

The problem was then conducted with the solution of the following objectives in mind:

1. To induce failure by fatigue in shear parallel to the grain for solid samples of wood.

2. To accurately measure specific gravity at the line of failure for specimens tested.
3. To show the effect of specific gravity on the fatigue strength of wood in shear parallel to the grain on a tangential plane.
4. To show the effect of specific gravity on the static strength of wood in shear parallel to the grain on a tangential plane.
5. To obtain S-N curves with a minimum amount of experimental variation for several wood species.
6. To compare the shear strength of wood under static loads to the shear strength of wood subjected to fatigue loads.
7. To obtain statistical significance wherever possible for the objectives listed above.

EXPERIMENTAL PROCEDURE

The procedures used in this experiment were devised to minimize or eliminate experimental error. Standard testing methods were applied wherever such methods were applicable to the apparatus available. A detailed list of apparatus is shown in Appendix I of this report. Preliminary testing showed that some modification of certain pieces of apparatus was necessary or that different equipment would have to be used. The appropriate modifications and the design of new equipment are described in detail in later portions of this experimental procedure. The experimental procedure, as described in this paper and as used in the research, includes preparation of samples, static testing, fatigue testing, determination of moisture content, and determination of specific gravity.

SELECTION AND PREPARATION OF SAMPLES

The wood species selected for experimentation were white fir (*Abies grandis* [Dougl.] Lindl.), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). Throughout the remainder of this report the common names, white fir, western hemlock, and Douglas-fir, will be applied to the samples of the respective wood species. The identity of all stock from which the samples were obtained was confirmed by microscopic inspection. Coniferous tree species were used because of their relatively low resistance to failure in shear parallel to the grain direction. White fir, western hemlock, and Douglas-fir were selected because they were readily available in the dimensions desired and because these species are widely used in the various forest products industries. Douglas-fir wood, which is characterized by the presence of small, sparsely distributed resin canals, was tested as a portion of this project because it was assumed that the small size and number of resin canals would not significantly affect the results.

The stock was carefully scrutinized to detect any abnormalities that could influence the strength of the samples. Any evidence of brashness, compression wood, grain deviation, seasoning checks, or decay resulted in the elimination of such material for use as sample stock. The stock eventually used for samples was defect-free, straight-grained wood.

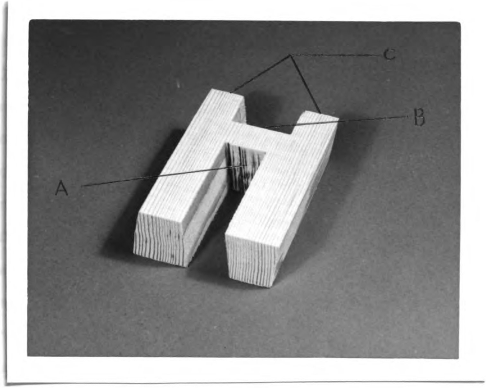
The white fir was used to determine the plane of minimum resistance to shear parallel to the grain. Stock with wide growth increments (Appendix I, No. 1)

was used in order to place the plane of maximum shear in different positions in the growth increments of different samples. Western hemlock and Douglas-fir stock were selected from material cut from large, slow grown trees with very narrow growth increments (Appendix 1, No. 2 and No. 3). Such material insured the close proximity of the plane of least resistance to the plane of maximum shear stress parallel to the grain. It was assumed that all the samples of western hemlock and Douglas-fir would then fail at the weakest point in the wood.

Preliminary testing showed that the shape of the shear specimen could have a pronounced effect on the magnitude of stress at failure. The ideal shear specimen is characterized by shear only, without bending moments on the plane of maximum shear. Unfortunately, bending moments cannot be eliminated; they can only be minimized (7)(32). The design of the shear block specimen used for all samples tested in this research is shown on the following page in Figure 1. The most obvious advantage of the H-shaped sample is that the stresses that induce failure by cleavage are minimal at the plane of greatest shearing stress.

Test samples for static testing as well as for fatigue testing were machined to form and dimension on a band-saw (Appendix I, No. 4). All samples were

Figure 1. Photograph of test sample used for static and fatigue testing. The sample in the picture is about two-thirds of the actual size.


C
B
A

cut to the same shape and the same dimensions within the limits of accuracy of the machine. The interior faces of the testing-head groove in the samples were machined to be as nearly parallel as possible. In addition, the testing-head surface (A in Figure 1), the lower surface of the shear section (B in Figure 1), and the plane of the supports (C in Figure 1) were made mutually parallel within the machining accuracy of the band-saw. All samples were fashioned to make the plane of maximum shear tangent to the growth increments in order to avoid the possibility of failure across more than one growth increment. Matching fatigue samples were cut from material adjacent in a tangential direction to the static samples. The testing-head groove for each matched pair of samples was cut into the same growth increment in an attempt to have identical material along the planes of maximum shear. The samples were marked to insure their identity.

After machining, all test samples were conditioned to a moisture content of about twelve percent. The purpose of the conditioning period was to minimize error induced by changes in moisture content. The shear area of each sample was measured and recorded. After conditioning, the samples were placed in polyethylene bags to reduce the rate of change of moisture in the wood. The samples were stored until the mechanical tests were conducted.

STATIC TESTING

All static testing was performed on a Baldwin-Emery, SR-4 Testing Machine (Appendix I, No. 5). The samples were tested at a machine speed of 0.024 inches per minute (1). The testing head was the same that was used for fatigue testing. A small, flexible rubber strip was inserted between the testing head and the specimen to obtain uniform distribution of the load. Samples were supported on a universal bearing to minimize the effect of horizontal components of the load.

As static loading progressed on a sample, it was closely inspected to determine the position of initial failure. Samples were excluded from further consideration when the initial failure was other than in shear parallel to the grain at the plane of maximum shear. A common type of failure was in cleavage occurring at the vertical center of the load-bearing section. All samples that failed initially due to cleavage exhibited secondary failure in shear parallel to the grain. These samples were not included in the analysis because the load-bearing section was not horizontally continuous after cleavage. In addition, the magnitude of the bending moment across the plane of maximum

shear was different from one such sample to another. Approximately thirty percent of the original number of static samples were rejected because of failure in cleavage.

The samples in which the initial failure occurred in shear parallel to the grain at the plane of maximum shear were considered for further analysis. The line of failure was inspected for the presense of any abnormalities that may have influenced the resistance of the sample to the load. Samples were eliminated if the failure plane was characterized by grain deviation, pin knots, decay, or accumulations of resin. The latter consideration applied only to the Douglas-fir samples. This inspection eliminated about five percent of the original samples in Douglas-fir and western hemlock and about fifteen percent in white fir. The data recorded for each acceptable samples were the stress at failure and the position of the line of failure with respect to the summerwood and springwood (Appendix II, Tables a, b, and c).

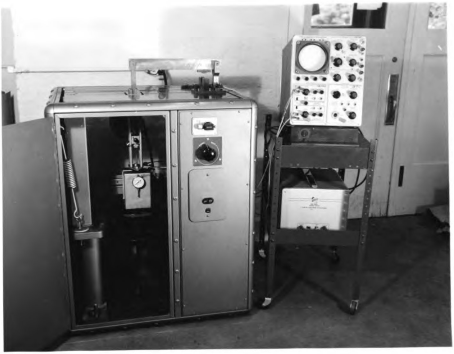
FATIGUE TESTING

All fatigue testing was performed on a Sonntag fatigue testing machine (Appendix 1, No. 6). The machine consisted of a large stationary platen and a smaller reciprocating platen. The oscillating force was produced through the reciprocating platen by means of an unbalanced rotating mass operating at a constant speed of 1800 cycles per minute. The machine was capable of operating either with or without a static preload. To satisfy the requirements of this research the machine was to be operated on the tension side with the vibratory load fluctuating from zero to the maximum load desired. It was therefore necessary to place a static preload one-half the magnitude of the total load on the sample. Preliminary testing showed that the maximum load capacity of the machine was not sufficiently high to satisfy the testing requirements of this research. Therefore a load multiplier was designed that was capable of delivering the loads desired.

Fortunately, a torsion load multiplier for the Sonntag machine was available for study as a prototype (2). The torsion fixture was a fixed-pivot lever arm designed to produce an alternating torque from an alternating force. It was obvious that the use of a freely-pivoting lever arm would produce a large alternating force from a relatively small alternating force. This was the principle that was used in the design of the load multiplier for this problem. One pivot was rigidly attached to the reciprocating platen and the second pivot was securely fastened to the stationary platen. The exact position of the test specimen on the stationary platen between the pivots determined the load multiplication factor of the fixture. A photograph of the Sonntag machine with the attached fixture is shown in Figure 2 on the following page.

Additional preliminary testing revealed that the load multiplier required calibration of load for complete satisfaction. Strain gages (Appendix 1, No. 7) were cemented to opposite sides of the rear pivot post. The purpose for the opposite placement of gages was to compensate for bending of the post. Predetermined tensile, static loads of incresing magnitude were applied and the strain was measured with a strain amplifier (Appendix 1, No. 8). The calibration curve of the strain system is shown in Figure 3, page 16. The strain was then measured on the fatigue machine for the same loads and was compared to the static load calibration. The curves in Figure 3 show that a portion of the load applied through the machine was lost in the load-multiplier. This was probably due to frictional losses at the pivots and at the testing-head guides. The load on a sample to be tested and the load on the reciprocating platen could then be easily calculated by use of moments. The reciprocating platen load was divided equally into two components, a static preload and a dynamic oscillating load.

Figure 2. Photograph of Sonntag Fatigue Machine used in this research. The load-multiplier is mounted on the platens of the machine. The oscilloscope was used to calibrate the loading system.



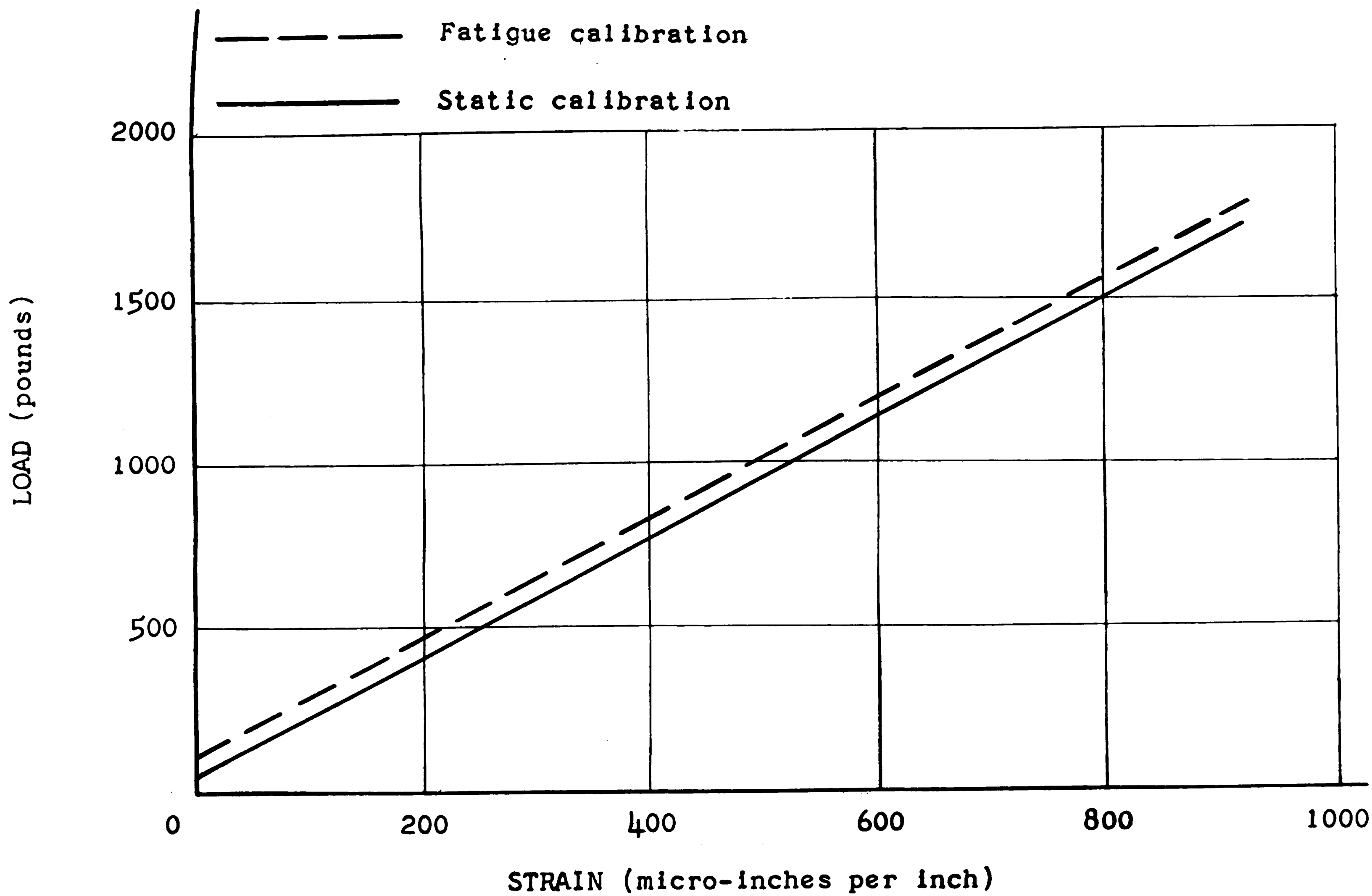


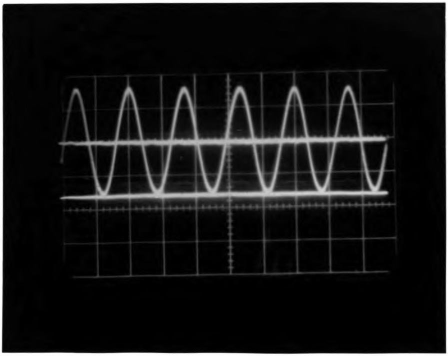
Figure 3. Strain calibration curves obtained by static loading and by fatigue loading.

The loading cycle is shown in Figure 4, page 18. The dynamic load varies sinusoidally from zero to maximum stress and the static load is equal in magnitude to one-half the total load.

Some difficulty was encountered in maintaining the static component at a constant level. The static preload diminished as a function of time when the samples were loaded. This phenomenon was the result of creep in a vertical direction and of local crushing under the testing head in the test specimens. It was necessary to stop the machine and readjust the preload at frequent intervals during testing. Figure 5 illustrates clearly that as the number of cycles increased it was not necessary to readjust the preload as often.

The initial fatigue testing was based on the use of stress levels that were a predetermined percentage of the stress at static failure of a matched sample. A short analysis showed that if any relationship existed, it was drastically influenced by the specific gravity on the line of failure. Since it was physically impossible to measure the specific gravity at the line of failure before failure occurred, it was impossible to predict failure at any predetermined stress level. Therefore, it was decided to do the fatigue testing initially at very low stress levels

Figure 4. Fatigue loading cycle at a machine load of thirty pounds static preload and thirty pounds dynamic load. The median line represents the static component and the dynamic component oscillates from maximum load to zero.



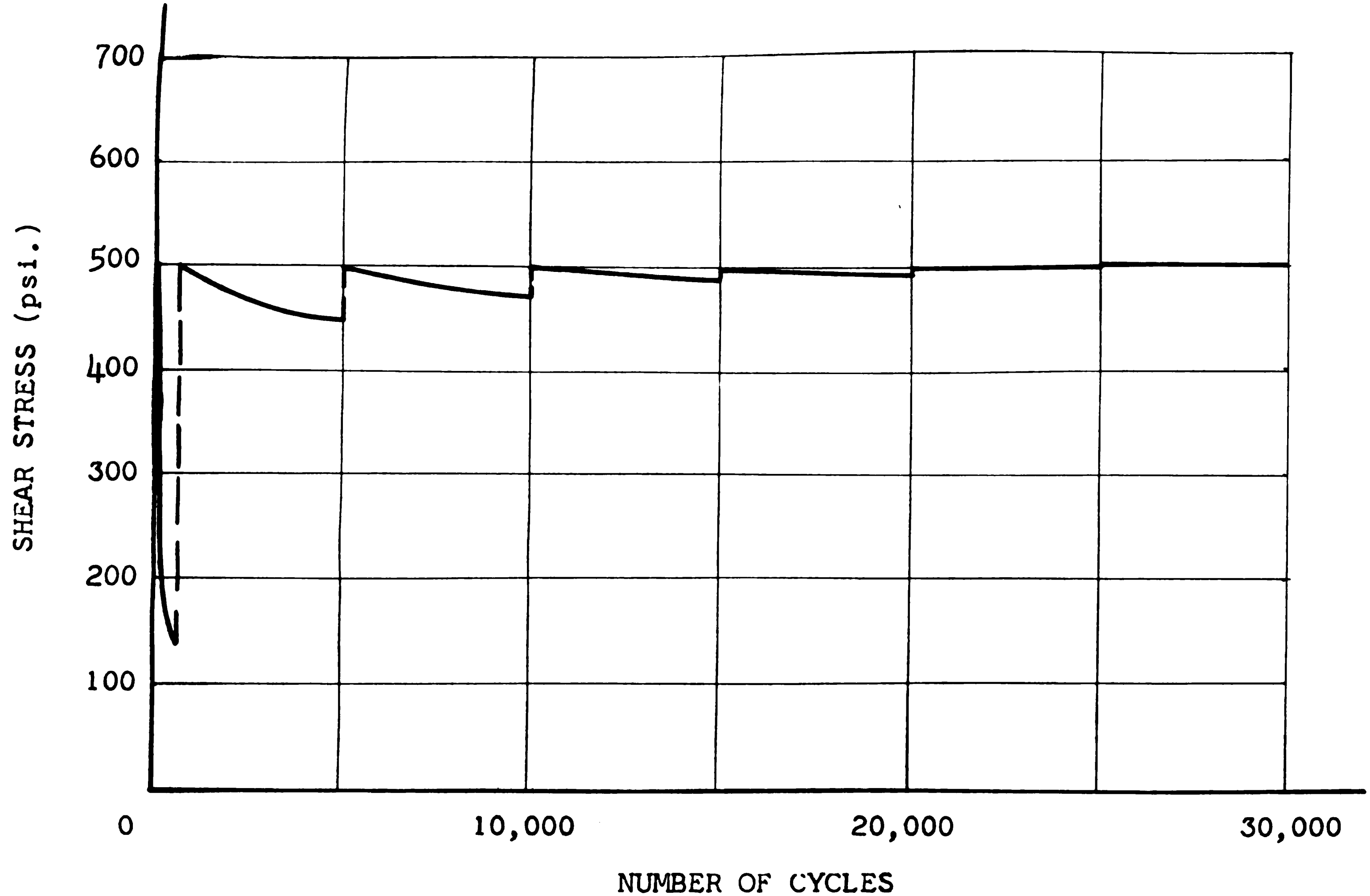


Figure 5. Stress relaxation in a typical fatigue sampe from an initial stress of 500 psi. The static preload was readjusted at 500, 5000, 10000, 15000, and 20000 cycles.

and to increase the stress level after a certain number of cycles if failure did not occur. The stress level was elevated at 100,000 cycles. The data recorded for each sample were the maximum shear stress at failure, number of cycles to failure, and the position of the line of failure with respect to springwood and summerwood (Appendix II, Tables d, e, and f). Any samples that exhibited evidence of grain deviation, pin knots, decay, accumulations of resin, or failure in clevage were eliminated from further consideration. This final inspection eliminated about fifteen percent of the original number of white fir samples and approximately five percent in Douglas-fir and western hemlock.

DETERMINATION OF MOISTURE CONTENT

All samples were weighed on a triple-beam balance (Appendix 1, No. 9) immediately after failure. The balance pan and pivots were cleaned and the instrument adjusted for zero before any measurements were made. The zero balance position was checked periodically during the course of the data collection. The weight immediately after failure was recorded for each sample. The samples were then placed in a drying-oven (Appendix 1, No. 10) and allowed to dry until no further loss of weight occurred. The drying temperature varied from 100 to 102 degrees Centigrade.

The constant weight that was eventually attained was recorded for each sample. The moisture content at the time of failure was computed on the basis of weight loss expressed as a percentage of the oven-dry weight for each sample. This moisture content was then recorded for each sample (Appendix II).

DETERMINATION OF SPECIFIC GRAVITY

The design of this research problem called for a measurement of specific gravity of the wood directly adjacent to the line of failure. Therefore, it was necessary that very thin chips or shavings be obtained from the failure line. Ideally the thickness of the sections should have been the diameter of a woody plant cell. This would have been very difficult to determine because the cell is characterized by decreasing diameter from large springwood cells to very small summerwood cells. The average tangential diameter of a tracheid of white fir and Douglas-fir is from 35-45 microns while western hemlock tracheids, with an average tangential diameter of 30-40 microns, are somewhat smaller (4). Micro-sectioning was not possible since the lines of failure were usually anything but straight and flat. There remained the one method that was actually used; sections sliced with an exceedingly sharp knife. The sections varied from sixty to one-hundred microns in thickness and usually contained two or three tangential rows of cells. The thickness measurements were made with a micrometer.

Preliminary tests showed that the usual methods for obtaining specific gravity were not suitable for very thin sections. The problem was to determine the volume of the sections quickly and accurately to avoid error due to volume change resulting from intake or exodus of water. It was eventually decided to use the method of liquid mercury displacement. A mercury displacement volumeter (Appendix 1, No. 11) was designed with the aid of a prototype (Appendix 1, No. 12) loaned to the author. The volumeter was calibrated by measuring the displacement of precision ground ball bearings of varying diameters. The calibration curve for the volumeter is shown in Figure 6 on the following page.

Before measurements were made for the specific gravity determination, the wood samples were again conditioned in a constant temperature-humidity room to a moisture content of approximately twelve percent. Thin sections were cut from each side of the line of failure and weighed on a grammatic balance (Appendix 1, No. 13). Material from one side of the failure was measured for weight and volume separately from material from the opposite side of the same line of failure.

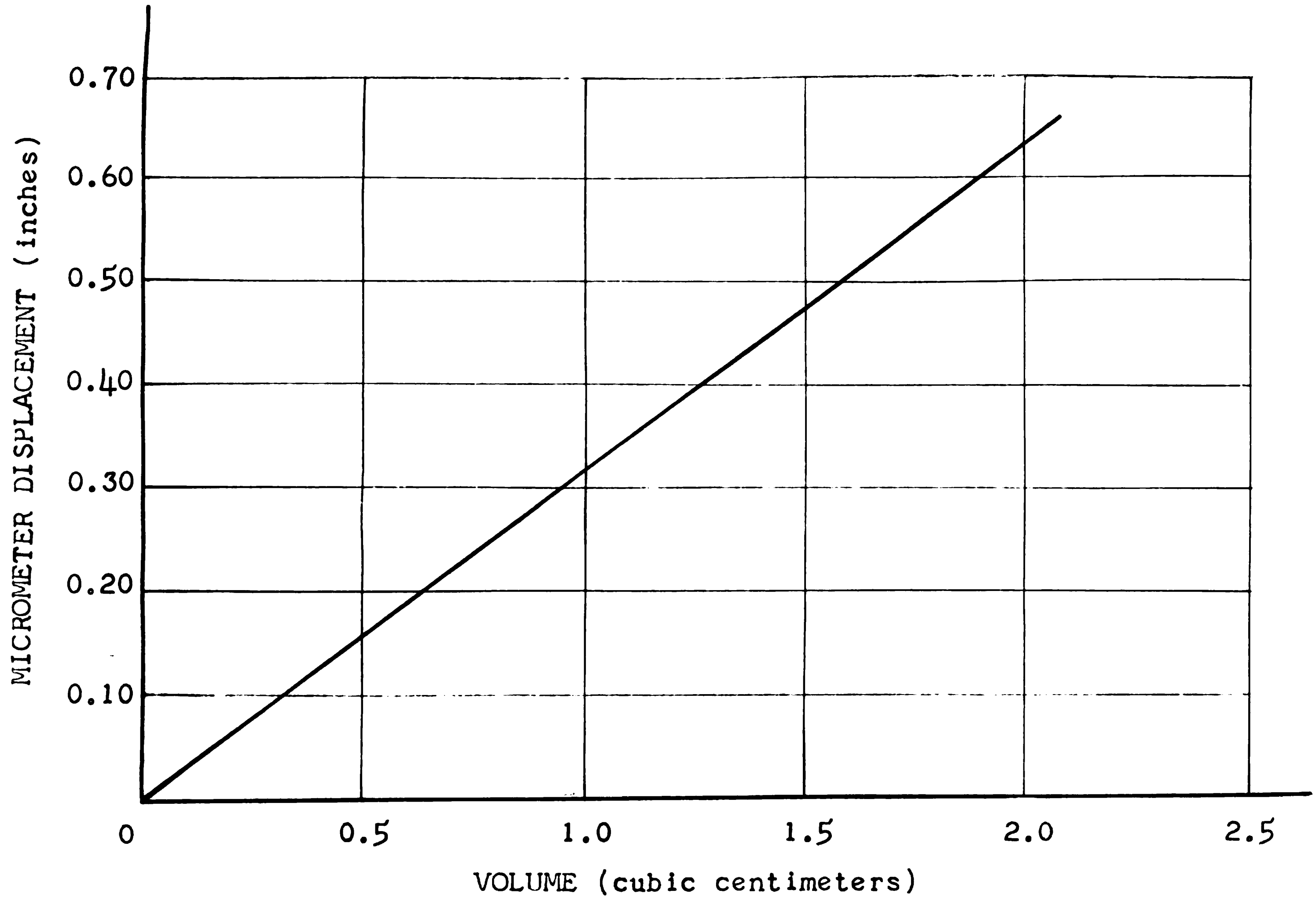
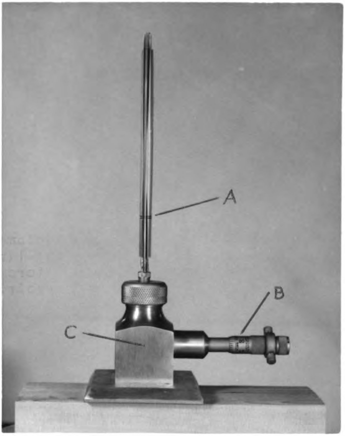


Figure 6. Calibration curve for mercury displacement volumeter.

The sections were placed in the volumeter, the mercury was moved up to a reading-line on the sight tube, and the micrometer reading was recorded to the nearest ten-thousandths of an inch (Figure 7, page 25). The chips were extracted from the micrometer and the mercury was displaced up to the reading line, and the zero micrometer displacement was recorded. The difference between the two micrometer readings was converted directly into cubic centimeters. The specific gravity was then computed for each side of each line of failure in every sample. The average specific gravity at the line of failure was computed arithmetically and recorded (Appendix II).

The specific gravity as referred to in this paper is based on weight and volume of the wood at about twelve percent moisture content. All samples were measured under the same conditions and the resulting specific gravity data were intended to show only the possible effect of this variable within one species. The average specific gravity figures in this paper should not be compared to species averages from any source unless such measurements were made in exactly the same manner as in this research.

Figure 7. Mercury displacement volumeter. A indicates the reading-line on the sight tube, B is the micrometer and C is the mercury reservoir.


A
B
C

ANALYSIS AND RESULTS

All portions of the analysis for this study were completed with the use of acceptable statistical systems. Computations were worked out and individually checked on an automatic calculator (Appendix I, No. 14). Each species was analysed separately for variation in specific gravity at line of failure and moisture content at time of failure. In addition the relationship between specific gravity and shear stress at failure was explored for the statically loaded specimen. The data obtained from fatigue testing were used to determine the influence of the specific gravity and the shear stress at failure on the number of cycles to failure.

SPECIFIC GRAVITY

Analysis was conducted on each species to determine the variability in specific gravity that was observed between the statically loaded samples and the fatigue samples. The null hypothesis was assumed and simple group comparison with the *t* test for significance was applied. The statistical results are summarized in Table 1.

Table I. Summary of the statistical analysis to test the mean difference of specific gravity between static and fatigue samples in each species.

Species	White Fir		Western Hemlock		Douglas-fir	
Testing Method	Static	Fatigue	Static	Fatigue	Static	Fatigue
Mean	0.306	0.316	0.357	0.393	0.428	0.437
Variance	0.0891	0.0676	0.0427	0.0340	0.0372	0.0366
Pooled Variance	0.004124		0.002017		0.001943	
Standard Error	0.0203		0.01419		0.01394	
t	0.680		2.297*		1.000	

*statistical significance at the 95 percent level.

The *t* values shown in Table I were interpreted to yield the results listed below:

1. The null hypothesis was accepted for white fir and Douglas-fir. It may be assumed that all the specific gravity data were obtained from a common population and that the average specific gravity at the line of failure for the fatigue samples was not different from that of the static samples.
2. The null hypothesis was rejected for western hemlock. It may be assumed that the specific gravity at the line of failure for the fatigue samples was significantly greater than for that of the static samples.

MOISTURE CONTENT

An analysis was made in each species to study the variation in moisture content between the statically loaded samples and the fatigue samples. The null hypothesis was assumed and simple group comparison with the *t* test for significance was applied. The results are summarized below in Table 2.

Table 2. Summary of the statistical analysis to test the mean difference of moisture content between static and fatigue samples in each species.

Species	White Fir		Western Hemlock		Douglas-fir	
Testing Method	Static	Fatigue	Static	Fatigue	Static	Fatigue
Mean	10.88	10.23	13.43	11.77	12.34	11.13
Variance	1.821	7.300	2.989	22.207	0.827	1.071
Pooled Variance	0.2400		0.6631		0.04996	
Standard Error	0.1549		0.2575		0.0707	
t	4.183*		6.447**		17.086**	

**statistical significance at the 99 percent level.

The summary shown in Table 2 indicates that in all three species the moisture content at the time of static failure was significantly greater than the moisture content at the time of fatigue failure.

STATIC FAILURE

The method of linear regression was employed to determine the effect of specific gravity on the shear stress at failure parallel to the grain in each of the species tested. This method was applicable since the variance was homogeneous, specific gravity was measured without error, and the shear stress was random. The results of the regression analysis are shown in Table 3.

Table 3. Summary of regression analysis to demonstrate the effect of specific gravity on the magnitude of shear stress at failure.

Species	Regression Coefficient	t-value
White fir	2606.0	9.112**
Western hemlock	3282.3	5.659**
Douglas-fir	3581.5	6.707**

	Regression Equation
White fir	$Y = -336.6 + (2606.0) X$
Western hemlock	$Y = - 26.0 + (3282.3) X$
Douglas-fir	$Y = -460.0 + (3581.5) X$

Table 3.-Continued.

** statistical significance at the 99 percent level.

Y estimated shear stress for any value of specific gravity.

X any value of specific gravity.

The t values shown in Table 3 denote a statistically significant, linear, positive regression of shear stress on the average specific gravity at the line of failure. Figures 8, 9, and 10 show the regression and the 95 percent fiducial limits of estimated shear stresses for white fir, western hemlock, and Douglas-fir respectively. The regression line is based on the premise that the sum of squares of deviations from linear regression are minimum (27). The confidence interval of the stresses was determined by direct calculation over a range of specific gravity figures (29). In figure 11 the regression lines of all three species are shown on one graph. The greatest shear stress at the average specific gravity was developed in western hemlock, followed by Douglas-fir and white fir in that order. This successive relationship corresponds closely to published values of shear parallel to the grain.

The shear line of failure for western hemlock and Douglas-fir occurred at the point of maximum shear stress in all samples included in the analysis. In

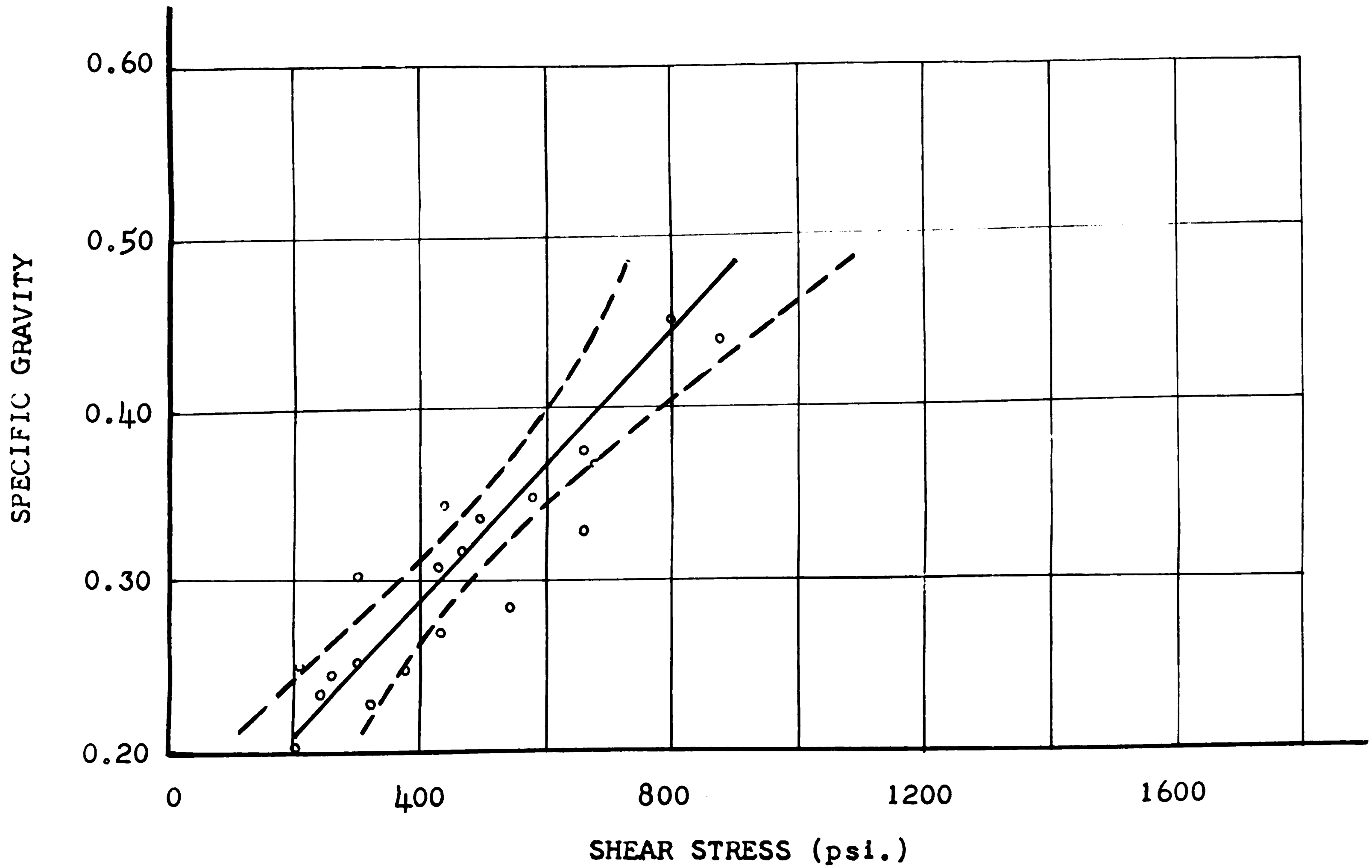


Figure 8. Regression of shear stress on specific gravity for white fir. The broken lines indicate the 95 percent fiducial limits of estimated stresses and are closest to the regression line at the point of the average specific gravity.

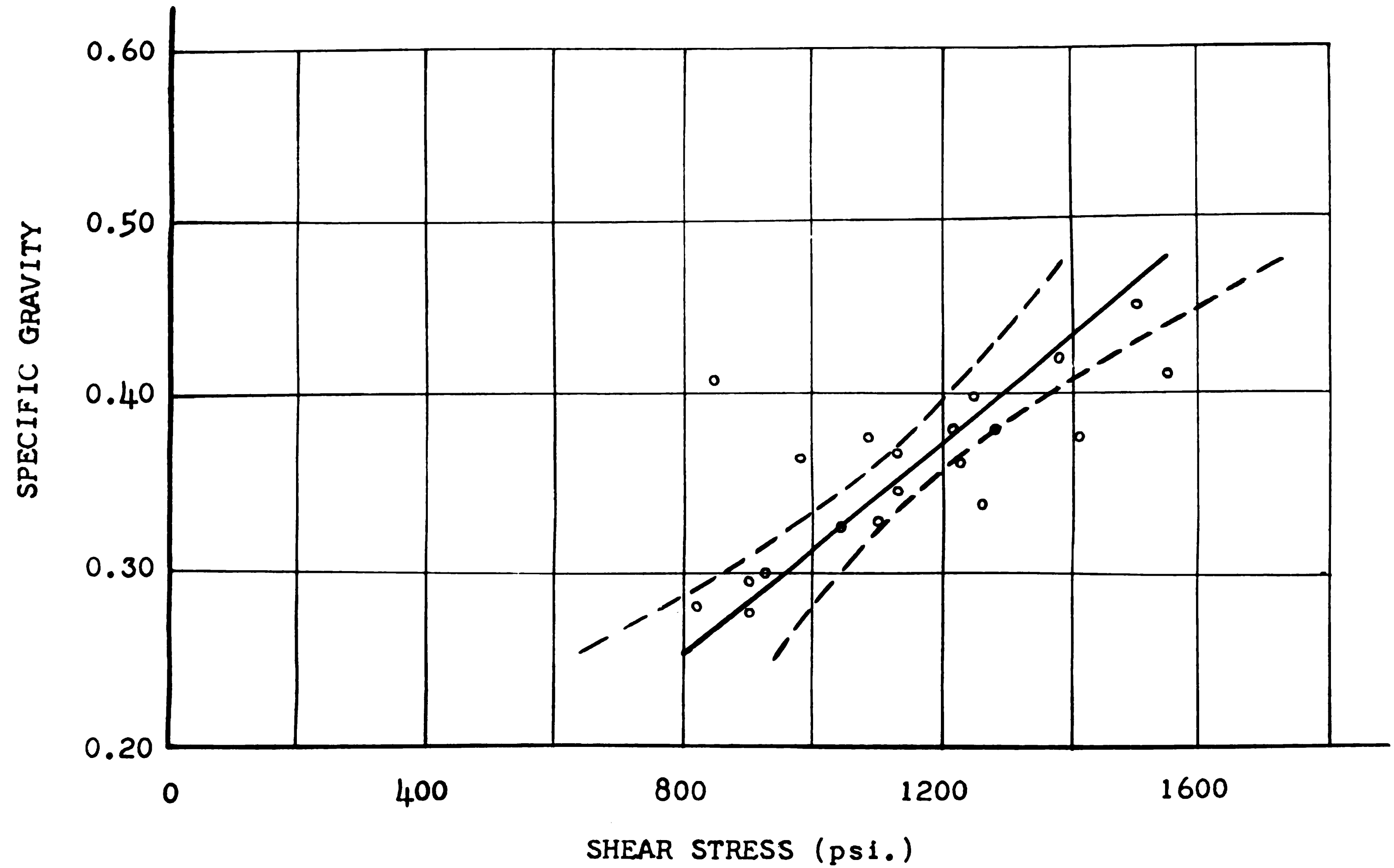


Figure 9. Regression of shear stress on specific gravity for western hemlock. The broken lines indicate the 95 percent fiducial limits of estimated stresses and are closest to the regression line at the point of the average specific gravity.

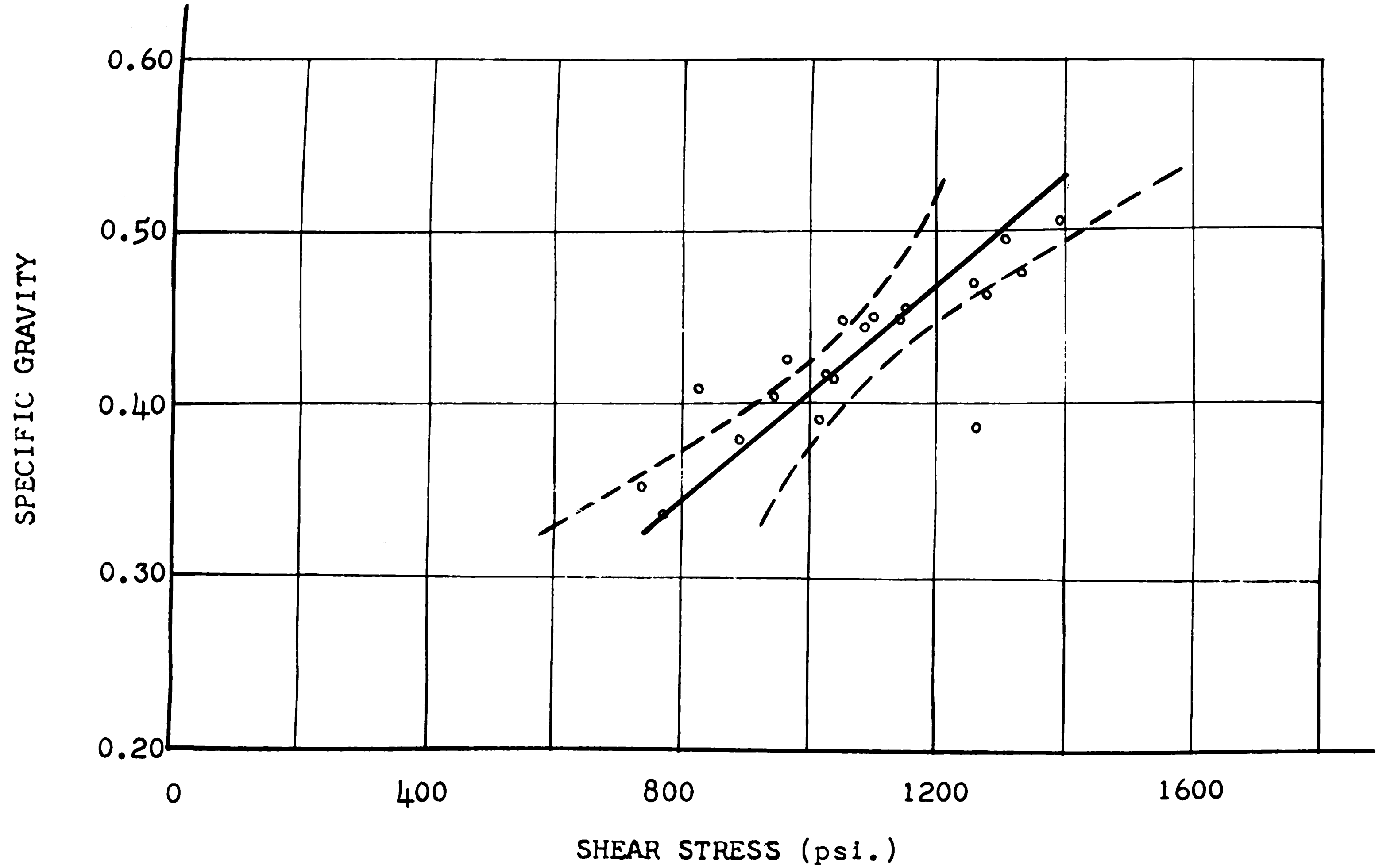


Figure 10. Regression of shear stress on specific gravity for Douglas-fir. The broken lines indicate the 95 percent fiducial limits of estimated stresses and are closest to the regression line at the point of average specific gravity.

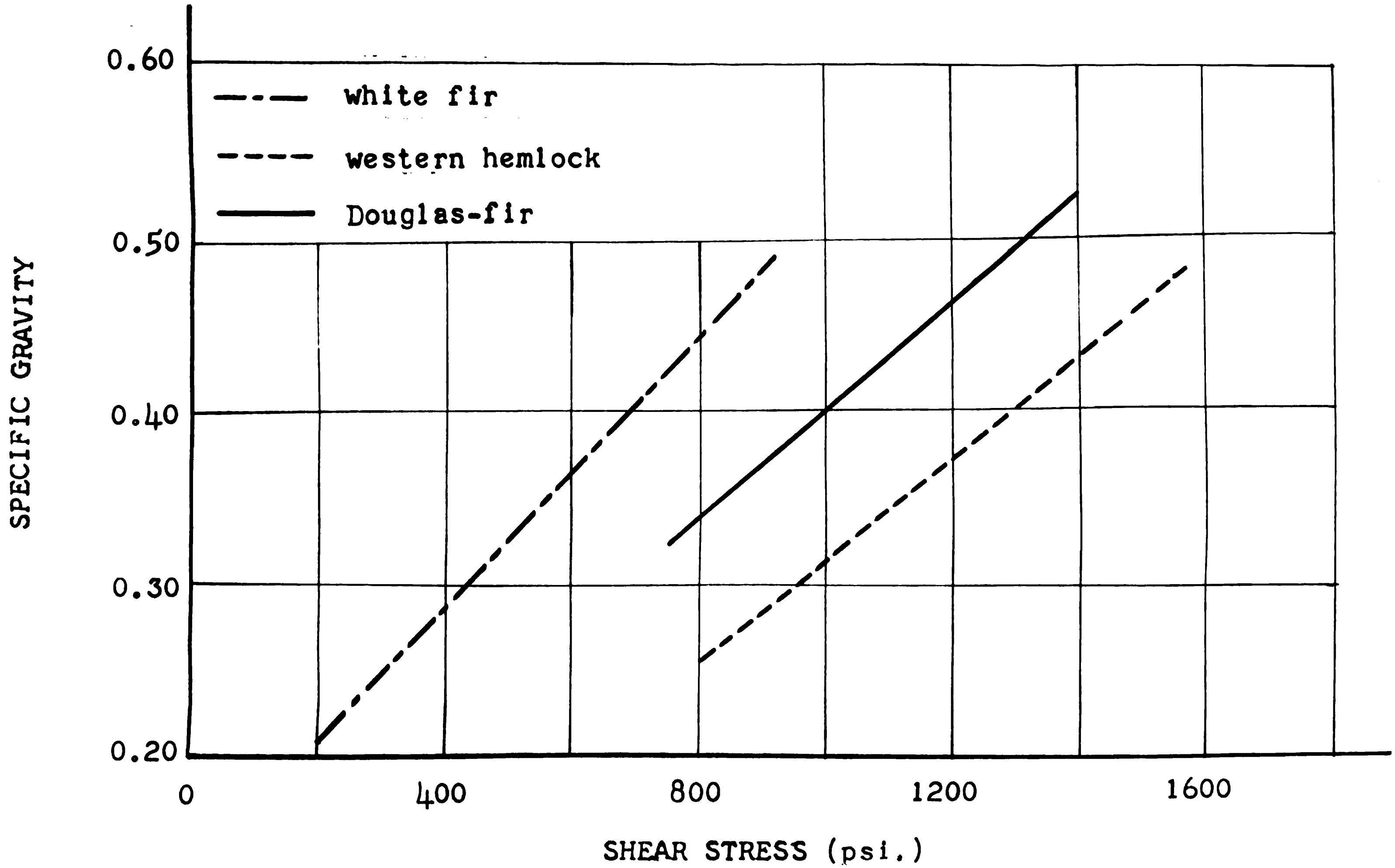


Figure 11. Regression of shear stress at failure on specific gravity for the three species tested.

addition, the line of failure was parallel to the grain direction in all samples. The line of failure characteristically occurred either in the springwood or on the line between the summerwood of an increment and the springwood of an adjacent increment. No failure took place entirely in the summerwood of the samples. The white fir samples were more variable than the other species with respect to the location of the line of failure. For the majority of the samples, shear failure began at the point of maximum shear and then migrated toward the early springwood. A photograph showing this phenomenon can be seen in Figure 12, page 36. The migration of the failure line always occurred at an angle to the grain and never progressed into a summerwood portion of a sample. The resulting oblique failure line was found only in samples that had summerwood at the point of maximum shear directly under the edge of the testing-head. If the early springwood was at the point of maximum shear stress, the failure line was characteristically straight and parallel to the grain direction. This more normal type of failure is shown in Figure 13, page 37. Several samples in all three species exhibited another type of failure line when summerwood was at the point of maximum shear. The failure occurred between the summerwood of one increment and the springwood of the

Figure 12. Migration of the static failure line. The arrow indicates the failure line slanted towards low-density springwood.

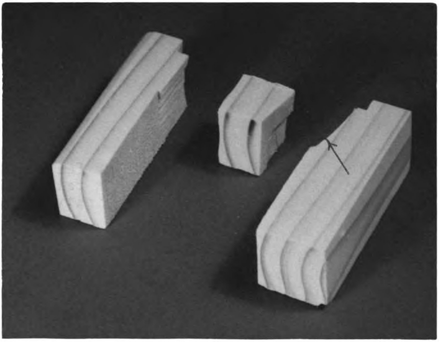


Figure 13. Straight-line shear failure in static specimen. The failure in this specimen occurred at the plane of maximum shear.

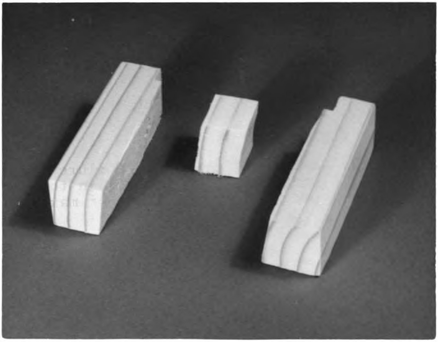
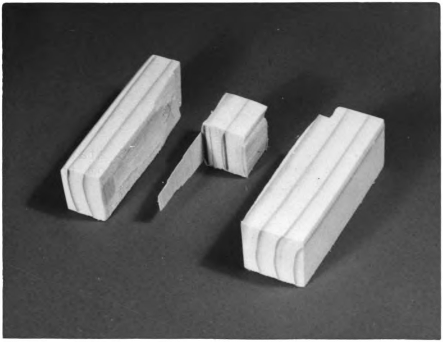


Figure 14. Failure occurring in a statically loaded specimen away from the plane of maximum shear stress.



following increment at a plane removed from the point of maximum stress. This resulted in material being sheared from the side of the testing-head groove as shown in Figure 14, page 38.

FATIGUE FAILURE

The method of multiple regression was used to determine the effect of specific gravity and stress level on the number of loading cycles to failure. A graph of the data on linear paper evidenced an exponential relationship between the three variables. Semi-logarithmic plotting and analysis did not yield significant results. Log-log plotting finally showed a relationship that could be subjected to analysis by the method of multiple regression. A search of the literature revealed that multiple logrithmic regression can be appropriately used as a method of statistical analysis (26). In order to facilitate the use of this analysis, the data for specific gravity were converted from three-place decimals to three-digit, whole numbers. The purpose for the translocation of the decimal point was to avoid the use of negative logarithms in the subsequent analysis. All data were converted to logarithms and analysed with the standard multiple regression procedure. The results are summarized in Table 4.

Table 4. Summary of the results of the regression of number of cycles to failure on shear stress and specific gravity for white fir, western hemlock, and Douglas-fir.

	White Fir	Western Hemlock	Douglas-fir
Mean specific gravity	316'	393'	437'
Mean shear stress	315 psi	486 psi	480 psi
Mean no. of cycles	1569	888	1175
$b_{y1 \cdot 2}$	0.597	8.105	10.249
t for $\bar{b}_{y1 \cdot 2}$	0.066	3.742**	3.034**
$b_{y2 \cdot 1}$	-7.424	-8.481	-10.625
t for $\bar{b}_{y2 \cdot 1}$	1.901	13.252**	7.601**
R	0.821**	0.942**	0.838**

Species	Equations of Multiple Regression
White Fir	$Y = (1.814)(10)^{20} X_1^{0.597} X_2^{-7.424}$
Western Hemlock	$Y = (50828) X_1^{8.105} X_2^{-8.481}$
Douglas-fir	$Y = (31160) X_1^{10.249} X_2^{-10.625}$

' the mean specific gravity figures are actually 0.316, 0.393, and 0.437.

** statistical significance greater than the 99 percent level.

Table 4.-Continued.

$b_{y1\cdot2}$	is the regression of number of cycles on specific gravity independent of shear stress.
$b_{y2\cdot1}$	is the regression of number of cycles on shear stress independent of specific gravity.
R	is the multiple correlation coefficient.
Y	is the estimated number of cycles to failure.
X_1	is specific gravity expressed as a three-digit whole number.
X_2	is shear stress at failure.

The multiple regression of number of cycles on specific gravity and stress was significant for all three species. A closer inspection of the partial regression coefficients reveal that in all three species the number of cycles to failure varies directly with exponential functions of specific gravity and varies inversely with exponential functions of shear stress. The equations of multiple regression define a curved, three-dimensional plane. In order to show the S-N curve graphically, it was necessary to hold one variable constant. Because it was the S-N curve that was desired, the relationships shown in Figures 15, 16, 17, and 18 were obtained for the average specific gravity in each species. The resulting two-dimensional curves are line intercepts on their respective three-dimensional, curved planes. The broken lines in Figures 15, 16, and 17 represent one standard deviation

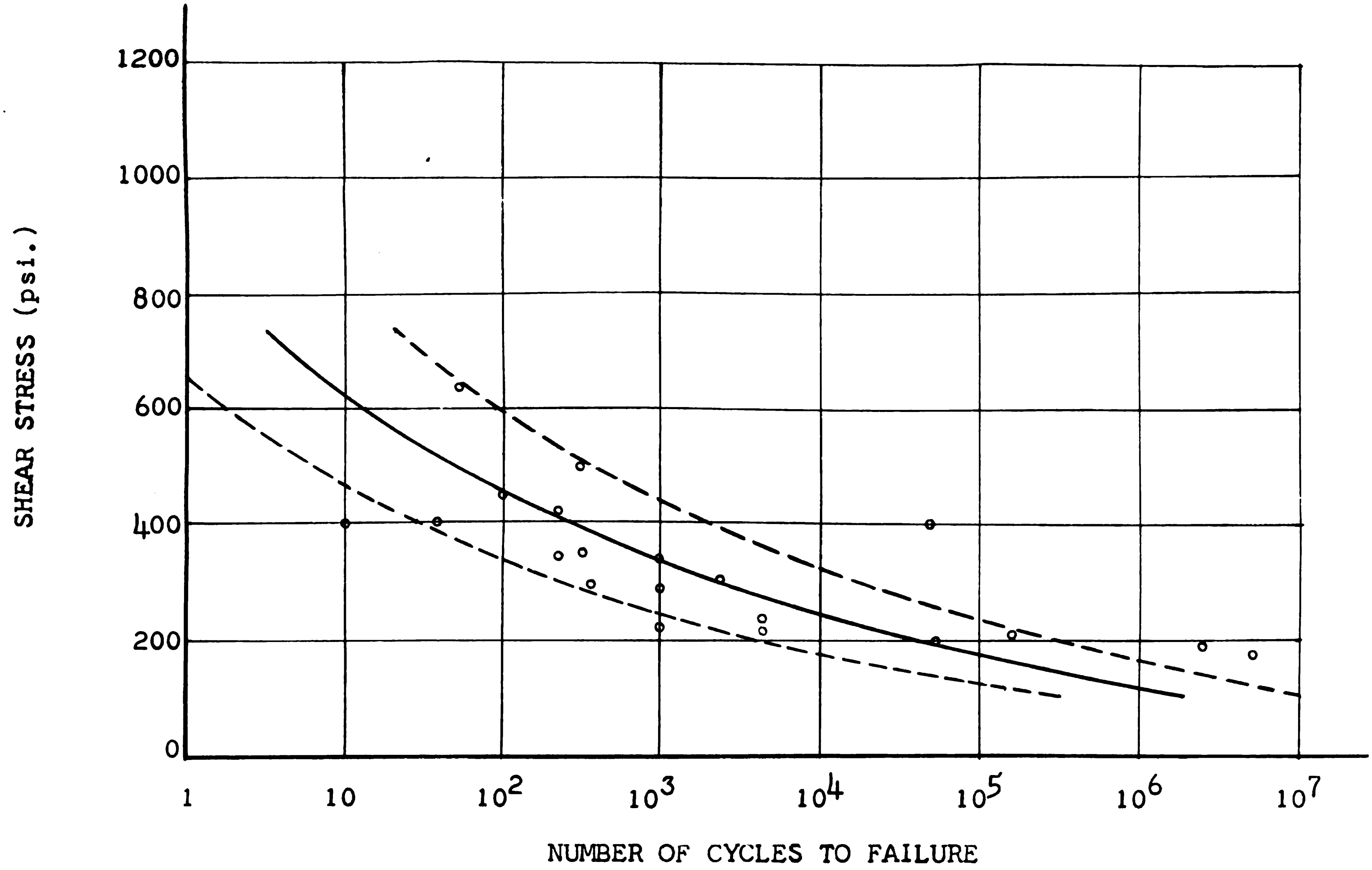


Figure 15. S-N curve for white fir. The curve was obtained for an average specific gravity of 316 (0.316). The broken lines indicate one standard deviation.

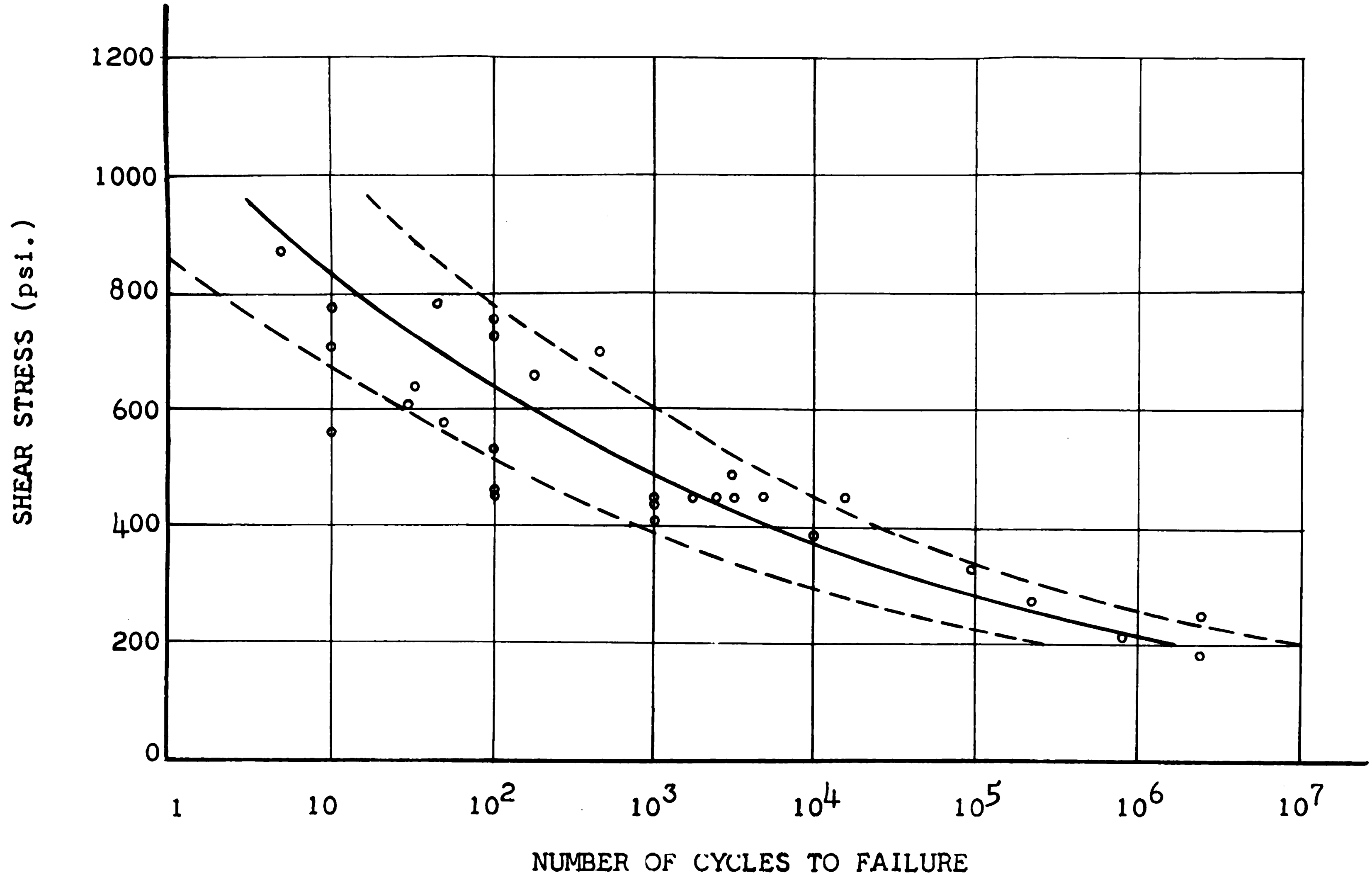


Figure 16. S-N curve for western hemlock. The curve was obtained for an average specific gravity of 393 (0.393). The broken lines indicate one standard deviation.

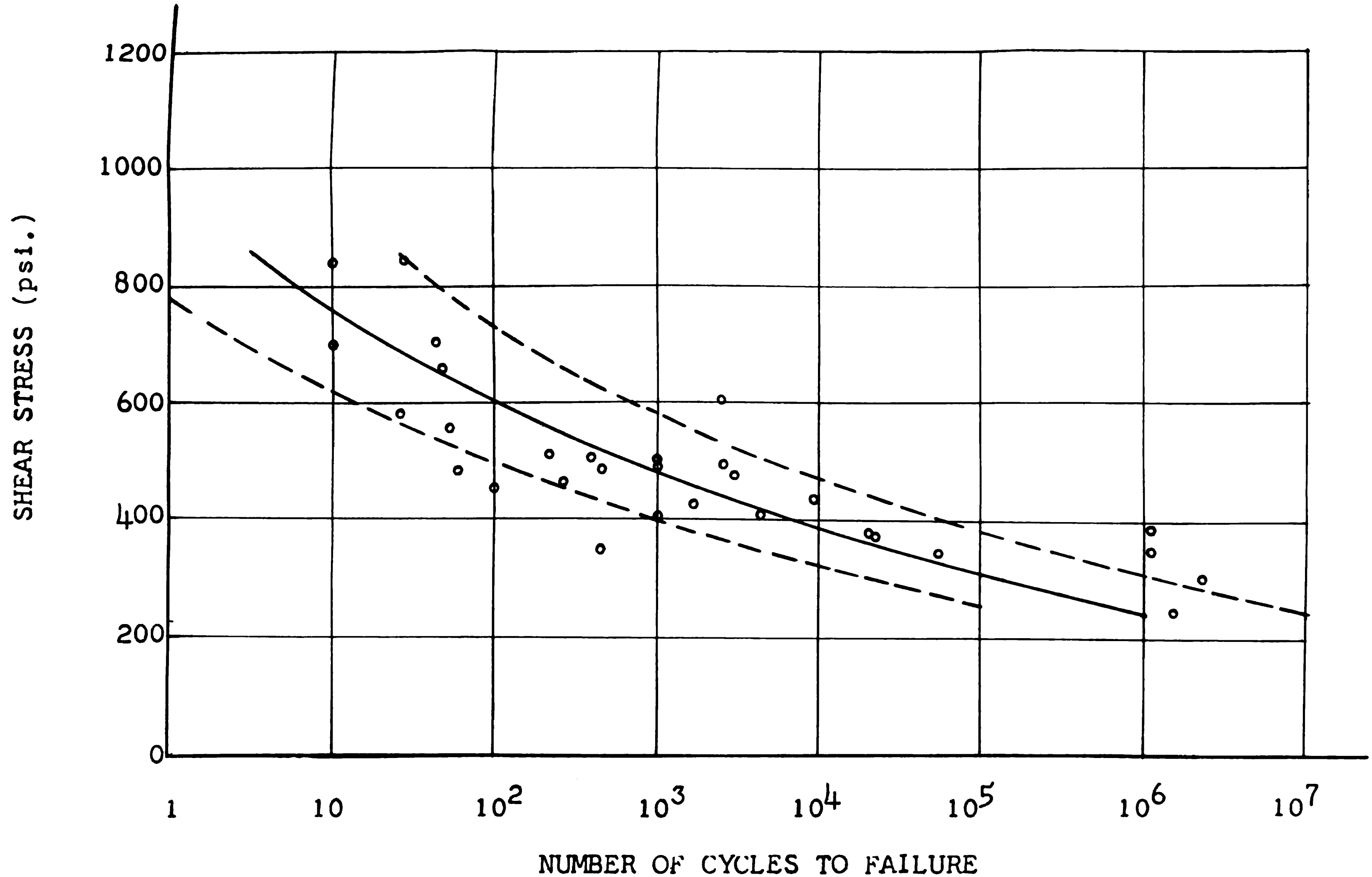


Figure 17. S-N curve for Douglas-fir. The curve was obtained for an average specific gravity of 437 (0.437). The broken lines indicate one standard deviation.

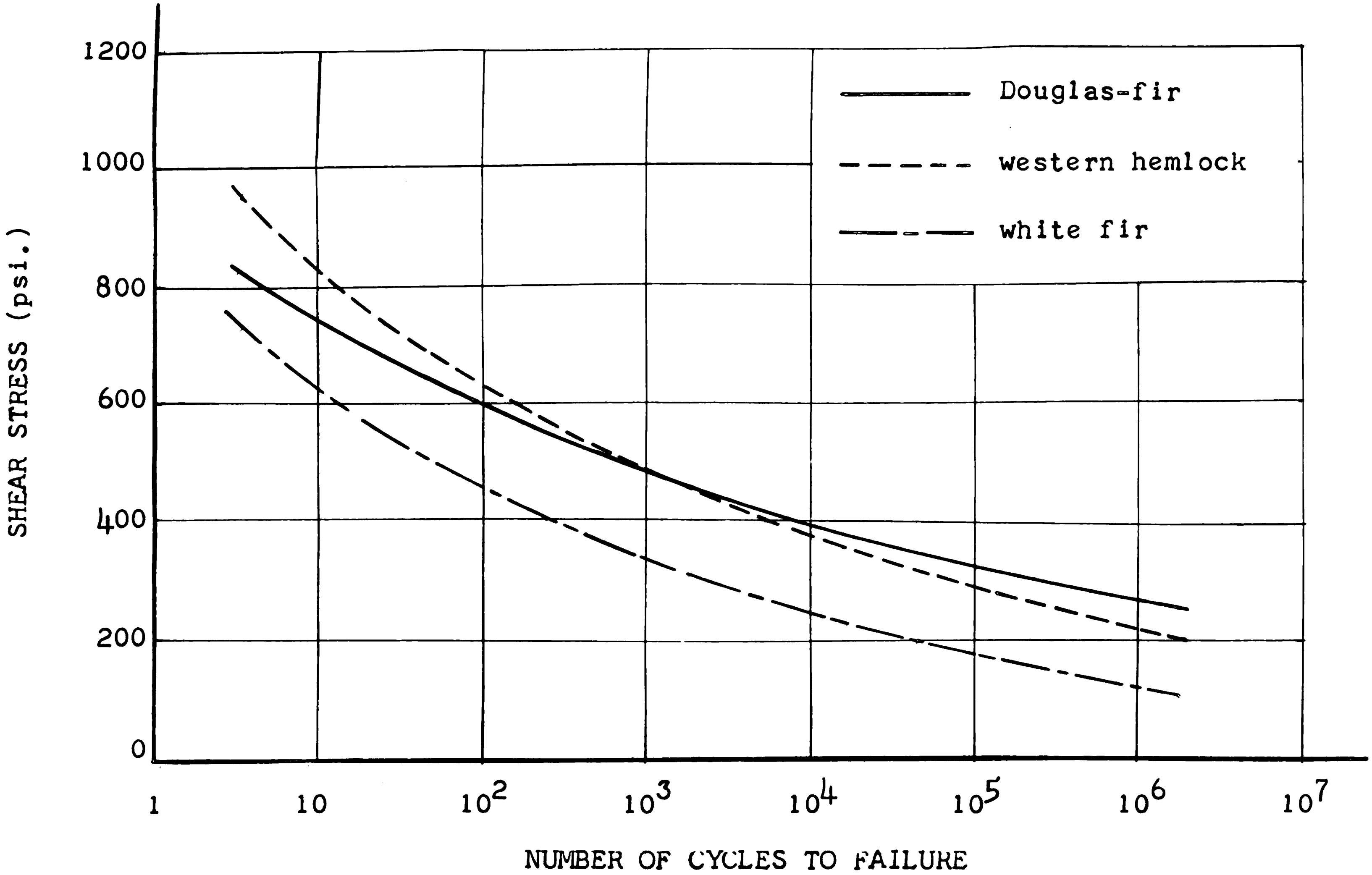


Figure 18. S-N curves for all three species tested in this investigation.

of estimated number of cycles. The magnitude of the deviation was obtained by the direct count of the number of logarithmic units separating the regression line from the plotted data points. The square root of the quotient of the sum of the deviations squared, divided by the degrees of freedom, yielded the logarithmic magnitude of the standard deviation. Inspection of Figure 18 reveals that the S-N curves are approximately the same shape for all three species. In addition the relationship between the stress levels for the three species at less than 100 cycles is about the same as under static loading.

The failure line in fatigue samples occurred at the plane of maximum shear. The failure line was straight and parallel to the grain in all cases. Unlike the static samples, no migration of the line of failure toward low density material occurred in the fatigue samples.

It was extremely difficult to compare the shear stresses at failure obtained from static testing to those obtained from fatigue testing. The specific gravity dependence and the varying number of cycles to failure makes a direct comparison meaningless. The results indicated, however, that for samples in the same species with comparable specific gravity figures, the fatigue stress at failure was always lower than the static stress at failure. The ratio of fatigue strength to static strength in shear parallel to the grain varied from 0.90 to 0.24 in Douglas-fir, 0.88 to 0.17 in western hemlock and from 0.95 to 0.36 in white fir. The above variations are averages and have no statistical significance between species.

DISCUSSION OF RESULTS

The purpose of this section of the thesis is to review the sources of error with respect to the results obtained by the analysis. The results of this research are not in themselves the total answer to the questions probed during the course of the study. Careful examination must be made of the sources of error and of the underlying factors that occasion the variables that were measured as a portion of this research. To insure clarity, the origin of error in specific gravity and moisture content determination will be discussed in separate portions of this section. The relationship between specific gravity and shear stress at failure for the statically loaded specimens will also be covered in the discussion. Lastly, the factors that affected the regression of number of cycles to failure on the specific gravity and on the shear stress in the fatigue specimens will be reviewed.

SPECIFIC GRAVITY

To satisfy the purposes of this research, the sections of wood used to determine specific gravity were cut from both sides of the failure line. These sections were very thin. As a result, the volume of such sections was correspondingly small and the ratio of surface area to volume decreased rapidly with an increase of thickness of the section. It was anticipated that the percent possible error in specific gravity of a thin section would be many times greater than the percent possible error for a relatively thick section. In addition, it was obvious that any accurate control of thickness for the specific gravity sections was impossible. The percent possible error in specific gravity was estimated with the partial differential method and was found to vary from almost 100 percent for very thin sections to approximately one percent for the thickest sections. An effort was made to cut the specimens at a thickness that would yield an error of about fifteen percent. This figure allowed for sections thin enough to obtain material directly adjacent to the line of failure and of sufficient thickness to measure with an acceptable amount of error.

The specific gravity at the line of failure was greater in the fatigue specimens than in the static specimens for all three species tested in this research (Table 1, page 27). This difference was caused by the tendency for the failure line to migrate toward low density springwood in the statically loaded samples. The average for a group of such samples would necessarily be lower than for the fatigue samples in which failure occurred in the early springwood only if such material was at the plane of maximum shear stress. Because the western hemlock stock had a large proportion of summerwood, the specific gravity for fatigue samples was significantly greater than for the static samples. Douglas-fir and white fir stock had a greater proportion of springwood and, as a result, a non-significant difference in specific gravity appeared between the static and fatigue samples.

The physical sources of error in the determination of specific gravity were as listed below:

1. Thickness of sections. The thickness of each section was variable due to small deviations in the plane of the failure. It was not possible to cut a section so that the plane of the cut was equidistant from the plane of the failure at all points. The resulting error could be either positive or negative.
2. Roughness of failure plane. In many samples the plane of failure was characterized by alternating grooves and ridges. The size of the grooves limited the mercury contact since, at standard temperature and pressure, mercury will not pass through an opening

smaller than two-thousandths inches. The resulting error in specific gravity was negative in all cases.

3. Fuzziness of failure plane. The failure plane in western hemlock was characterized by a fuzzy appearance caused by the partial separation of some cells from the mass of material. These cells inhibited full contact by the mercury and induced a negative error in specific gravity figures.

4. Change of moisture content. The time required for the measurement of the weight and volume of each section was approximately three minutes. Since this work was conducted under controlled temperature and humidity conditions, it was exceedingly unlikely that any large error was introduced by changes in weight or volume.

5. Trapped air in mercury reservoir. Trapped air could be avoided by using the same mercury for only ten or twelve specific gravity measurements. Minute particles of wood caused air bubbles to appear in the volumeter sight-tube if more than a dozen determinations were made without changing or cleaning the mercury. In this research, the mercury was

changed when air bubbles began to appear. The presence of air bubbles induced either a positive or negative error in the specific gravity.

6. Change of temperature. The mercury volumeter was extremely sensitive to changes in temperature due to the relatively high coefficient of thermal expansion of mercury (13).

The sources of error listed above were controlled as closely as possible during the experimental work and it may be said with assurance that the physical errors were relatively unimportant in the summation of their effect on the specific gravity of a specimen. The mercury displacement volumeter provided the writer with a useful, accurate instrument for the determination of volume for small, hygroscopic pieces of material.

MOISTURE CONTENT

The results of the moisture content determinations showed that in each species the average moisture content of the static samples was greater than that of the fatigue samples. The difference was caused by the time required for testing. Each static sample was tested over a time interval of one to two minutes in contrast to the fatigue samples that required from several minutes to ten hours. The moisture conditions at the time of fatigue testing were such that water was lost from the wood. As the results in Table 2, page 28, point out, this loss of moisture was significant for fatigue samples. The moisture loss was undoubtedly accelerated by higher temperatures in the wood induced by friction of the testing-head against the wood.

Despite the significance of the moisture content difference between static and fatigue samples, the magnitude of the difference was quite low. In western hemlock, where the difference was the greatest, the average moisture content of the fatigue samples was only 1.7 percent higher than that of the static samples.

The physical sources of error in the moisture content determinations were as listed below:

1. Change in humidity. Static and fatigue testing were conducted day and night during the early summer months when the relative humidity differential can be unusually high. Samples that were tested and weighed at night exhibited a higher moisture content than those measured at mid-day. The resulting change in moisture content was either positive or negative.
2. Balance inaccuracies. The samples were weighed on a triple beam balance before and after

oven-drying. Any inaccuracy intrinsic to the balance would produce an error in the moisture content. The balance was zeroed periodically to minimize error. The change in moisture content was either positive or negative.

3. Moisture movement during weighing. A small amount of error was introduced by the addition of moisture during the time required to obtain the oven-dry weight of the specimens. The error was the same for each sample and induced a negative effect on the moisture content.

The maximum, possible, physical error was calculated by the partial differential method at the extremities of the moisture content range. The percentage possible error due to physical measurement varied from seven percent to ten percent. Inspection of Table 2, page 28, shows that the moisture content variance for each test method in each species is relatively low. This indicates that the error due to physical measurement was insignificant and it can be assumed that all the moisture content figures for either test method in each species, were drawn from a common population.

STATIC FAILURE

The results summarized in Table 3, page 29, indicate that the stress level at shear failure under a static load varies directly with the specific gravity of the wood at the line of failure. The variance of this relationship was influenced by error in specific gravity (see page 50) and by errors made in the determination of stress level at failure for the statically loaded shear specimens. The sources of error for loading are listed below:

1. Stress concentration. The possibility existed that the specimen did not support the load evenly at all points of the contact area between the testing-head and the sample. This could occasion failure at a stress level considerably lower than was anticipated. The error due to stress concentration was minimized by the use of a rubber mat under the testing-head to distribute the load over the shear section of the sample.
2. Loading. The testing machine was recalibrated previous to this research to give an error of about one percent at the load range for the static testing to be done as a portion of this problem. The error induced by loading could have been either positive or negative.
3. Shear area. The shear area could not be measured exactly until after failure had occurred and could not be measured exactly

when the plane of failure was rough. The result was higher stress values than were actually present.

The percent possible error for shear stress under static loading was computed by the method of partial differentials. The error in stress varied from six percent for the greatest load to nine percent for the smallest load. The scatter of the data shown in Figures 8, 9, and 10 was influenced more by error in specific gravity than by error in stress. Since the regression of shear stress at failure on specific gravity was significant for all three species, the combined experimental error may be considered unimportant.

FATIGUE FAILURE

The multiple regression of number of cycles to failure on specific gravity and stress level was influenced by physical error in the measurement of all three factors. The error contributed by specific gravity is discussed on pages 48 to 52 of this paper. The physical error involved in determining the number of cycles to failure was extremely small and may be ignored. The factors listed below are those that influenced the magnitude of the measurement error for shear stress at failure:

1. Stress concentration. The stress concentration factor for fatigue loading was the same as

for static loading (see page 55).

2. Loading. The magnitude of the load at failure constituted the most significant source of error in the estimation of the fatigue strength in shear. The error was occasioned by the stress relaxation that occurred in the specimens and by the subsequent decrease in the static preload on the testing machine. The error was more pronounced at a relatively low number of cycles to failure because the reduction of the static preload was most pronounced at the early stage of loading. This source of error would have been virtually eliminated if the testing machine had an automatic preload adjustment. Unfortunately, such equipment was not available for this research. The decrease of static preload resulted in a negative error in shear stress and a positive error in the number of cycles to failure.

3. Bending moment. The presence of a bending moment across the shear section produced error in the shear stress and, consequently, in the number of cycles to failure. Because the bending moment at the plane of maximum shear was

small, the error was small when the failure occurred at the plane of maximum shear.

4. Horizontal load components. The testing-head guides were designed to make the load-multiplier transfer only the vertical component of the machine load. However it was unreasonable to assume that the horizontal loading component was zero. The horizontal components of load resulted in positive error in shear stress and negative error in the number of cycles to failure. This factor somewhat compensated for the error induced by the decrease in the static preload.

The percent possible error for fatigue shear stress was determined for the highest and lowest values of load by the method of partial differentiation. The percent error varied from eight percent for the highest load to seventeen percent for the smallest load. Because change of stress is reflected directly in the number of cycles to failure, a small change in stress at the end of the S-N curve would yield a relatively unimportant change in the number of cycles to failure. The same change of stress at the beginning of the S-N curve could lead to an extremely significant change in the number of cycles to failure.

CONCLUSIONS

THEORIES OF FATIGUE FAILURE

The exact mechanism of fatigue failure in wood is an unknown quantity. This is not surprising since there exist many schools of thought concerning fatigue failure for materials that have received a great deal more attention than has wood. There is no doubt that the mechanism of fatigue in wood is similar in some respects to that for metals, plastics, and glass. This portion of the paper is devoted to a review of the more important theories of failure and a discussion of their utility for wood. The theories mentioned in this section are secondary stresses, hysteresis, and molecular slip.

Secondary Stresses

This theory states that a difference exists between the actual strengths of solid materials and the strengths they ought to possess by reason of molecular cohesive forces (6). All materials contain sub-microscopic defects that reduce the actual strength. These defects occur on both the interior and exterior of the material and furnish a position for failure to begin before the maximum stress can be developed. In addition, the

presence of internal stresses can reduce the magnitude of stress at failure. When applied stresses are imposed on pre-existing residual stresses, the resultant stresses are impossible to determine before failure actually occurs (12).

The theory of secondary stresses appears at least partially significant to explain the mechanism of fatigue failure in wood. There are innumerable factors that can introduce microscopic defects and internal stresses to wood, both in the growing tree and in the preparation of wood for any particular use. In the growing tree, defects and internal stresses are occasioned by such factors as the weight of the tree, wind loads, snow loads, and frost action. In addition, all the many environmental conditions that influence the growth rate of a tree could also affect the amount and distribution of microscopic defects and residual stresses in the wood. These defects and stresses can be magnified and increased numerically by the logging and machining methods that are necessary to convert the tree into a wood product. The inevitable drying of the wood complicates the picture further by the addition of still more defects and residual stresses.

If all the microscopic defects and residual stresses could be somehow eliminated, the natural morphology of wood itself contains factors that account for increased stress. Some of the more important characteristics of wood that may be stress-raisers are listed below:

1. Specific gravity. Difference in specific gravity in adjacent portions of wood are a function of cell wall thickness. The relatively high specific gravity of summerwood in softwoods results from thick cell walls in contrast to the low specific gravity of wood resulting from thin-walled springwood cells. When the cells are supporting a load parallel to their long axis, there is a greater cell wall area sustaining the load in summerwood with a resulting lower stress. At the same load, the thin-walled springwood cells, with a smaller cell wall area, must withstand a greater stress. As a result, it may be theorized that the weakest portion of the wood is in the early springwood where the specific gravity is lowest. The results of the research reported here appear to substantiate this theory.
2. Type of cells. The type and the amount of cells that are supporting or resisting a load on wood can have a pronounced influence on the stress at failure in shear parallel to

the grain. Some cell types are characteristically thin or thick walled in certain species. The number of cells of a particular kind will produce a specific gravity dependence as described above. Parenchyma cells, for example, are normally thin-walled in some species and, if present in a sufficient number, could introduce a source of stress concentration.

3. Slope of fibrils. The secondary cell wall of woody plant tissue exhibits fibril orientation at an angle to the long axis of its cellular components (5). The fibril angles in the three layers of the secondary wall are generally totally different from one another, resulting in a complex stress formation inside the cell wall. Stress concentration could be expected to be maximum where the deviation of fibril alignment was greatest between adjacent layers of the secondary cell wall. In addition, the fibril alignment is variable from one cell to another. This could be a significant factor between summerwood and springwood where the difference in fibril alignment is maximum in adjacent cells.

4. Pits. Woody plant cells are characterized by the presence of pits between adjacent cells. These recesses in the secondary cell wall distort the normal fibril alignment in the cell walls and are effective stress raisers. The number, size, and distribution of the pits vary from one species to another and, as a result, may have a greater or lesser influence on the magnitude of the stress.
5. Sub-microscopic structure. The pattern of the cellulose in plant cell walls is not continuous. The long chain molecules of cellulose within the fibrils have alternate regions of parallel and non-parallel arrangement. The parallel regions are called crystalline and the disorganized regions are known as the amorphous areas (5). The discontinuity formed by the amorphous regions may serve as a stress raiser in shear parallel to the grain.

<u>Hysteresis</u>

Wood is not a perfectly elastic material. The slightest load on a wood member will induce some permanent deformation too small to measure. In addition, if stress-strain diagrams are made for the loading and unloading of a sample, the points will not coincide exactly but will form a loop, called the hysteresis loop (16)(28). The area inside the loop is directly proportional to the amount of energy lost in the cycle, and the strain after one complete cycle is the permanent deformation. The energy loss is probably due to friction and is given off as heat.

The hysteresis loops occur even within the elastic regions of wood. The hysteresis effect is very slight in wood for a single loading and unloading cycle at very low stress. However, if the stress is greater and if the stresses are repeated with sufficient rapidity, the strain can accumulate until failure eventually occurs. For very low, alternating stresses, the hysteresis loop may be a straight line. As the fatigue loading progresses, the hysteresis loop broadens more and more to eventual failure.

Molecular slip

Repeated stresses in metals result in the formation of "slip bands" in the crystals (9). These slip bands increase with the number of stress applications until failure occurs when the bands cover the entire surface of the crystal. An analogous feature called the slip plane, has been found in the cellulose of wood that has been subjected to mechanical stress (14)(17)(25)(30). There is some doubt regarding the origin of the slip planes in wood, but the possibility certainly exists that these planes represent minute failure in the crystalline region of the fibril. Continued fatigue loading would cause the formation of new slip planes and the enlargement of already existing slip planes to failure.

APPLICATION OF FAILURE THEORIES

This study has shown that wood appears to have a definite fatigue limit in shear parallel to the grain. The exact fatigue limit for a particular sample is difficult to determine in advance because of the strong influence of specific gravity at the plane of maximum shear. The fatigue strength of wood in shear parallel to the grain is different for different species and must be determined experimentally for each species.

The exact mechanism of fatigue failure appears to be different from the mechanism of static failure. Previous research has shown that static failure of wood in compression occurs along a shear plane between the outer and central layers of the secondary cell wall and that the failure spirals along the length of the cell (3). This indicates that the maximum stress position rotates as failure progresses. If this holds true for shear failure under static load, it partially explains the migration of the static, shear failure observed in this experiment. The maximum stress could be transferred through the isotropic compound middle lamella from a strong cell of high specific gravity to a weaker cell of lower specific gravity. This may have taken place since in all cases the migration was toward a region of low specific gravity. It is evident that investigation into the anatomy of shear failure under a static load is essential to the eventual solution of this portion of the problem.

If it is assumed that the theory, postulated above, for the mechanism of static, shear failure is correct, then it is evident that the mechanism of fatigue shear failure is different. The evidence to support this contention lies in the fact that there was no migration of the shear line of failure in the fatigue specimens. Since the line of failure was straight there was little lateral transformation of shear stresses. This suggests several possibilities. First, the possibility exists that the stress occurred primarily in the isotropic region of the compound middle lamella. If this actually happened, then the mechanism of fatigue failure was probably a combination of secondary stresses and hysteresis. The hysteresis loops would be progressively broadened by the energy loss attributable to failure by secondary stresses in the middle lamella. Another possibility for failure in fatigue is that it may occur within the cell wall. The mechanism of failure is then a combination of secondary stresses, hysteresis and molecular slip.

In this study, as in many others in wood research, emperical equations were obtained through laboratory testing and statistical analysis. In original research it is important to first demonstrate the presence of a phenomenon; in this study the phenomenon was shear failure parallel to the grain in wood subjected to fatigue loading. This occurrence was shown to be inclusive by the method of testing and by the manner of failure. If the concent of fatigue in shear for wood is accepted, the next portion of the research should properly be an effort to determine the influence of various agencies on fatigue in shear. In this study, the influence of stress level and specific gravity were studied in an effort to estimate their contribution to variation in fatigue. When all the sources of variation have been explored, it should be possible to begin further research to learn the exact origin and mechanism of fatigue failure in shear for wood. Such research is not possible until all the sources of error have been estimated, to enable the researcher to either elimate or account for them. Such errors may be occasioned by variables that have not been evaluated in this study. These include moisture content, temperature, residual stresses, presence of extractives, degree of lignification, damping capacity, and elastic and plastic deformation. All these variables, however, can be called superficial. They are merely outward manifestations of some internal change in the wood itself. The internal changes constitute the real failure due to fatigue loading. It is the author's intention to continue this research to its logical conclusion.

SUMMARY

1. Wood can be made to fail by fatigue loading in shear parallel to the grain on a tangential plane.
2. There is a linear relationship between shear stress and specific gravity at the line of failure for samples tested in static shear parallel to the grain on a tangential plane.
3. There is a significant regression of stress level and specific gravity at the line of failure on the number of cycles to failure in shear parallel to the grain on a tangential plane.
4. A linear relationship exists between shear stress and specific gravity at the line of failure in wood tested by fatigue loading in shear parallel to the grain on a tangential plane.
5. The early springwood offers the least resistance to loading in shear parallel to the grain.
6. The mechanism of fatigue failure in shear is different from that of static shear failure.
7. The stress level at failure for fatigue shear samples is less than for samples tested under a static load for samples of the same species with comparable specific gravity values.

8. Additional research into the mechanism of fatigue failure in wood is necessary.

APPENDIX I

LIST OF APPARATUS

1. White fir stock from which samples were prepared contained about four and one-half growth increments per inch.

2. Western hemlock from which test samples were prepared contained about twenty growth increments per inch.

3. Douglas-fir stock from which test samples were prepared contained about twenty-one growth increments per inch.

4. Band-saw. 36 inch band-saw, Model B-18388, made by the Yates-American Machine Company, Beloit, Wisconsin.

5. Static Testing Machine. Baldwin-Emery, SR-4 Testing Machine, Model F6T, manufactured by the Baldwin-Lima-Hamilton Corporation, Philadelphia.

6. Fatigue Testing Machine. Sonntag Universal Fatigue Testing Machine, Model SF-01-U, designed by the Sonntag Scientific Corporation, Greenwich, Connecticut.

7. Strain Gages. SR-4 Strain gages, Type AD-7 with a resistance of 120 ohms and gage factor of 1.95. Gages manufactured by the Baldwin-Lima-Hamilton Corporation, Philadelphia.

8. Strain Amplifier. Baldwin SR-4, Type M, Portable Strain Indicator manufactured by the Baldwin-Lima-Hamilton Corporation, Philadelphia.

9. Triple Beam Balance. Cenco Agate Bearing, Triple Beam Balance, made by the Central Scientific Company, Chicago.

10. Drying Oven. Fisher Senior Forced Draft Isotemp Oven, made by the Fisher Scientific Company, New York.

List of Apparatus.-Continued.

11. Volumeter. Mercury displacement volumeter designed by the author from a prototype and made by the Metal Machining Company, Lansing.

12. Volumeter. Mercury displacement volumeter designed by Dr. Everett Ellis, Associate Professor, University of Michigan and made at the University of Idaho machine shop, Moscow, Idaho.

13. Grammatic Balance. Gram-matic Balance made by E. Mettler, Zurich, Switzerland, and distributed in the United States by the Fisher Scientific Company. New York.

14. Calculator. Friden Automatic Calculator Model STW, manufactured by Friden Inc. San Leandro, California.

APPENDIX II

DATA

Table a. Data recorded for white fir samples tested in static shear parallel to the grain.

Moisture Content (%)	Specific Gravity	Shear Stress (psi)
9.46	0.338	492
10.64	0.452	800
9.43	0.317	456
9.66	0.348	575
9.74	0.268	427
10.79	0.439	879
10.69	0.365	678
9.76	0.250	260
10.63	0.304	309
10.75	0.284	564
10.70	0.250	208
9.30	0.232	232
10.73	0.206	204
9.47	0.328	656
10.67	0.306	425
9.40	0.346	435
10.66	0.250	295
10.76	0.228	315
10.78	0.242	385
10.67	0.374	643

Table b. Data recorded for western hemlock samples tested in static shear parallel to the grain.

Moisture Content (%)	Specific Gravity	Shear Stress (psi)
13.87	0.275	910
14.05	0.344	1130
14.06	0.368	1129
13.55	0.296	896
13.63	0.280	817
13.80	0.360	1234
13.77	0.420	1386
13.76	0.446	1498
13.59	0.323	1114
13.56	0.326	1057
13.43	0.338	1249
13.13	0.382	1212
13.09	0.412	1540
12.95	0.301	922
12.95	0.375	1407
12.84	0.398	1251
13.13	0.352	991
13.03	0.374	1084
12.89	0.372	1276
13.44	0.405	833

Table c. Data recorded for Douglas-fir samples tested in static shear parallel to the grain.

Moisture Content (%)	Specific Gravity	Shear Stress (psi)
12.27	0.441	1071
12.44	0.408	825
12.62	0.380	883
12.46	0.404	941
12.59	0.360	756
12.55	0.414	1022
12.27	0.454	1162
12.24	0.389	1263
12.55	0.470	1270
12.56	0.496	1307
12.55	0.391	1011
12.31	0.416	1023
12.01	0.449	1155
12.10	0.505	1397
12.26	0.464	1268
12.40	0.336	781
12.38	0.426	979
12.16	0.473	1323
12.04	0.448	1093
11.94	0.446	1050

Table d. Data recorded for white fir samples tested in fatigue.

Moisture Content (%)	Specific Gravity	Shear Stress (psi)	Cycles to Failure
10.66	0.306	340	1,000
10.56	0.324	448	100
11.11	0.313	294	1,000
10.74	0.285	347	200
10.66	0.338	170	1,650,000
10.93	0.310	429	200
10.67	0.279	242	4,000
11.22	0.297	190	1,250,000
11.32	0.363	225	1,000
11.25	0.282	219	190,000
11.09	0.384	656	50
11.11	0.281	500	300
10.83	0.542	400	10
11.00	0.318	400	40
11.04	0.322	300	400
10.69	0.306	225	4,000
10.71	0.279	200	49,000
10.67	0.294	300	2,000
11.29	0.313	400	5,000
10.08	0.268	350	300

Table e. Data recorded for western hemlock samples tested in fatigue.

Moisture Content (%)	Specific Gravity	Shear Stress (psi)	Cycles to Failure
12.60	0.347	544	100
12.17	0.380	657	175
12.67	0.390	876	5
12.55	0.420	706	500
12.82	0.340	716	10
13.06	0.436	384	10,000
12.81	0.366	604	30
12.84	0.370	439	1,000
11.78	0.366	414	1,000
11.85	0.368	268	200,000
11.66	0.422	334	98,000
11.22	0.410	450	5,000
11.68	0.448	450	2,000
11.74	0.342	450	1,500
9.84	0.358	450	1,000
9.53	0.380	450	3,000
10.74	0.326	634	30
9.65	0.486	734	100
11.69	0.394	782	50
12.33	0.444	450	16,000
11.77	0.384	453	100
11.82	0.350	564	10
12.24	0.354	763	100
12.19	0.379	572	50
12.11	0.512	500	3.000
10.63	0.410	217	750,000
11.69	0.409	466	100
12.47	0.412	784	10
11.33	0.380	191	3,000,000
11.05	0.491	268	3,000,000

Table f. Data recorded for Douglas-fir samples tested in fatigue.

Moisture Content (%)	Specific Gravity	Shear Stress (psi)	Cycles to Failure
11.50	0.532	536	2,000
10.86	0.424	660	50
11.32	0.493	442	9,000
10.55	0.471	847	20
10.91	0.450	454	100
11.35	0.444	511	1,000
11.28	0.386	581	20
11.00	0.432	505	2,500
11.02	0.394	700	10
11.55	0.418	408	5,000
11.19	0.390	404	1,000
11.21	0.442	358	52,000
10.83	0.456	520	200
11.20	0.449	367	1,250,000
11.14	0.402	824	10
11.09	0.420	514	400
11.28	0.491	392	1,200,000
11.06	0.384	464	300
11.22	0.530	602	2,500
10.98	0.439	253	1,500,000
10.87	0.466	428	1,500
10.67	0.440	495	60
9.68	0.396	706	40
10.82	0.430	565	50
10.95	0.504	378	22,000
11.11	0.382	307	2,200,000
11.32	0.313	349	500
10.92	0.520	505	1,000
10.87	0.418	381	21,000
11.13	0.485	498	500

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