THE EFFECT OF SLOPE OF GRAIN AND OTHER WOOD VARIABLES ON ELECTRIC RESISTANCE STRAIN MEASUREMENTS

Thesis for the Degree of M. S.

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William Henry Friday

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THESIS

THE EFFECT OF SLOPE OF GRAIN AND OTHER WOOD VARIABLES ON ELECTRIC RESISTANCE STRAIN MEASUREMENTS

by

William Henry Friday

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies
of Michigan State University of Agriculture and
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MASTER OF SCIENCE

Department of Agricultural Engineering

1959

APPROVED: James S. Boyd

WILLIAM HENRY FRIDAY ABSTRACT

The sensitivity, accuracy and convenience of SR-4 electric resistance strain gages if applied properly on homogeneous materials like steel or aluminum are well known. Wood research can make use of such a strain measuring device, but the effects of slope of grain, the most important single characteristic of wood, have not been investigated thoroughly.

The strain measurements for SR-4 gages were compared to standard deflection calculated strain values for 0, 30, 60 and 90 degree slopes of grain. Because slope of grain can not be isolated from other wood variables, modulus of elasticity, specific gravity or moisture content, they were included in the study. Randomly selected wood samples were cut from straight grained stock so that the grain made the desired angle with the edge of the test specimen.

The results of many tests showed that the slope of grain had an important effect on SR-4 strain measurements. A regression equation having a high correlation showed that the percent variation between the two strain measurement methods increased more than one quarter of one percent per degree of grain rotation. However at zero degree slope of grain the percent variation was within experimental error.

There were indications that in sloped grain material at high values of modulus of elasticity the percent variation tended to increase in compression and decrease in tension. The equations expressing this were not conclusive because they had poor correlation with randomly located experimental data. On straight grained material it was concluded that the modulus of elasticity had little effect on the percent variation between the strain measurement methods.

The percent variation between the strain measurement methods on sloped grain material tended to decrease at high values of moisture and specific gravity. Again the equations expressing these effects were not conclusive. It was concluded that moisture and specific gravity had little effect on percent variation when the material was straight grained.

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I. INTRODUCTION

The potential of using electric resistance strain measurement of wood can be limitless. Radcliffe (8) with his work on elastic constants of wood and Boyd (2) with his work on truss tests indicate the range through which SR-4 electric resistance strain gages have been tried.

The sensitivity and accuracy of SR-4 gages if applied properly on homogeneous material such as steel or aluminum is common knowledge, and wood research needs this type of sensitive accurate strain indicator. The physical make-up of SR-4 strain gages which permits them to be cemented unobtrusively to a structural member coupled with the electric circuitry make remote observations practical. Switching devices make many observations at one time feasible. Such strain measurements made on a wood structure undergoing actual loading conditions would provide data to help modify existing analysis procedures. Since the SR-4 gage is an inexpensive instrument and not removable from a test member, structural systems can be tested to failure without damaging more expensive reusable instruments. This extended strain data is of value in wood design.

Problem

Wood structural analysis has been hampered by the fact that wood does not behave as other homogeneous materials. The use of SR-4 gages in wood research is still questionable. Their reliability in wood testing is not proved. There is printed material available, but reports that no special problems were encountered does not provide the fundamental knowledge to validate unlimited use of SR-4 gages. Because wood is not uniform and is affected by external conditions, there is need for an investigation of the effect of these variable properties of wood on SR-4 strain measurements.

The surface of a wood member to which an SR-4 gage must be applied is not homogeneous. There exist areas of different density due to nonuniform rates of growth during the life span of the tree. These areas known as growth rings produce the grain of a wood member. The slope of grain is probably one of the most variable features of wood.

To isolate the slope of grain as an independent variable is impossible, for the physical constants of wood change with slope direction and density variations which are responsible for the graining effect. Moisture content of wood also influences the physical properties.

Objectives

The objectives of this study follow:

1. To investigate the effect that the slope of grain has on the reliability of SR-4 gage strain measurements.
2. To investigate the effect that the modulus of elasticity has on the reliability of SR-4 gage strain measurements.
3. To investigate the effect that specific gravity has on the reliability of SR-4 gage strain measurements.
4. To investigate the effect that the moisture content of wood has on the reliability of SR-4 gage strain measurements.

II. REVIEW OF LITERATURE

Many excellent papers concerning electric resistance gages found in the volumes of the Proceedings of the Society for Experimental Stress Analysis (1954) were concerned mainly with metal materials. Hetenyi (1950) presented a thorough treatment of the subject of strain gages and gaging methods. The subject matter in these volumes provided experience in use, operation and theory of SR-4 strain measurement.

SR-4 strain gages were not new in wood research. Ernst (1945) pointed out and illustrated that the SR-4 gage had been used for a variety of purposes in the testing of wood and wood products. Yet Radcliffe (1955) expressed that there was a slowness on the part of wood research agencies to realize their potentialities. These statements sounded contradictory, but when compared to the use of SR-4 gages in metals research their use in wood testing was negligible. The major problem Radcliffe (1955) indicated was the large variation of elastic constants in wood which necessitated the calibration and determination of the physical properties for each piece. This calibration would need to be done for all types of strain indicators.

Ernst (1945) stated that the majority of the SR-4 applications in wood testing were done with a scanning recorder to obtain sufficient points for an adequate stress pattern. But Radcliffe (1955) pointed out that enough success had been obtained at his laboratory using an intermittent loading method to conclude reliable results. In either case it was necessary to plot the stress-strain pattern to correct for the inherent creep in wood. Intermittent loading provided the possibility of multiple strain readings at the same load levels. Boyd (1954) in preliminary tests of square beams compared calculated stress values with SR-4 gage values and found the variation within ten percent. These reporters indicated that no special difficulties were encountered in using the SR-4 gage. It was assumed that all the preceding work was done on straight grained wood.

The measurement of strain in wood presented several problems not common to most other materials.

> It has been only in the last thirty or so years that the physical, chemical, and mechanical properties of wood have been sufficiently studied to furnish a basis for the use of wood as an engineered material. Because of woods heterogeneous structure the determination of its basic properties, such as sound transmission and heat conductivity, vary with the longitudinal, tangential and radial direction of each piece of wood it is understandable why the development of basic data on wood has but recently been studied in any degree.[1]

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[1]Nicholas V. Poletika (1954), Slope of grain in engineered wood, Jour. of Forest Products Research Soc., 4, p. 401.

Wood, considered to be orthotropic, has twelve physical constants instead of three. These constants vary in each of the three planes, longitudinal, radial and tangential. However as Radcliffe (1955) admitted, a piece of lumber was not sawn with the respective faces truly radial or tangential. Because of this the strain measured at any point was subject to the variation of the material at that point. When differences in orthotropic constants were small, wood could be analyzed as other homogeneous materials.

A point considered in study of the homogenity of wood was the hollows in the material due to voids in the cell structure. Wood cells are of various sizes and shapes that are firmly united together. In dry wood the cells are generally hollow and empty. As stated in the Wood Handbook (1955) the strength of wood does not depend upon the length of these fibers (cells) but on the thickness and structure of their walls. In this sense these voids do not constitute weakening the wood but do make a nonuniform surface for the application of an SR-4 gage. To correct this situation Ernst (1945) used a liberal coat of bonding cement applied to the wood and allowed to harden before the SR-4 gage was cemented in position.

Slope of grain occurs when the fibers do not run parallel to the main axis of a board. Poletika (1954) believed that slope of grain was the most important single characteristic of wood. This feature of a wood member influenced

practically all of its physical and mechanical properties. Slope of grain is inherent in wood and must be contended with in most boards. Boyd (1954) substantiated the effect of slope on the physical properties when he found in preliminary tests that the modulus of elasticity varied with the direction of the grain in both plywood and fir.

Elastic constants were not only affected by the slope of grain but also by moisture content and specific gravity. The <u>Wood Handbook</u> (1955) published data expressing the variations of physical properties with respect to both. In general the modulus of elasticity decreased as the moisture content increased, and it increased as specific gravity increased.

Testing of small clear timber specimens was clearly specified by the American Society for Testing Materials (1952) for compression tests parallel to grain, compression tests perpendicular to grain and tension tests parallel to grain.

Moisture determinations of timber specimens were included and called for the sample to be dried at a temperature slightly above 212°F until the weight became constant. The loss of weight divided by the weight of the oven-dry wood was the proportion of moisture in the piece. However Markwardt (1943) stated that moisture as thus determined was subject to inaccuracy because the loss in weight included substances in wood other than moisture evaporating at 100°C. Such errors usually did not affect the practical application.

III. PROCEDURE

For this investigation a representative group of wood test specimens were prepared with predetermined slopes of grain to measure their effect on SR-4 gage strain measurement. The group of samples were loaded in a Universal testing machine, and the strain was measured two ways. A statistical analysis was made to determine the effect of slope of grain and other variables, modulus of elasticity, moisture and specific gravity, on SR-4 strain measurements.

Preparation of the Test Specimens

Stock selection

Douglas-fir planks, 2 by 12, from which the test specimens were sawn, were selected from a local lumber yard on the basis of straight uniform grain. Four of these planks were marked and each cut into sixteen 2 5/8 by 10 inch blocks. The longitudinal axis of each block was positioned with respect to the grain so that it intersected the direction of the grain at one of the following angles: 0, 30, 60 or 90 degrees. Four specimens at each slope were cut from one plank. Sixty of the 64 specimens were used as the compression test samples.

Three other planks were likewise marked and each cut into ten 2 5/8 by 20 inch blocks. Only 0 and 30 degree grain

slope samples were obtained from the material. These thirty blocks were used as the tension test specimens. All the test specimens were later sized more accurately.

Establishment of moisture content

The test specimens were divided equally into three groups on the basis of slope of grain, type of testing specimen and parent plank. The wood blocks were placed into saturated salt solution controlled humidity containers in an effort to obtain equilibrium moistures of 10, 15 and 20 percent. Markwardt (6) presented an Equilibrium Moisture-Relative Humidity curve, Figure 1, which served as the basis for selecting the necessary relative humidity level of the containers. Hodgman (5) supplied the necessary data to produce these relative humidities. Saturated solutions of Aqueous Sodium Bromide ($NaBr\text{-}2H_2O$), Sodium Chloride ($NaCl$) and Potassium Chloride (KCl) at 77°F room temperature produced relative humidities of 56, 75.8 and 87 percent respectively.

Heat sealed two mil plastic bags were used as the containers. An example is shown in Figure 2. These plastic bags provided easy access to the wood samples. Heat sealing the bags seemed to provide airtight containers. The bags were opened and the specimens weighed at intervals on a Toledo spring scale.

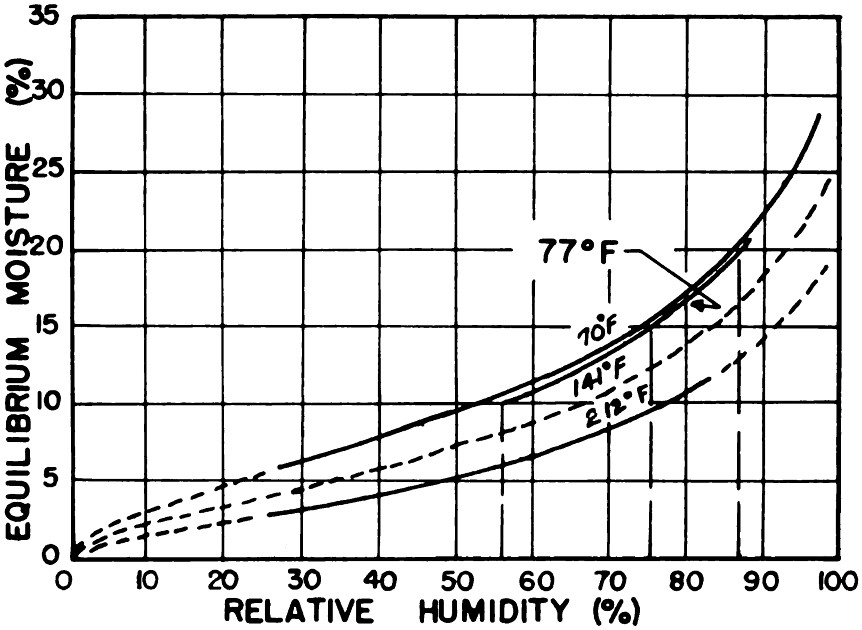

Figure 1. The equilibrium moisture-relative humidity curve.

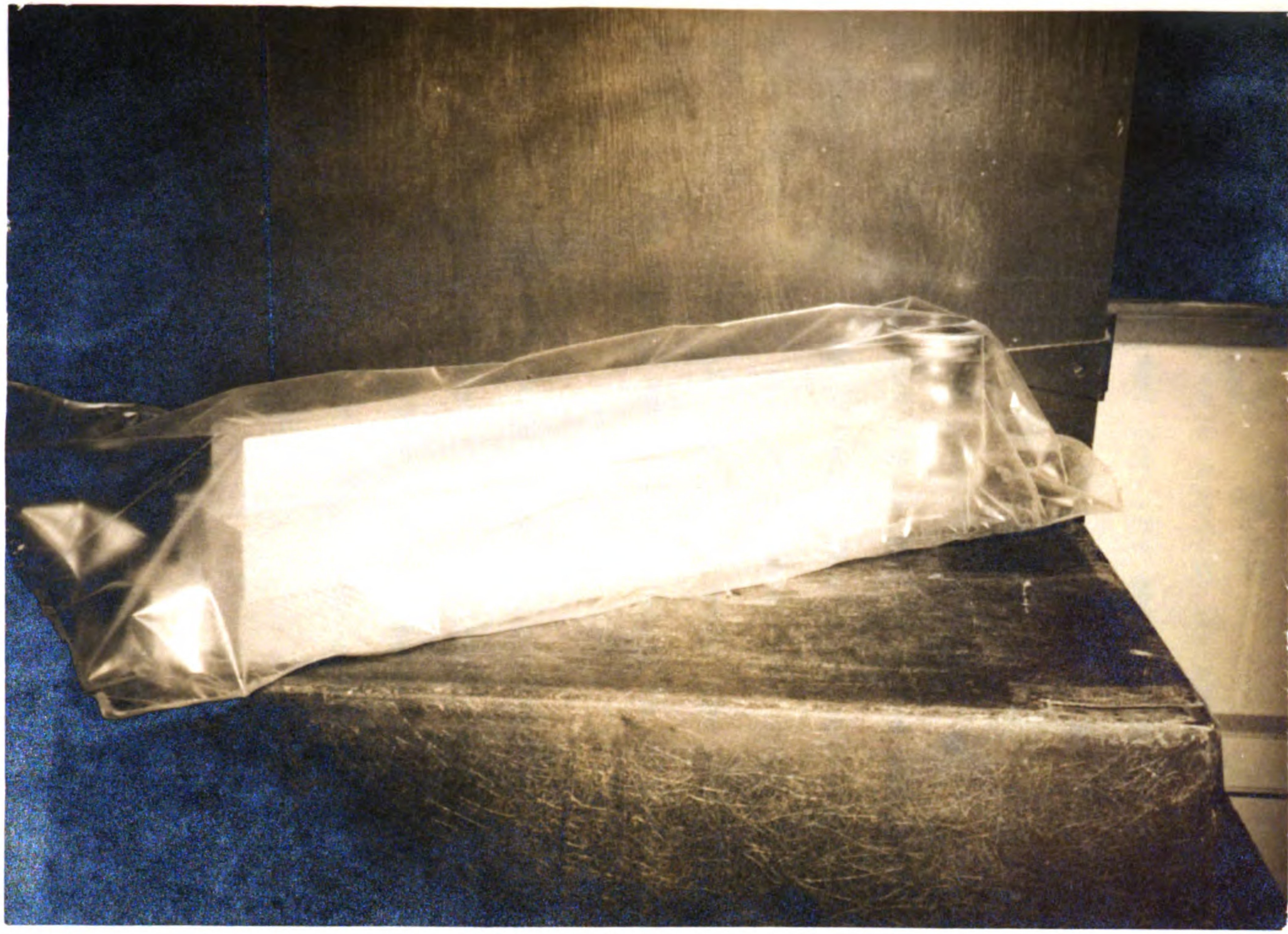

Figure 2. Tension samples in a heat sealed plastic controlled relative humidity container.

When the weight of the sample became constant it was assumed that moisture equilibrium in the wood had been obtained. This process took a period of from four to five weeks. Figure 3 shows a typical weight-time sheet and a weight-time curve used for the purpose of determining when moisture equilibrium was reached.

At the outset of this investigation exact moisture contents of 10, 15 and 20 percent were not expected, but it was believed that a narrow range of moisture around the intended moisture could be obtained. The span between the desired moistures of 10, 15 and 20 percent was great enough to permit a variation of at least one moisture percentage without overlapping the next moisture band. In practice this was not obtained.

There was no attempt made to control the temperature of the sample storage room. A Brown recorder placed in the room recorded only a five degree variation in temperature. This was considered sufficient temperature control for the purpose of the experiment.

<u>Sample sizing</u>

The specimens originally sawn 2 5/8 by 10 inches and 2 5/8 by 20 inches were sized at a later date to 1½ by 1½ by 8 inches for compression testing and 1½ by 1½ by 20 inches for tension tests. This was done to correct any warping or twisting due to a moisture change. The sizing was done after the apparent moisture equilibrium was obtained. At that

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MOISTURE EQUILIBRIUM DATA

SAMPLE B-3-0-15 CONTAINER NO. 10

RELATIVE HUMIDITY 75.8% SOLUTION NaCl

DATE	WGT/g	NOTES	DATE	WGT/g	NOTES
5/19	155	start	6/13	136	gage
5/21	154		6/24	136.5	test
5/25	153.5		6/29	119	dry
6/4	151.5		6/30	119	final
6/8	151.5				
6/8	134.5	sized			
6/13	134.5				

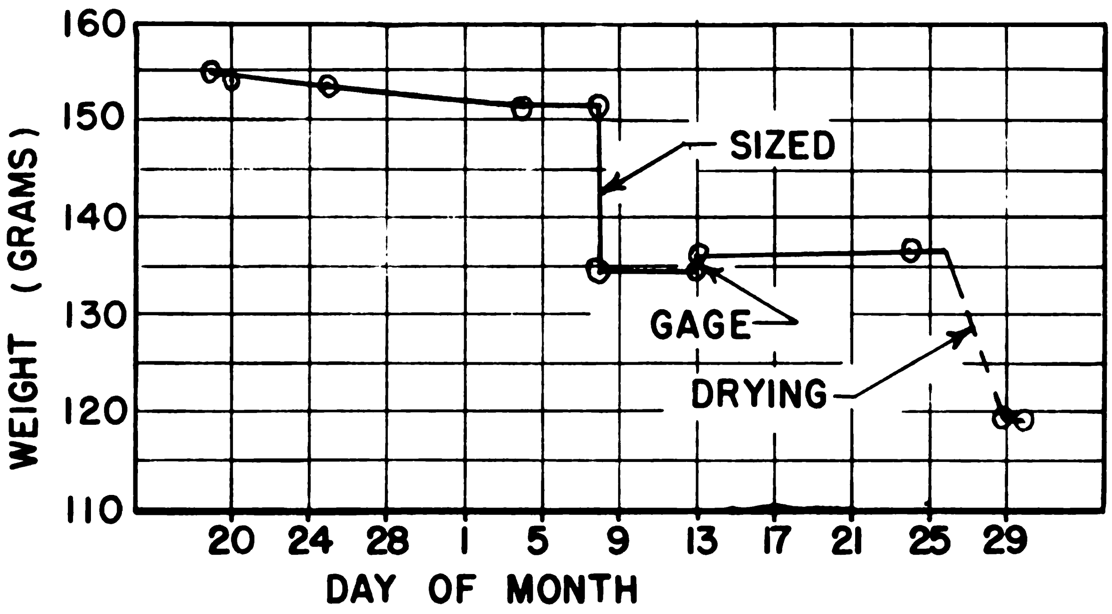

Figure 3. Moisture equilibrium data for sample B-3-0-15 and a graphical plot of weight versus time.

time the specimens were sawn to dimensions of 1/32 of an inch over size and then sanded to size. A smooth surface for the SR-4 strain gage application was obtained. The ends of the compression specimens were sanded square to the axis of the block to eliminate bending during the tests.

The tension specimens were drilled with two ¼ inch holes a distance of 16 inches apart and equidistant from the center line of the block. The tension load was applied at the holes. The tension loading brackets are described under test apparatus. The horizontal and vertical axis of the samples were marked so the SR-4 strain gages could be positioned. Squared marks were made on the specimens so that a six inch gage length compressometer could be attached. The specimens were weighed before and after the sizing operation and returned to the controlled humidity containers until further tests could be performed.

SR-4 application

At the time of SR-4 strain gage application the samples were removed from the humidity chambers and weighed. A special precaution was taken to see that the surface was prepared with a liberal coat of Duco cement to fill pores. The surface of the specimen was again coated liberally with cement and the SR-4 gages applied as recommended in the Baldwin instruction manuals. The gages were gently pressed into position and squeezed lightly until the extra cement rolled from under the edge. Because of the large number of gages which were to be applied a group of pound weights were cut from 2 by ½ inch steel flats and these were placed on the SR-4 gages for a two hour period. Extreme care was taken to square the gage with the axis of the specimen.

Two gages were placed on every specimen so that average strain values could be obtained to nullify any bending effects. Satisfactory application of the gages was obtained as only one dead gage occurred in the 192 tested.

Testing

Test apparatus

A Tinius Olsen 60,000 pound hydraulic testing machine was used to load the specimens for this research. Care was taken that a consistent loading rate of .05 inches per minute as indicated on the load control panel was applied throughout each trial. The machine performed well, and it was found that a load level could be held constant while a series of strain readings were taken.

A standard four dial compressometer having a gage length of six inches was used to measure the deflection of the specimen. The Ames deflection gages were estimated to the ten thousandth of an inch. Upon completion of the tests the gage length was checked by measuring the distance between the gage insert marks on the specimens. It was determined that the gage lengths were consistent.

The 0 degree slope compression tests followed ASTM procedure. The same size specimens were used for the 30, 60 and 90 degree slopes. ASTM standards were deviated from for the tension test so that sufficient space would be available for the application of the SR-4 gages. The resulting specimen was prismatic throughout and of the same cross sectional area as that of the compression sample. It was necessary to devise a bracket to suspend the tension samples in the testing machine. A standard metal test specimen was cut in two, and a three inch piece of channel was attached to each half. These channel sections were bolted to the specimen with $\frac{1}{4}$ inch bolts. The metal test specimen ends permitted the use of the standard spherical tension test mounts. Axial loading resulted from their use.

A type AM strain indicator manufactured by the Young Testing Machine Company was used to read the SR-4 strain values. This strain indicator was calibrated to read directly in microinches of strain.

Because there were two sets of SR-4 strain readings to take on every specimen a switching mechanism was devised. The basic element of this was a war surplus Air Force radio communication channel selector. At first it was thought that all the SR-4 leads would have to be soldered into the circuit so the channel selector was wired for all seven channels. This would permit three specimens to be soldered in the circuit at one time. However a circuit using alligator

clips was tried, and it was found that only a difference of one tenth an ohm existed between the two types of circuits. It was decided to use the alligator clips not only because they would provide a quick connection but also all the specimens could be handled with the same circuit throughout the investigation.

During the investigation of the SR-4 circuit a reading consistency test was performed with both potential operators alternately reading the instrument. The results of this test using two SR-4 gages under a load showed that the two channels selected for use could be read within a spread of 1.7 microinches of strain.

A temperature compensating dummy SR-4 gage was used during the tests. The actual test equipment is pictured in Figure 4, and a schematic diagram of the testing arrangement is found in Figure 5.

Specimen loading

It was planned that during this investigation all loading would be done within the plastic range. To predetermine the load level and gain experience operating the hydraulic testing machine three blocks at each slope similar to the test specimens were loaded until failure. The average loads required to produce failure of these blocks were 517, 3647, 1747 and 1160 pounds for 0, 30, 60 and 90 degree slope respectively. The Wood Handbook (10). allowable stress values

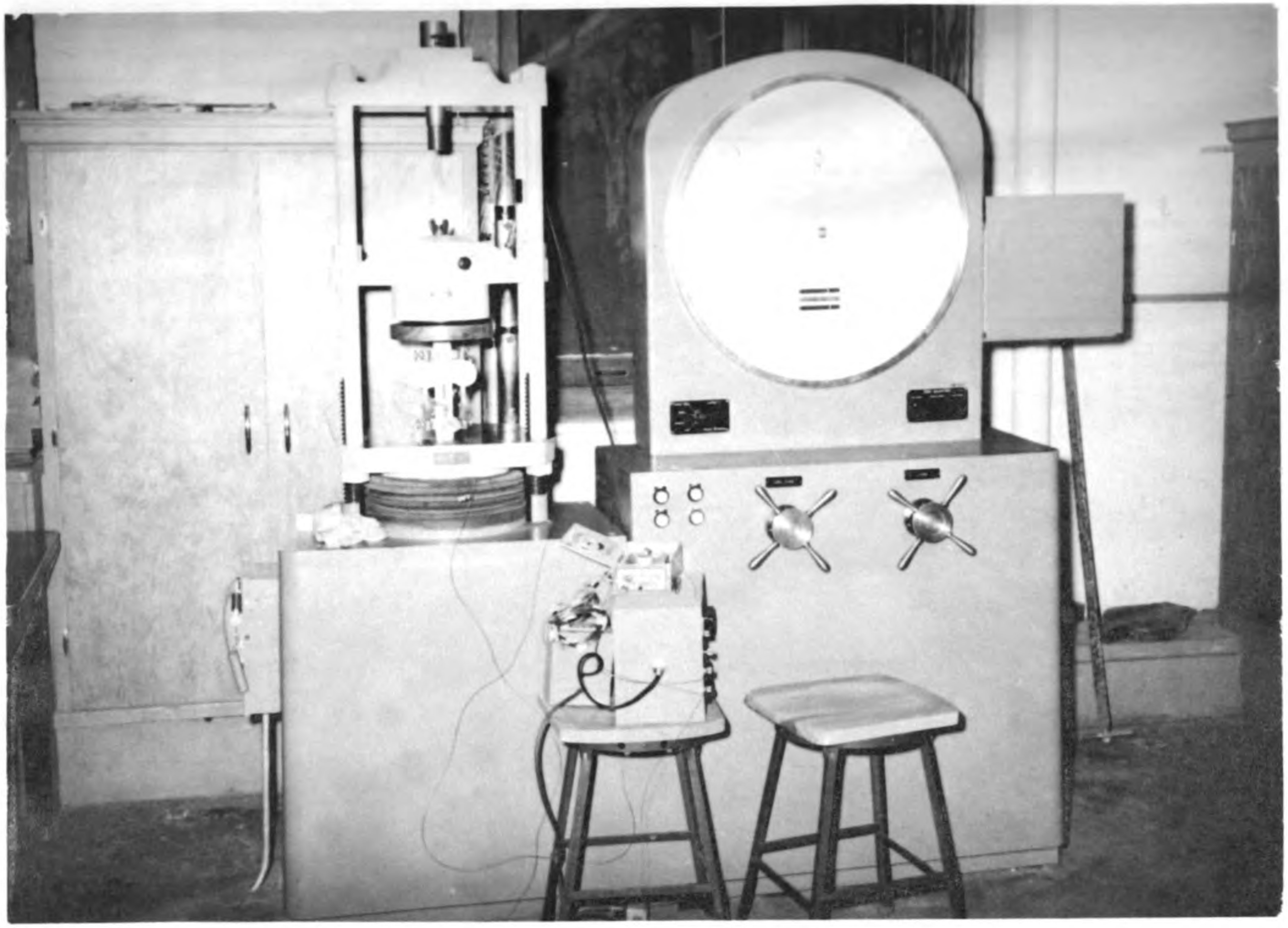

Figure 4. The testing equipment with a specimen under test

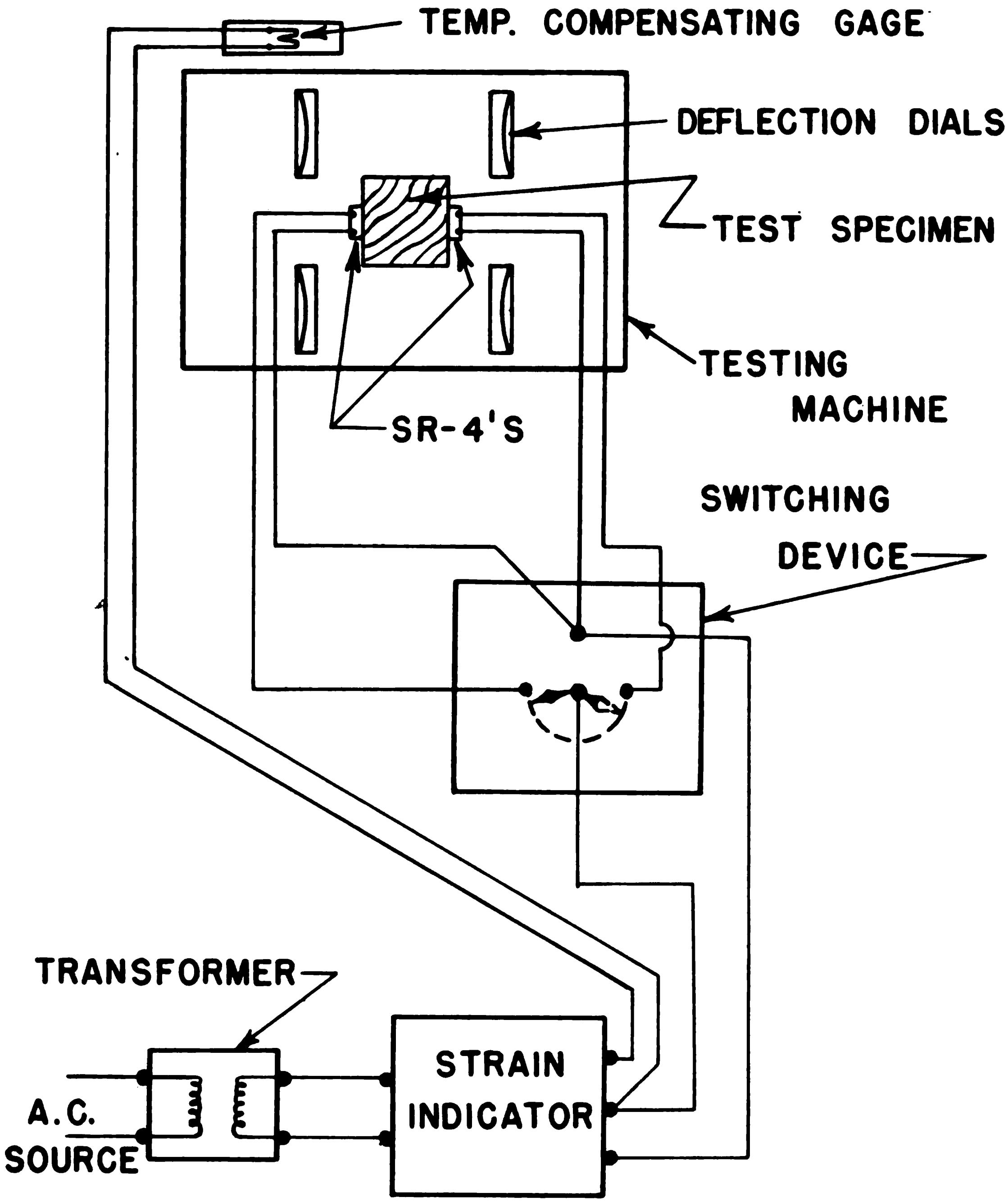

Figure 5. A schematic diagram of the testing arrangement

would permit using 3500 psi stress parallel to the grain and 800 psi stress perpendicular to the grain for Douglas-fir. Maximum test loads for the slopes of 0, 30, 60 and 90 degrees were set at 8000, 2000, 1200 and 800 pounds respectively. These loads were slightly over 50 percent of that required to produce failure and would be 3555 psi for the 0 degree samples, 889 psi for the 30 degree samples, 533 psi for the 60 degree samples and 355 psi for the 90 degree samples.

During testing it was not possible to obtain the maximum load for all the higher slope specimens due to premature failure. The data in these cases was taken only to that point at which a constant strain could be maintained for a specific load. It was impossible to read either a continually moving deflection dial or an unbalanced galvanometer needle.

The procedure for loading the specimens was as follows:

1. An initial load of 200 pounds was placed on the sample; the deflection dials were zeroed, and initial SR-4 strain readings were taken.
2. Intermittent deflection and SR-4 strain readings were taken at loads of 400, 600, 800, 1000, 1200, 1500, 2000, 3000, 5000 and 8000 pounds. In some cases intermediate readings were taken in the high sloped samples so that more points would be available for analysis.

Method of Analysis and Calculations

Calculation of strain values

The calculation of the deflection determined strain value was done by summing the four compressometer readings at each load and dividing by four. This average was then divided by the gage length of six inches to produce the strain value in inches of deformation per inch of length.

The SR-4 readings were made on a Young type AM strain indicator which read directly in microinches of strain. The zero load strain reading for each gage was subtracted from the strain value at each load position. The two strain differences at each load were averaged to eliminate bending effects on the sample. The result was an average SR-4 strain value for each load increment.

Regression equation calculations

Each set of data, both by SR-4 and deflection method, was plotted on a strain-load graph. The regression equation for this data was determined using the following general formula:

$$e = a + b\,(L - \bar{L})$$

where

$$a = \bar{e} = \frac{\sum e}{N}$$

and

$$b = \frac{\sum (L - \bar{L})e}{\sum (L - \bar{L})^2}$$

The resulting b value was the reciprocal of the slope of line for a load-strain curve.

The standard deviation was determined for each equation. A t test for significance was performed upon the sample slope values at the 90 percent confidence level. The equation used for the t test was as follows:

$$t = \frac{b_s - b_d}{S\sqrt{\frac{2}{\sum (L - \bar{L})^2}}} \quad \text{where}$$

$$S^2 = \frac{\sum (e_s - \bar{e}_s)^2 + \sum (e_d - \bar{e}_d)^2 - (b_s^2 + b_d^2) \sum (L - \bar{L})^2}{N_s + N_d - 4}$$

Modulus of elasticity calculations

The modulus of elasticity for each sample and by both strain measurement methods was determined two ways. The first was to divide the b term of the regression equation into the reciprocal of cross sectional area for each sample. The second method was to divide the maximum load by both the cross sectional area of each sample and the strain value at the maximum load. Both methods produced identical values for the modulus of elasticity.

Modulus of elasticity adjustment

The modulus of elasticity is known to vary with moisture change. Adjustments were made to correct each E value to its equivalent at the 12 percent moisture level. The following equation was used for these calculations (10):

$$\text{Log } E = \text{Log } E_1 + (M_1 - 12) \frac{\text{Log } E_{12}/ E_g}{(M_p - 12)}$$

Strain difference calculations

Strain difference between the two strain measurement methods was calculated for each sample at the maximum load level by using the regression equation. Two calculations were necessary for the strain difference (one at the maximum load and the other at zero load). The true maximum strain was the algebraic sum of the strain at the maximum load and the strain at zero load. The strain difference at the maximum load between the measurement methods was the difference between the two maximum values. The strain difference at any intervening load would be directly proportional.

Moisture and specific gravity calculations

The percent moisture (M) content of the samples was calculated by the standard manner of dividing the weight loss of an oven-dry sample by the final sample weight. Care was taken that the gage weight was subtracted from the divisor or final weight before it was divided into the weight loss of the oven dried sample. Specific gravity (G) was the resultant of the final weight of an oven dried sample less the gage weight divided by the weight of an equal volume of water.

Method of analysis

The method of analysis for this research was to establish statistically the constants and physical properties of each sample and to plot graphically and to determine statistically the prediction equations for this data with respect to the variable. The following investigations were made:

1. Modulus of elasticity variation.
2. Percent modulus of elasticity variation-slope of grain relationship.
3. Percent modulus of elasticity variation-modulus of elasticity relationship.
4. Percent modulus of elasticity variation-specific gravity relationship.
5. Percent modulus of elasticity variation-moisture relationship.

IV. RESULTS

For convenience and easier reading the following shortened forms are used in this section:

1. The percent of modulus of elasticity variation is referred to as the percent variation.
2. A slope of grain sample or group is referred to by the numerical value of its slope followed by the first letter of the type load applied; for example, 30°C group means the 30 degree compression loaded slope of grain group.
3. The terms modulus of elasticity, specific gravity and moisture content are referred to by their common notations of E, G and M respectively.

The standard deviations of the load-strain regression equations increased as the slope of grain increased (Appendix Tables A and B). Table I presents a summary of the range of the standard deviations for all slope of grain groups and the coefficients of variation within each group.

The range of standard deviations for the load-strain equations widened as the slope of grain increased for both the SR-4 and deflection gage methods indicating difficulty in making accurate strain measurements. The coefficient of variation of the standard deviations was less in each group for the deflection calculated equations than its counterpart by SR-4. This did not mean that one method was more accurate than the other but that one was influenced less by other factors; for example, Poisson's ratio or shear in the grain line. The deflection gage measured an average deformation between two pairs of points without regard to what took place between while the SR-4 was adhered to the surface of the wood in a small increment of length and was subjected to local variation.

TABLE I

SUMMARY OF STANDARD DEVIATION RANGE

Grain Slope	SR-4 Method		Deflection Method	
	Range $x10^{-4}$	Coef. of Variation	Range $x10^{-4}$	Coef. of Variation
0°C	.05-1.12	111	.11-1.04	46
30°C	.19-1.84	70	.18-1.18	48
60°C	.02-4.46	77	1.13-9.12	64
90°C	.44-3.82	69	1.16-5.25	40
0°T	.02-0.18	61	.02-0.18	51
30°T	.03-0.35	85	.05-0.85	96

The two E values calculated for each sample varied through a wide range (Appendix Tables C and D). Table II compares the mean E values of the 0°C group and the coefficient of variation for each method with the <u>Wood Handbook</u> (10) values.

TABLE II

MODULUS OF ELASTICITY
STRAIGHT GRAINED SAMPLES

Source	No Moisture Correction		Moisture Corrected to 12%	
	Ex10^5	Coef. of Variation	Ex10^5	Coef. of Variation
SR-4	175.17	22.5	182.72	22.6
Deflection	179.17	19.9	187.25	20.1
Handbook[1]	______	____	195.00	22.0

The mean experimentally determined E values were slightly less than accepted handbook values. This was attributed to a lower than average G value for the experimental samples. The mean G value for the samples was determined to be .44 and a handbook value was given at .48. The mean E value by both methods was within the 22 percent coefficient of variation range given. The coefficient of variation for the experimentally determined E values was similar to the handbook value. This illustrated that the wood samples were quite typical of average Douglas-fir.

As expected E decreased as the slope of grain increased, and the coefficients of variation increased with the slope of grain. Table III summarizes these facts.

[1]Handbook values mentioned in this section were taken from the Wood Handbook (10).

TABLE III

MODULUS OF ELASTICITY
ALL SAMPLE GROUPS

Sample Groups	SR-4 Method		Deflection Method	
	Mean E $x10^5$	Coef. of Variation	Mean E $x10^5$	Coef. of Variation
0°C	182.72	22.6	187.25	20.1
30°C	27.75	24.0	32.14	24.8
60°C	6.25	47.5	5.22	25.9
90°C	3.52	38.9	2.86	21.3
0°T	247.63	19.2	267.57	19.4
30°T	41.58	26.9	39.07	26.6

There were no handbook E values for wood sloped 30 and 60 degrees and no specific value for E perpendicular to the grain listed, but there was an E_r/E_1 handbook ratio which would compare to an E_{90}/E_0 ratio of the data presented in Table III. The handbook ratio value for E_r/E_1 was .068. The experimentally determined E_{90}/E_0 value of .019 for the SR-4 method and .015 for the deflection method was unusually low. The E values obtained for the tension samples were higher than handbook values.

The coefficient of variation values followed the same pattern for both measurement methods increasing through the 60°C and falling off for the 90°C groups. The 30°T coefficient of variation value was higher than 0°T in both methods.

Table IV presents the extremes in percent strain difference and the average percent difference for the slope of grain groups.

TABLE IV

PERCENT STRAIN DIFFERENCE

Slope Groups	Range (percent)	Average (percent)
0°C	1.29-24.72	7.70
30°C	.82-58.80	16.00
60°C	.03-88.56	26.45
90°C	2.66-55.79	23.67
0°T	1.03-24.79	10.71
30°T	2.12-56.06	21.81

The difference between the extremes of percent strain difference widened with increased slope of grain as did the load-strain curve standard deviations (Table I). The increase of the average percent strain difference to the 60°C group and the slight drop for the 90°C group was similar to the results obtained for the E coefficient of variation (Table III). The tension groups followed the same pattern with higher values.

The indicated strain by SR-4 was both higher and lower than the strain calculated by the deflection method. This occurred about equally for all grain slopes except for the

30°C group. In this group the SR-4 strains were almost all greater than the deflection calculated values.

In this section it was shown that the slope of grain increased variability of strain readings in three different ways. These were:

1. The increase of the range and coefficient of variation of the standard deviations for the load-strain curves.
2. The increase in the E coefficients of variation.
3. The increase in the range and average value for percent strain difference between the two methods of strain measurement.

Modulus of Elasticity Variation

The best criteria for discussing variations between the two methods of strain measurement is the modulus of elasticity (E). This is the most direct and meaningful comparison which can be made because E is a function of both stress and strain. If actual strain difference is used it would have to be qualified as a percentage and for a specific load. The deflection method E values will be used as the standard or basis for comparison because they are influenced less by the orthotropic properties of wood.

Figures 6, 7 and 8 are graphs which plot E determined by SR-4 and deflection methods. They show the E variation between the two methods. Variation limits of 10 percent

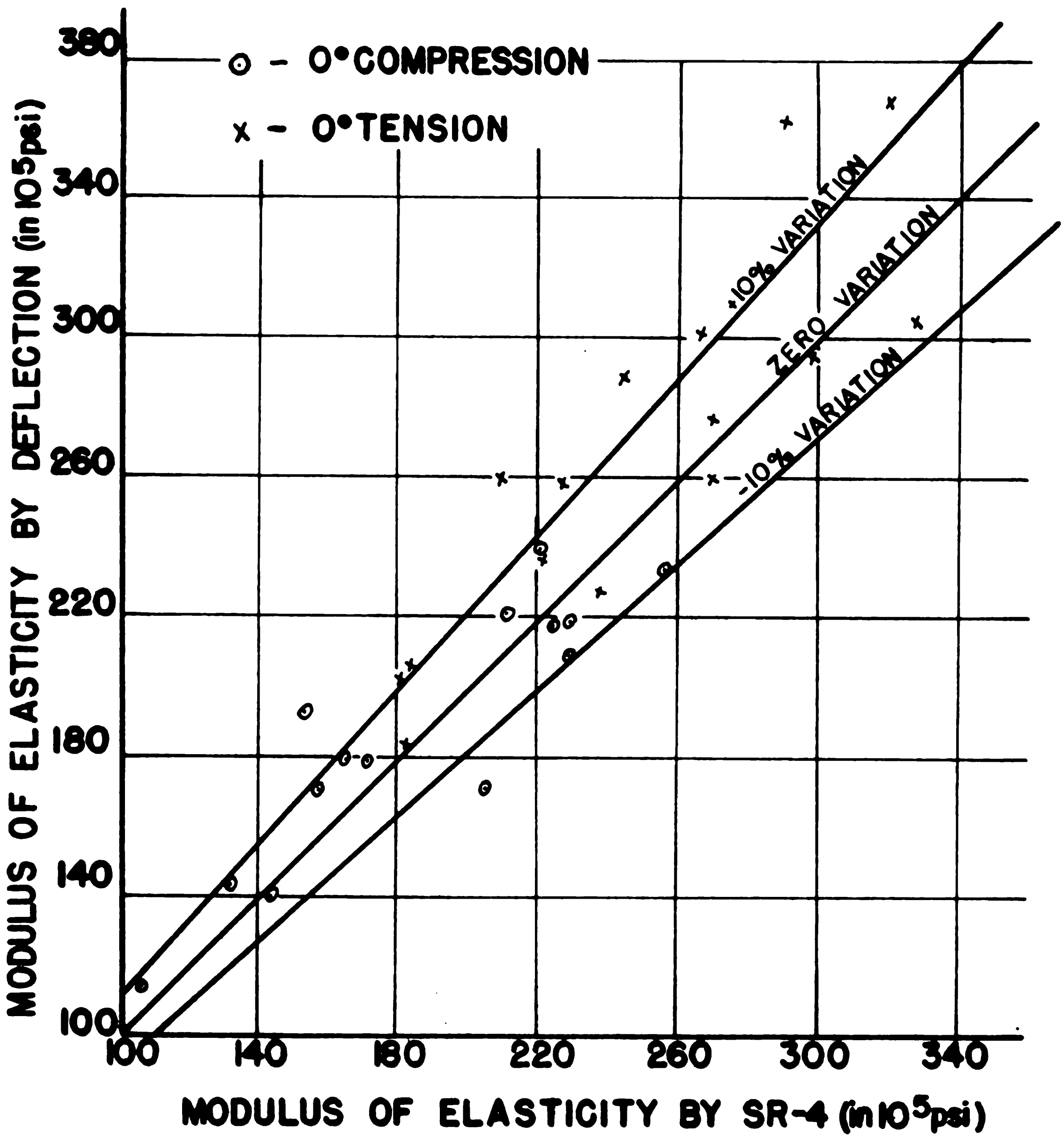

Figure.6. Modulus of elasticity variation between two strain measurement methods at 0° grain slope.

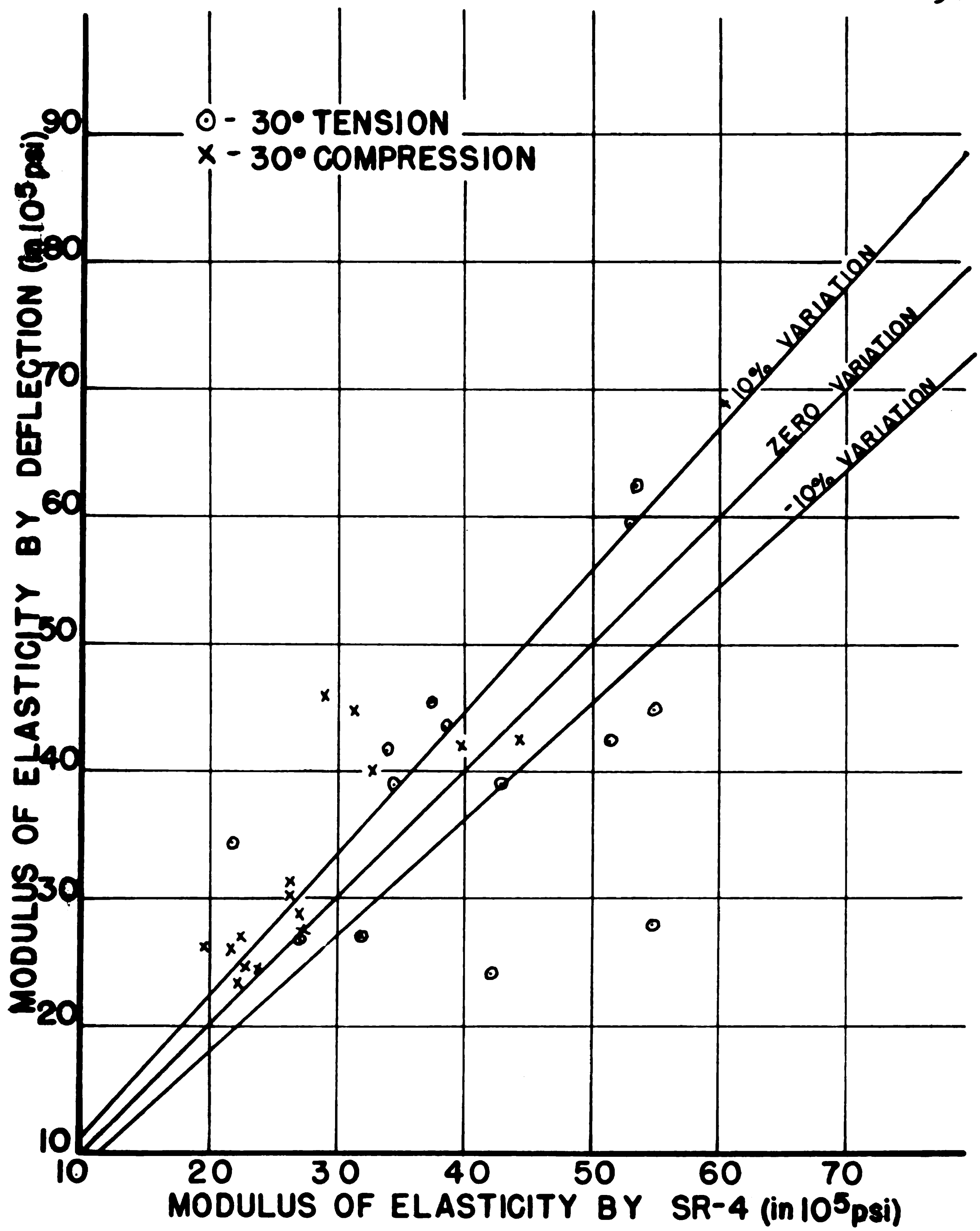

Figure 7. Modulus of elasticity variation between two strain measurement methods at 30° grain slope.

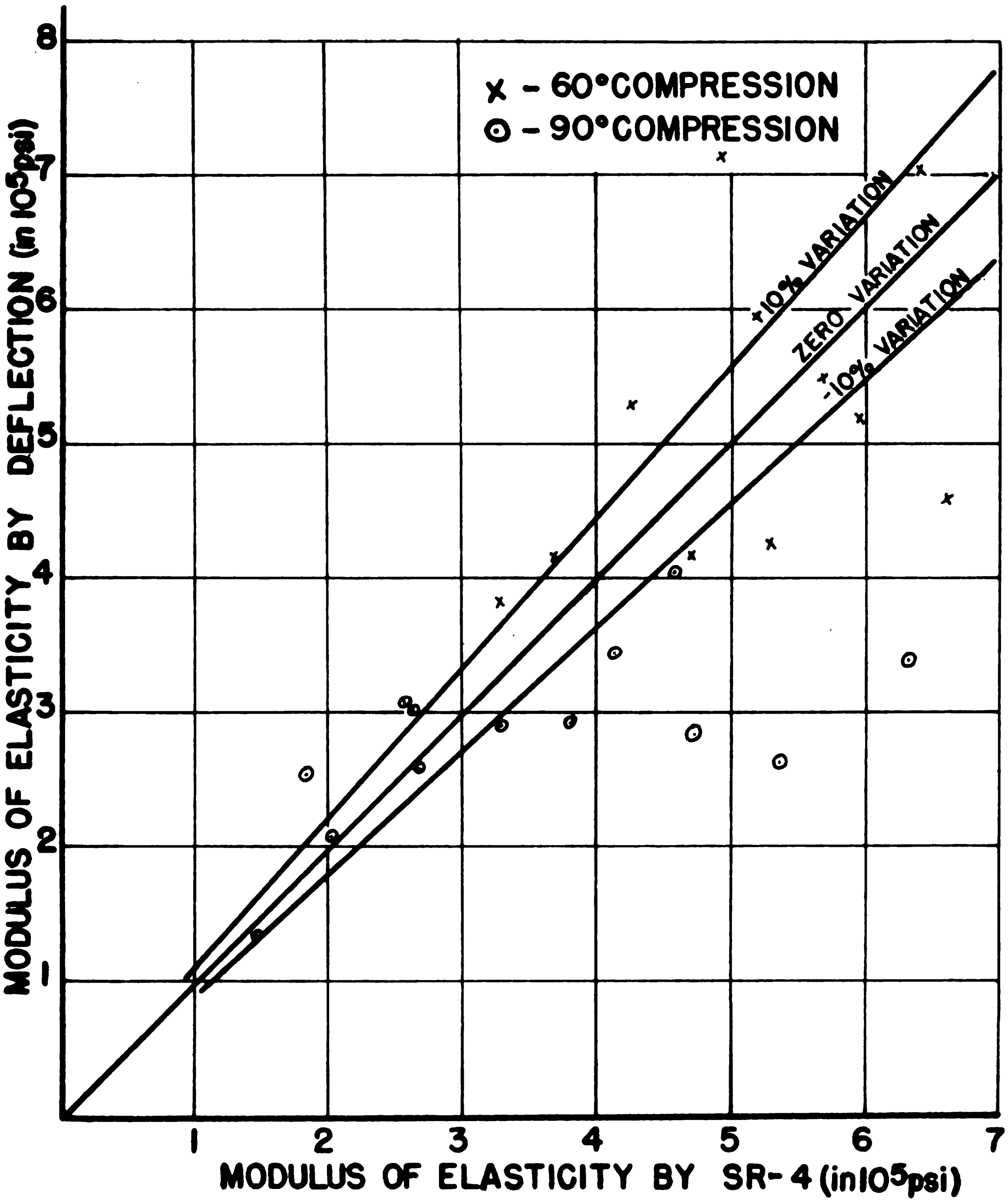

Figure 8. Modulus of elasticity variation between two strain measurement methods at 60° and 90° grain slope.

were established because the 10 percent figure is generally considered to be allowable error in wood research.

Figure 6 is a plot of the 0°C and 0°T groups. Only two of the compression samples had a variation which exceeded 10 percent while eight of the tension samples exceeded the limit. All the tension samples which had greater variation than 10 percent had higher E values by the deflection method than by SR-4 gages. This might be due in part to the difficulty of attaining uniform stress distribution in wood tension samples.

Figure 7 is a plot of the 30°C and 30°T values. Seven compression and eleven tension samples exceeded the 10 percent variation level. Samples in the 30°C group exceeded the 10 percent variation limit 3.5 more times than did samples in the 0°C group and 1.25 more times in the 30°T group than the 0°T group. In the 30°T group SR-4 method variations were both higher and lower than the deflection method values when in excess of 10 percent. This differed from the 0°T group.

In Figure 8, for 60°C and 90°C groups, ten of the 60°C and eleven of the 90°C samples exceeded the 10 percent variation level. This represented an increase of 5.0 and 5.5 times the samples exceeding the 10 percent variation in the 0°C group.

It was found that E exceeded the 10 percent variation limits more frequently as the slope of grain increased.

This was not in agreement with the work done by Youngquist (11) in 1957. He found little difference between compression E values obtained by SR-4 and other deflection caloulated methods for slopes of grain of 0, 45 and 90 degrees. This difference was probably due to different gage lengths. In all cases Youngquist used a short deflection gage length, and this might have subjected the gage to local variation and the influence of slope of grain.

A t test performed on the regression equation slope coefficient, the reciprocal of the E value when corrected to the proper units by the area, showed that at the 90 percent confidence level nine of the fourteen 0°C samples had slope coefficients which were significantly different (Appendix Tables A and B). It also showed that slope coefficients of eleven of fifteen 0°T samples, ten of fifteen 30°C samples and twelve of fourteen 30°T samples were significantly different. No t tests were performed on the 60°C and 90°C samples. In all cases samples which exceeded the 10 percent variation limit had slope coefficients which were significantly different.

The Effect of Slope of Grain on the Percent of Modulus of Elasticity Variation

The slope of grain was assumed to be the most important variable considered because as reported (7) the physical properties of wood are influenced more by slope of grain than by any other factor. Figure 9 is a graph representing the effect of slope of grain (Ø) on the percent variation (P). This graph shows that the assumption was correct.

The regression equation for the weighted percent variation means of the compression loaded slope of grain groups was:

$$P = 7.296 + .281\ \phi$$

This equation had a correlation coefficient of .965 which indicated a good linear fit of the data and high correlation of the variables. The equation indicated that the expected variation between the two strain measurement methods at zero slope of grain was seven percent. This figure was good considering the methods of measurement and the material under test. The most important result was that the slope of the regression equation line showed that the effect of slope of grain was greater than one quarter of one percent variation per degree of angle rotation. This was ascertained to be greater than allowable experimental variation and represented a sizable influence on strain measurements.

The regression equation for tension loading plotted from only two mean percent variation values was:

$$P = 9.37 + .561\ \phi$$

This equation, having only two points, was not of significant value, but its slope of line agreed with the slope of line obtained for the compression loaded group. The above equation had a slope or rate of change of percent variation

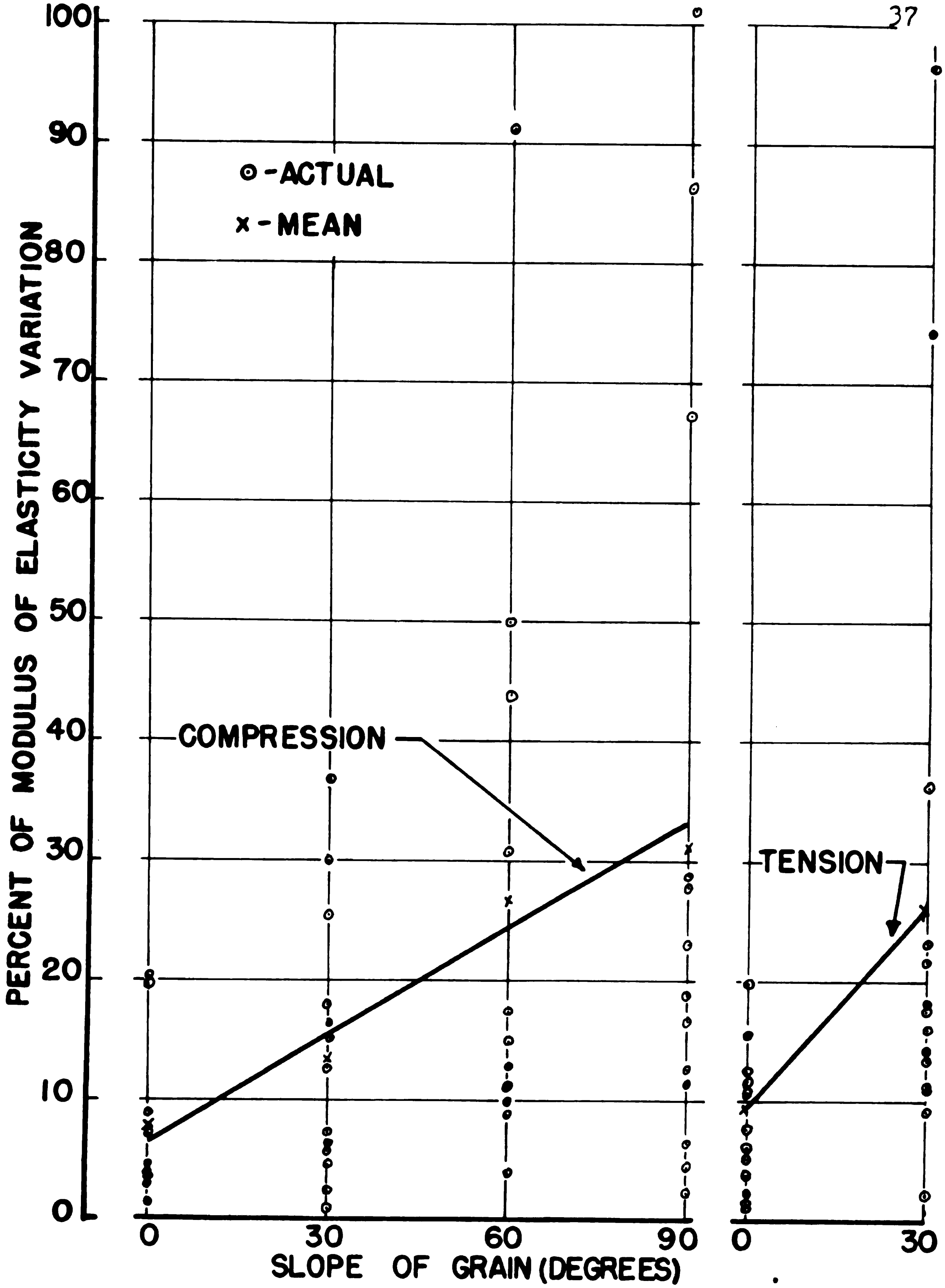

Figure 9. The effect of slope of grain on the percent of modulus of elasticity variation.

equal to twice that for the compression group. This was not considered valid. It was noted that the percent variations for the tension groups were larger than for comparable compression samples. This was true for E and G values also. It was expected that the rate of change of percent of variation would be higher for the tension samples due to these results.

The Effect of Modulus of Elasticity on the Percent of Modulus of Elasticity Variation

Another wood variable considered with slope of grain was modulus of elasticity (E). Figures 10, 11 and 12 show the plotted experimental data (Appendix Tables C and D) and the regression equation line for each slope of grain group. Table V presents the regression equations and their correlation coefficients for each slope of grain group.

TABLE V

THE EFFECT OF MODULUS OF ELASTICITY ON PERCENT VARIATION

Slope Group	Regression Equation	Correlation Coefficient
0°C	P = 10.984 - .0173E	.013
30°C	P = -6.857 + .629E	.237
60°C	P = 25.063 + 9.579E	.298
90°C	P = 8.220 + 8.121E	.027
0°T	P = -2.909 + .0459E	.162
30°T	P = 71.940 - 1.171E	.224

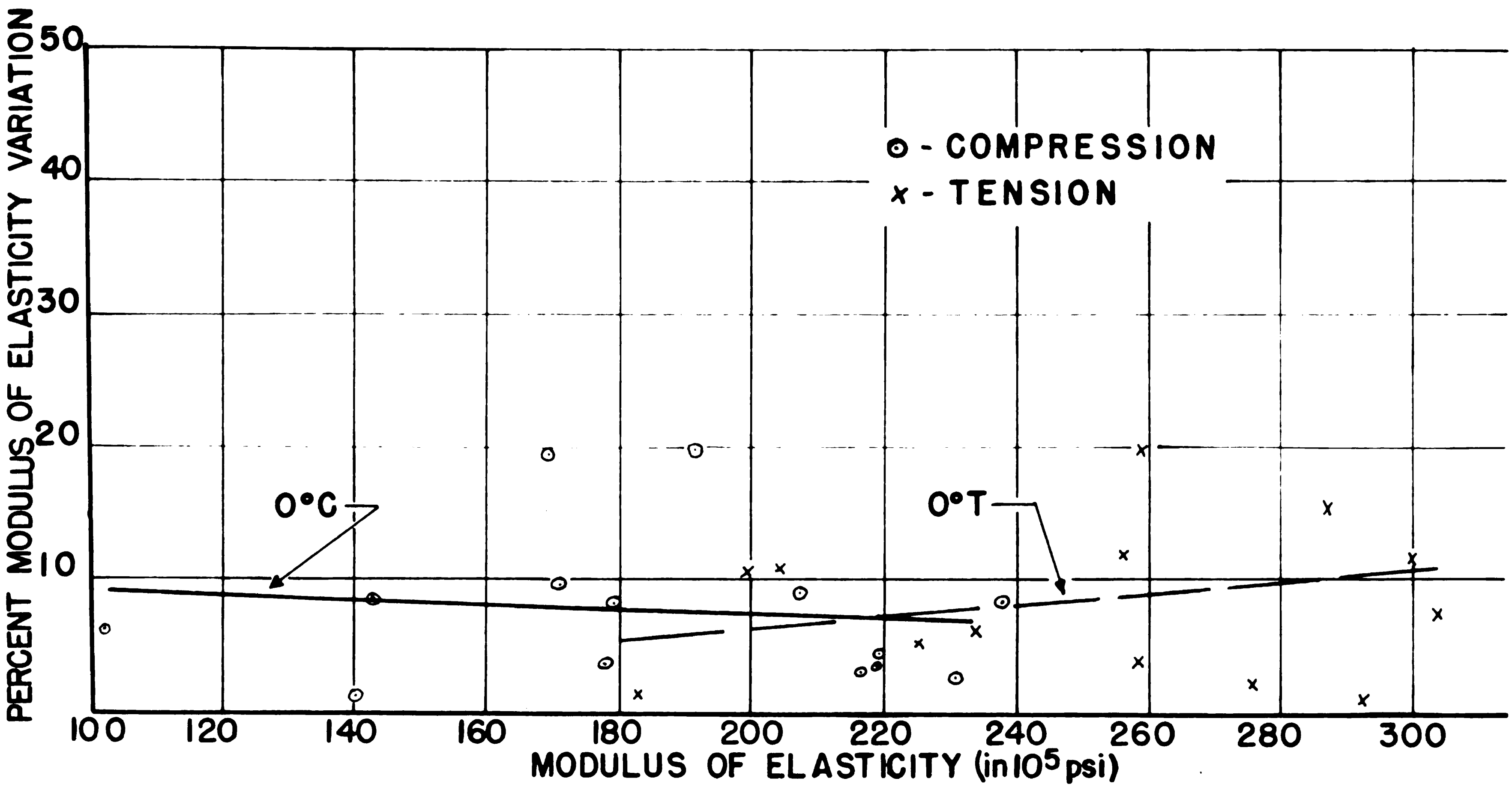

Figure 10. The effect of modulus of elasticity on the percent of modulus of elasticity variation at 0° grain slope.

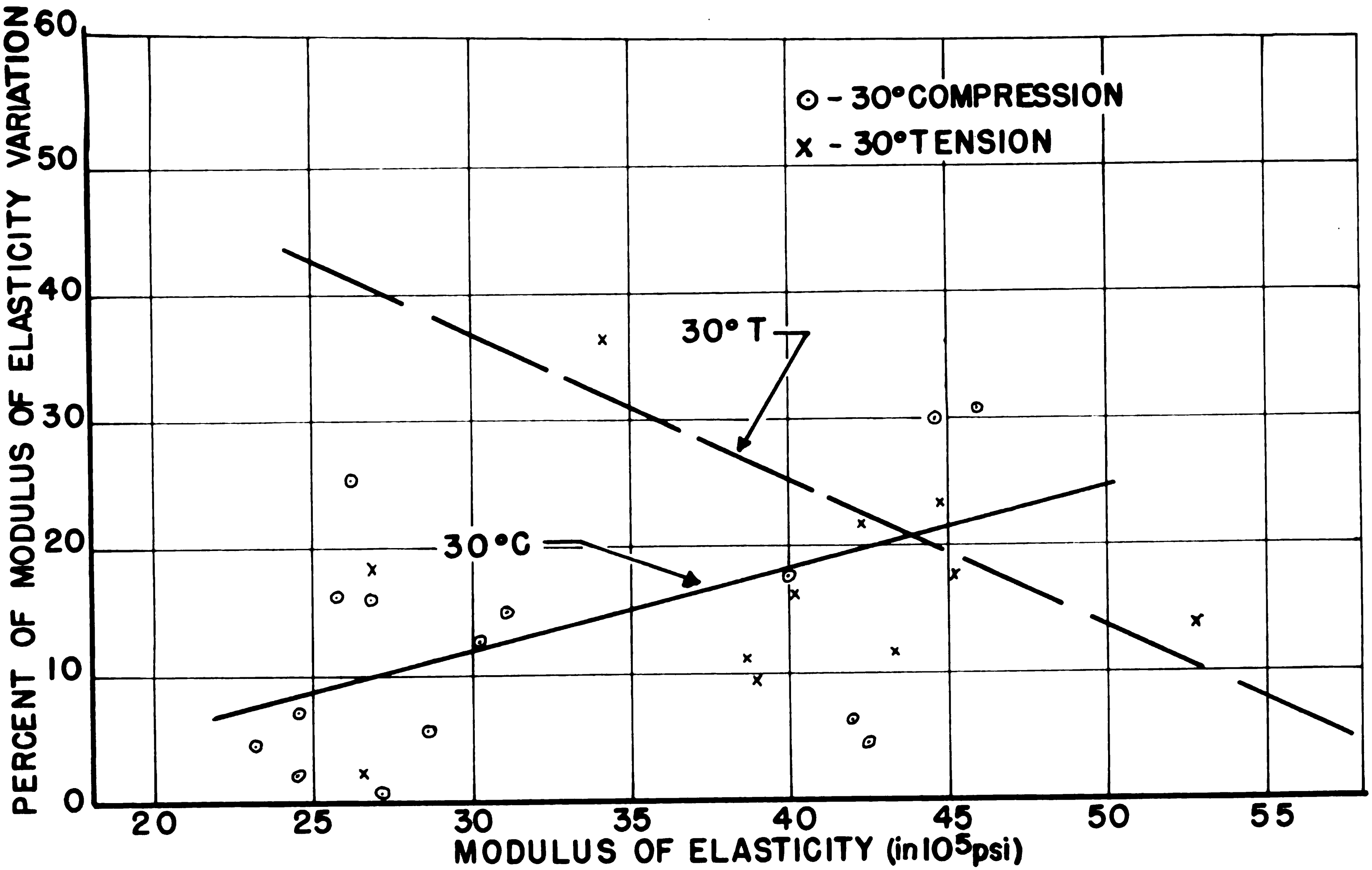

Figure 11. The effect of modulus of elasticity on the percent of modulus of elasticity variation at 30° grain slope.

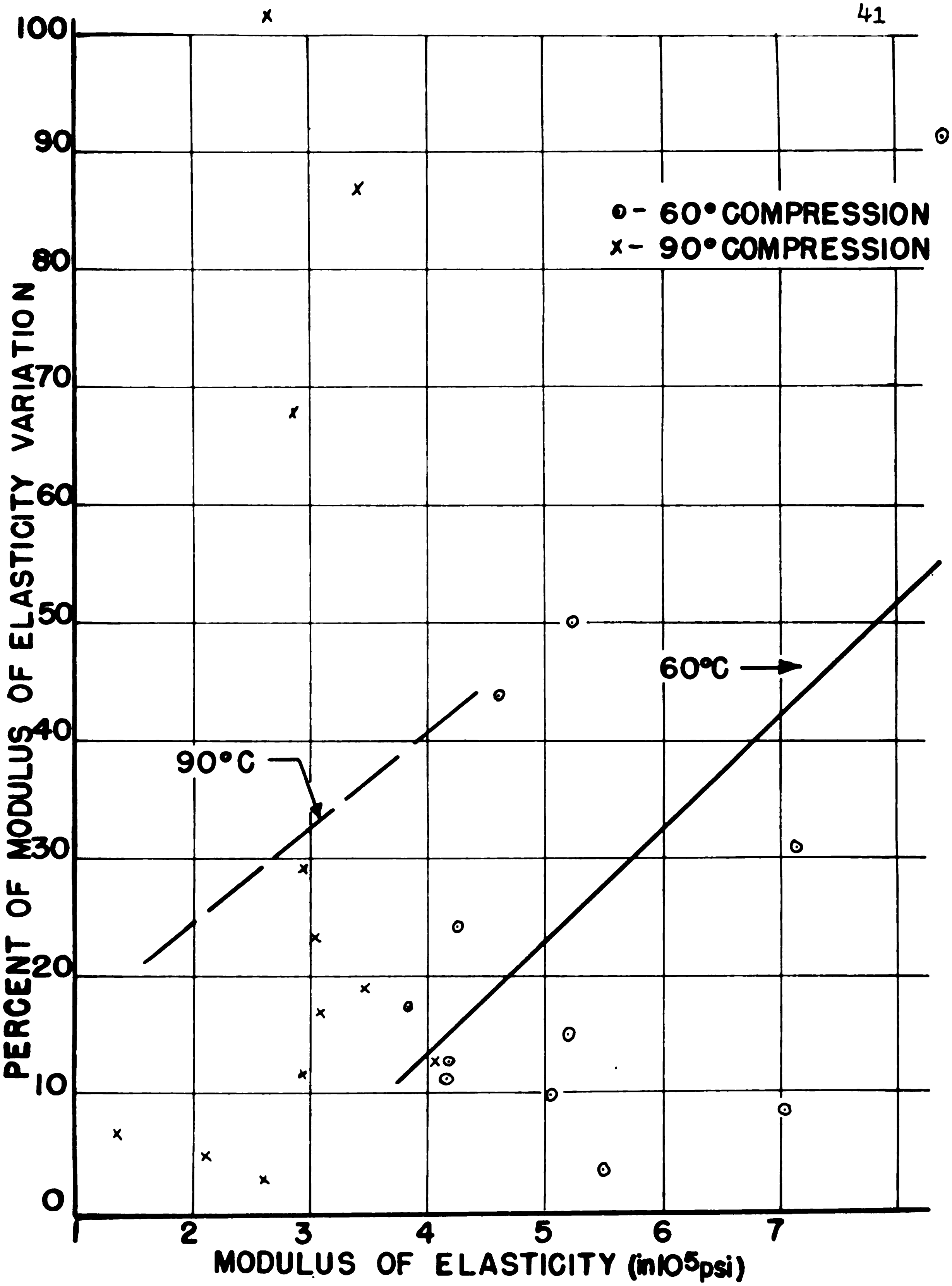

Figure 12. The effect of modulus of elasticity on the percent of modulus of elasticity variation at 60° and 90° grain slope.

The low correlation coefficients indicated a poor linear fit of the experimental data, but no reason was found to use nonlinear equations. The random location of the data contributed to the poor correlation coefficients. Although the 30°C, 30°T and 60°C groups showed a higher correlation between the percent variation and E, this was not considered sufficient to indicate reliable prediction equations.

The effect of E on the percent variation illustrated by the regression equations for both zero degree groups was almost negligible although the slope of the lines disagreed. The remaining compression loaded groups indicated a greater effect of E on the percent variation which increased as E increased. This was not expected but showed the influence of slope of grain. The 30°T group had a slope of line opposite that for the 30°C group. This followed the slope of line disagreement for the 0°C and 0°T groups. It was believed due to the stress reversal.

The Effect of Specific Gravity on the Percent of Modulus of Elasticity Variation

Specific gravity (G), another wood variable to affect the physical properties of wood, had less effect upon the percent variation (P) than E. Figure 13 shows the plotted experimental data (Appendix Tables C and D) and the regression equation line for each slope of grain group. Table VI presents the regression equation for each grain slope group.

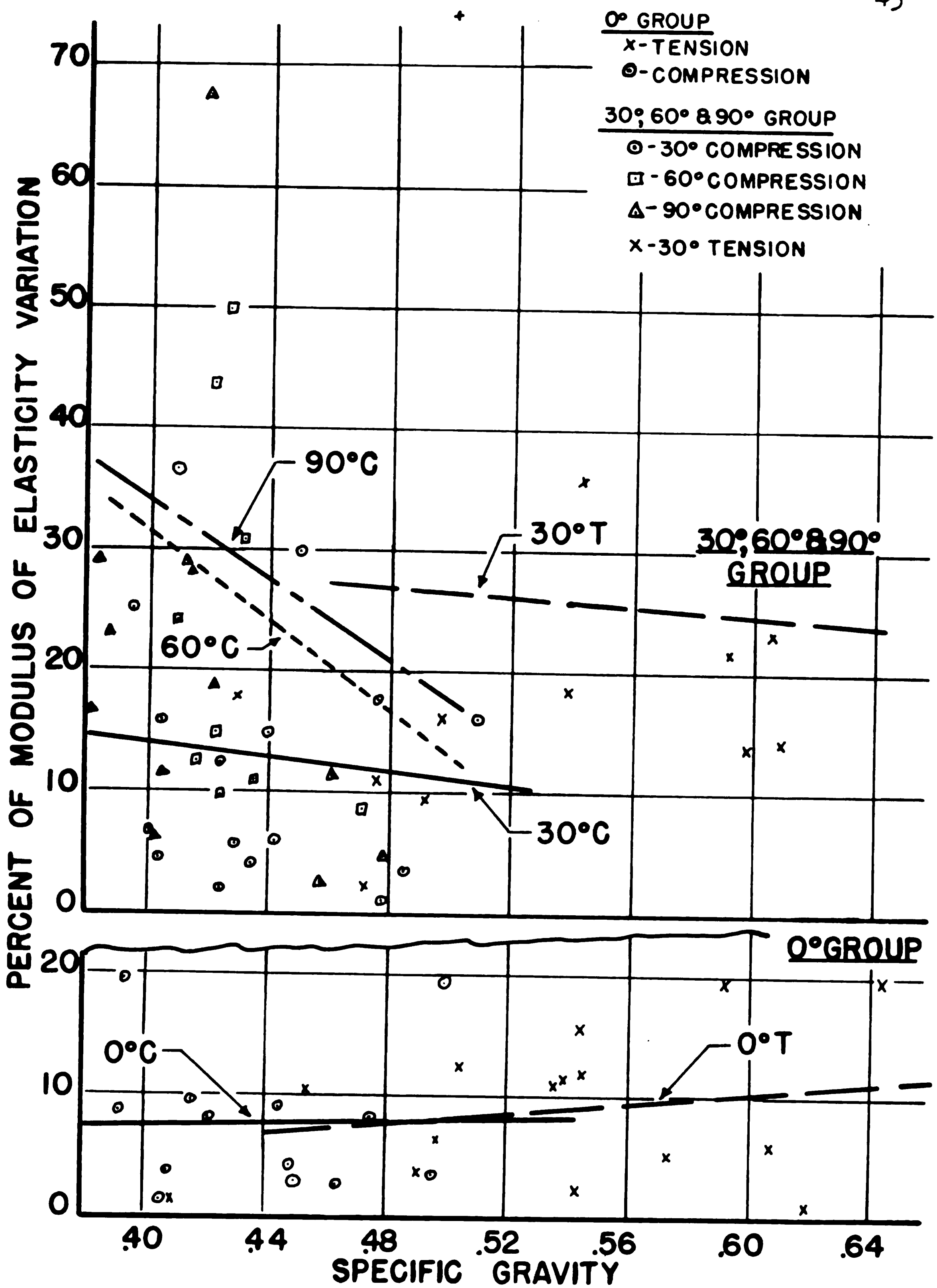

Figure 13. The effect of specific gravity on the percent of modulus of elasticity variation.

TABLE VI

THE EFFECT OF SPECIFIC GRAVITY ON PERCENT VARIATION

Slope Group	Regression Equation	Correlation Coefficient
0°C	P = 5.918 + 4.211G	.00083
30°C	P = 26.228 - 29.513G	.0082
60°C	P = 107.325 - 188.539G	.047
90°C	P = 100.363 - 164.210G	.024
0°T	P = -1.913 + 20.398G	.056
30°T	P = 36.522 - 19.569G	.0017

The very low correlation coefficients for all the slope groups indicated a very poor linear fit of the experimental data. The random location of the points justified the linear relationship. The prediction equations although not reliable indicated that the effect of G on the percent variation was small for all slope of grain groups except 60°C and 90°C.

The small effect that G had on the percent variation at zero grain slope was to increase the percent variation with an increase of the variable. This was shown by the positive slope of the 0°C and 0°T lines, Figure 13, and the positive regression equation slope terms, Table VI. For all other slope of grain groups the G effect was to decrease the percent variation with an increase of the variable.

This was illustrated by negative line slopes, Figure 13, and negative regression equation slope terms, Table VI.

The Effect of Moisture on the Percent of Modulus of Elasticity Variation

Experimental data (Appendix Tables C and D) plotted in Figure 14 shows the effect of moisture (M), another wood variable, on the percent variation (P). The regression equations and their correlation coefficients for the lines of Figure 15 are given in Table VII.

TABLE VII

THE EFFECT OF MOISTURE ON PERCENT VARIATION

Slope Group	Regression Equation	Correlation Coefficient
0°C	P = -1.051 + .612M	.028
30°C	P = 57.967 - 3.120M	.204
60°C	P = 14.601 - .890M	.0038
90°C	P = 66.458 - 2.581M	.024
0°T	P = 6.977 + .209M	.0024
30°T	P = -3.770 + 2.516M	.018

The low correlation coefficients for all the slope groups indicated a very poor linear fit of the experimental data, but the random location of these points gave no justification to use nonlinear equations. The random point

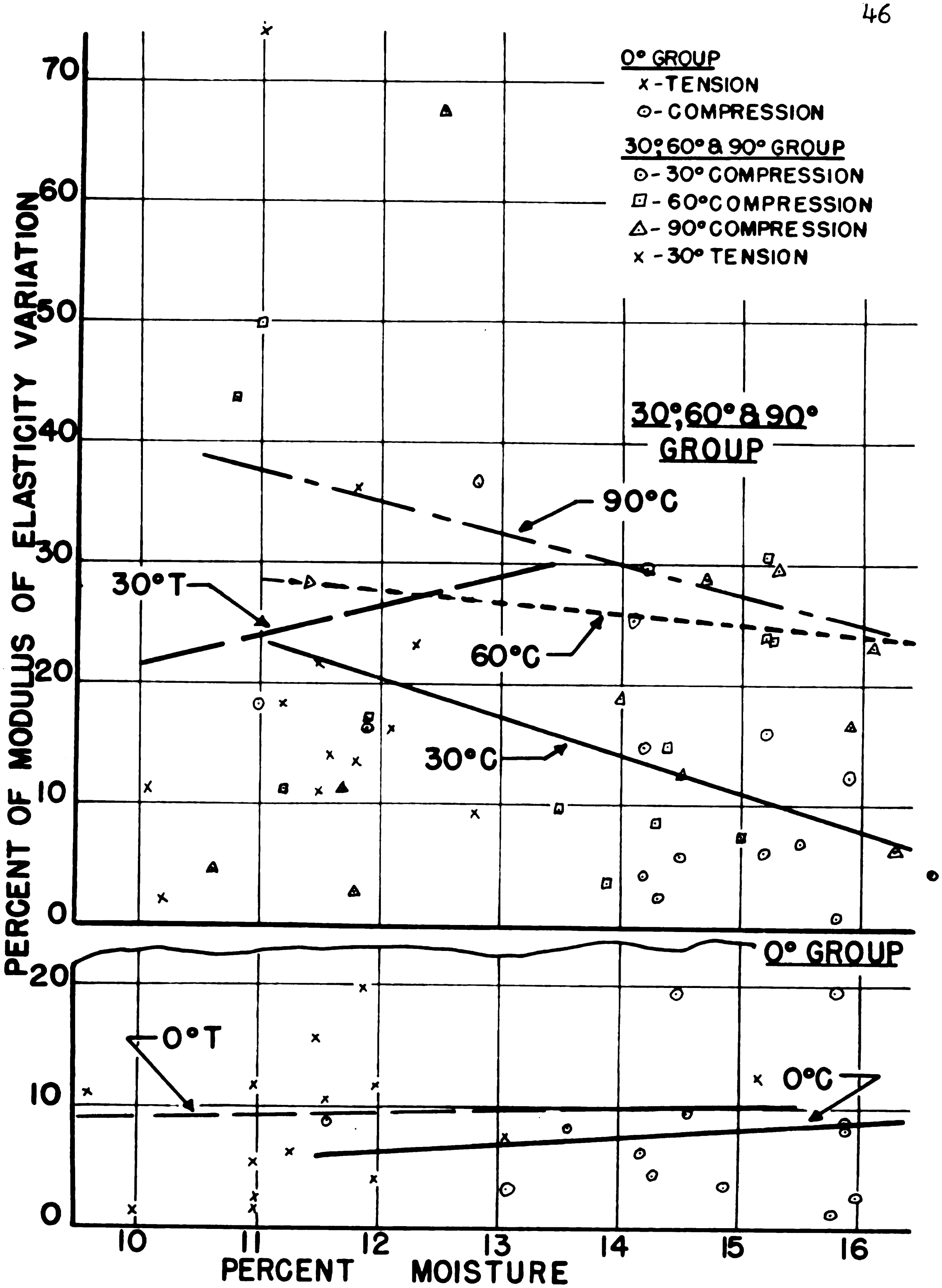

Figure 14. The effect of moisture on the percent of modulus of elasticity variation.

location and the low correlation coefficients indicated that the prediction equations for the effect of M on the percent variation were not reliable.

The small indicated effect that M had on the percent variation at zero grain slope was to increase the percent variation with an increase of the variable. This was illustrated by the positive slopes of the regression equation lines but was considered negligible. For all other grain slopes under compression load the indicated M effect was to decrease the percent variation with an increase of the variable. In the 30°T group the percent variation increased as M increased.

V. SUMMARY AND CONCLUSIONS

It was found that differences existed between SR-4 and deflection determined strain measurements. Using the deflection measurements as the basis this strain difference increased as the slope of grain increased. The range of these strain differences increased as did the average percent of difference. Although neither measurement could be considered accurate, the deflection calculated strain was subject to less variation from angled grain distortion.

The modulus of elasticity variation was considered the best method for comparing differences between measurement methods. The frequency of exceeding ten percent modulus of elasticity variation increased with the slope of grain.

The slope of grain had the most effect upon the percent of modulus of elasticity variation. A regression equation having high correlation showed that the percent of modulus of elasticity variation increased one quarter of one percent per degree of grain rotation. This had serious implications because transverse sensitivity readings made with SR-4 gages at an angle to the grain would be in error as well as stress calculations based on the measured strain.

It was concluded from the prediction equation that the modulus of elasticity of straight grained material had little influence on the percent of modulus of elasticity variation. Low equation correlation coefficients for the remaining slope groups made it impractical to draw conclusions. The other equations indicated that the effect of the modulus of elasticity was to increase the percent of modulus of elasticity variation for compression loaded sloped grain groups. The effect in tension was opposite the effect in similar compression groups.

The indicated effect in compression of the specific gravity on the percent of modulus of elasticity variation was that the variation decreased with the variable for all grain slopes other than zero. At zero degree grain slope the effect of specific gravity was negligible. The effect in tension was comparable. The specific gravity indicated less effect than the modulus of elasticity. Because the prediction equations had very low correlation coefficients no conclusions were made except on straight grained material.

The indicated effect in compression of the moisture content on the percent of modulus of elasticity variation was that the variation increased with the variable at zero degree grain slope and decreased with all other slopes. The effect in tension was that the variation increased for all slopes as the moisture content increased.

Very little reliance was placed on these equations because they had low correlation coefficients. The line slope for straight grained material was almost negligible, and it was concluded that this constituted little effect.

The following conclusions were drawn from this study:

1. It became increasingly difficult to make reliable strain measurements as the slope of grain increased. (pages 26, 29)
2. The slope of grain had a significant effect on SR-4 strain measurement variation. (page 36)
3. The percent variation between the two strain measurement methods on straight grained material was within experimental error. (page 36)
4. Modulus of elasticity had little influence on SR-4 strain measurement of straight grained material. (page 42)
5. Specific gravity had little influence on SR-4 strain measurement of straight grained material. (page 44)
6. Moisture content had little influence on SR-4 strain measurement of straight grained material. (page 45)

VI. SUGGESTED FUTURE STUDIES

The results of this study indicated that a difference existed between the two methods of modulus of elasticity determination. Both methods were dependent upon axial deformation of the member and the calculations were based upon isotropic behavior of the material. In order that more accurate stress analysis of wood can be made the following studies appear worthy of future investigation:

1. A study of the variation of SR-4 determined strain values from deflection calculated strain when they are evaluated or corrected in terms of the orthotropic properties of wood.
2. A study of the SR-4 measurement of combined stresses in wood.
3. A study of the effect that gage lengths have on strain measurement of wood.

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GLOSSARY

a - intercept of a regression equation

b - slope term of a regression equation

b_d - slope term of the deflection method regression equation

b_s - slope term of the SR-4 method regression equation

E - modulus of elasticity

E_g - modulus of elasticity of green wood

E_i - modulus of elasticity of a particular test sample

E_l - modulus of elasticity in the longitudinal direction

E_r - modulus of elasticity in the radial direction

E_0 - modulus of elasticity at 0° grain slope

E_{12} - modulus of elasticity at 12 percent moisture

E_{90} - modulus of elasticity at 90° grain slope

e - unit strain

$\bar{e}$ - mean unit strain

e_d - unit strain by deflection measurement

$\bar{e}_d$ - mean unit strain by deflection measurement

e_s - unit strain by SR-4 measurement

$\bar{e}_s$ - mean unit strain by SR-4 measurement

G - specific gravity

L - applied load

$\bar{L}$ - mean applied load

M - moisture content

M_1 - moisture content of a particular sample

M_p - fiber saturation moisture content

N - number of terms in a group

N_d - number of terms in the deflection method group

N_s - number of terms in the SR-4 method group

P - percent of modulus of elasticity variation between the two measurement methods

$\emptyset$ - angle of grain slope

Σ - sum of a group of terms

S - standard deviation

t - significant difference test value

APPENDIX

APPENDIX A

LOAD-STRAIN REGRESSION EQUATION INTERCEPTS, COEFFICIENTS AND STANDARD DEVIATIONS FOR THE COMPRESSION SAMPLES

General Equation: $e = a + b\,(L-\bar{L})$

Sample	SR-4 Gage			Deflection Gage			t Value
	$a \times 10^{-4}$	$b \times 10^{-6}$	$S \times 10^{-4}$	$a \times 10^{-4}$	$b \times 10^{-6}$	$S \times 10^{-4}$	
A-1-0-10	3.920	.2028	.05	4.222	.2088	.21	1.89
A-2-0-10	5.208	.2731	.12	4.752	.2625	.30	1.47
A-3-0-15	5.265	.2777	.17	4.275	.2549	.49	3.01
A-4-0-20	6.257	.3006	.14	5.255	.2719	.55	3.21
B-1-0-20	3.732	.2121	.31	3.884	.2063	.62	.58
B-2-0-15	4.108	.2105	.28	4.090	.2296	.57	2.28
B-3-0-15	5.461	.3096	1.12	5.419	.2482	.37	3.65
B-4-0-10	4.261	.2209	.10	4.249	.2110	.11	3.21
C-1-0-10	6.325	.3372	.34	5.434	.3079	.63	2.70
C-2-0-15	7.633	.4273	1.10	7.440	.4100	1.04	.78
C-3-0-20	6.386	.3346	.30	6.241	.3388	.88	.30
D-1-0-20	4.605	.2288	.11	5.691	.2734	.61	10.06
D-3-0-15	4.185	.2181	.06	3.743	.1999	.20	5.26
D-4-0-10	3.628	.1929	.10	3.702	.1919	.38	.24
A-1-30-20	12.791	1.7689	.51	11.308	1.5827	.77	2.75
A-2-30-15	14.629	1.9389	.24	13.848	1.8642	.28	2.79
A-3-30-20	14.776	2.0194	.70	12.241	1.7570	.62	4.92
A-4-30-10	9.815	1.5612	1.84	6.501	.9830	.59	4.09
B-1-30-10	12.459	1.6247	.46	12.873	1.5973	.42	.61
B-2-30-20	14.472	2.1909	1.36	14.433	2.0898	1.18	.77
B-3-30-15	12.421	1.7272	.53	12.085	1.6578	.66	1.12
B-4-30-15	15.185	2.0795	.50	12.942	1.8901	.87	2.58
C-1-30-15	16.987	2.3322	.52	13.031	1.7651	.40	9.36
C-2-30-20	8.544	1.1846	.35	8.298	1.1229	.28	2.07
C-3-30-10	7.346	1.0276	.44	8.240	1.0724	.21	1.70
D-1-30-10	10.884	1.4809	.46	7.661	1.0378	.62	7.72
D-2-30-10	9.977	1.3284	.19	8.055	1.0927	.18	12.23
D-3-30-15	15.076	2.0601	.56	12.923	1.7253	.56	3.17
D-4-30-20	12.890	1.7439	.49	12.805	1.7584	.56	.27

APPENDIX A (Continued)

Sample	SR-4 Gage			Deflection Gage			t Value
	$ax10^{-4}$	$bx10^{-6}$	$Sx10^{-4}$	$ax10^{-4}$	$bx10^{-6}$	$Sx10^{-4}$	
A-2-60-15	25.763	6.5523	1.32	35.633	9.4415	2.70	
A-3-60-10	26.389	5.5561	1.66	37.839	8.3287	4.29	
A-4-60-20	11.450	2.9100	.19	20.118	5.5685	2.11	
B-1-60-10	25.319	9.5317	1.22	15.973	6.5805	4.58	
B-2-60-15	37.460	10.0225	2.28	35.262	9.0570	1.13	
B-4-60-15	17.533	8.8938	.36	31.148	11.0215	2.27	
C-1-60-10	50.690	13.5325	3.58	42.936	11.5685	2.88	
C-2-60-10	32.904	7.7561	1.85	36.873	8.9257	3.07	
C-3-60-15	32.108	9.9450	1.80	38.424	11.1837	3.25	
C-4-60-20	50.767	9.7586	4.46	38.510	9.7609	9.12	
D-2-60-10	37.300	11.8362	3.44	31.926	10.4969	3.50	
D-3-60-20	26.163	7.1919	2.53	24.222	6.5732	1.70	
D-4-60-15	24.798	8.2615	.02	24.278	8.4105	1.50	
A-1-90-20	17.953	8.4751	1.56	36.438	17.2197	2.80	
A-2-90-10	11.383	6.9508	.44	20.950	12.9919	1.54	
A-3-90-15	16.683	9.4250	3.06	29.967	15.8250	2.38	
B-1-90-10	23.875	23.8750	.00	36.113	17.0850	2.75	
B-3-90-20	33.063	33.0625	.00	60.800	35.2000	13.60	
B-4-90-15	20.192	12.3850	.99	25.140	16.0082	3.35	
C-1-90-20	34.200	18.2375	3.22	29.267	15.4175	2.22	
C-2-90-20	26.654	12.1950	.97	39.530	15.7587	4.09	
C-3-90-10	22.188	10.1214	.71	24.750	11.4194	1.16	
C-4-90-15	40.081	18.4879	2.08	40.700	15.4459	2.70	
D-1-90-15	13.455	13.4550	.00	15.000	15.0000	.00	
D-2-90-10	36.788	16.4929	.60	35.950	16.9429	2.90	
D-3-90-10	40.268	21.4850	3.82	37.317	20.5125	5.25	
D-4-90-20	18.213	11.1557	.83	21.377	13.2825	1.66	

APPENDIX B

LOAD-STRAIN REGRESSION EQUATION INTERCEPTS, COEFFICIENTS AND STANDARD DEVIATIONS FOR THE TENSION SAMPLES

General Equation: $e = a + b\,(L-\overline{L})$

Sample	SR-4 Gage			Deflection Gage			t Value
	$ax10^{-4}$	$bx10^{-6}$	$Sx10^{-4}$	$ax10^{-4}$	$bx10^{-6}$	$Sx10^{-4}$	
E-0-1-10	1.774	.2329	.03	1.535	.2078	.12	2.83
E-0-2-15	1.420	.1932	.05	1.218	.1703	.08	3.26
E-0-3-20	1.329	.1838	.05	1.423	.1934	.04	3.74
E-0-4-20	1.205	.1620	.02	1.208	.1579	.02	2.21
E-0-5-15	1.604	.2150	.04	1.428	.1714	.08	7.07
F-0-1-15	0.743	.1381	.16	1.021	.1489	.16	.66
F-0-2-10	1.466	.1986	.05	1.361	.1871	.18	.83
F-0-3-20	1.175	.1460	.05	0.995	.1168	.08	4.26
F-0-4-10	1.041	.1442	.04	0.881	.1461	.15	.17
F-0-5-20	1.129	.1474	.04	0.870	.1293	.10	2.30
G-0-1-10	1.646	.2132	.05	1.146	.1705	.10	4.23
G-0-2-15	1.276	.1674	.02	1.111	.1480	.03	7.42
G-0-3-15	1.325	.1815	.04	1.061	.1528	.12	3.18
G-0-4-10	1.685	.2419	.18	1.443	.2358	.11	.28
G-0-5-20	1.724	.2455	.09	1.816	.2194	.11	2.45
E-30-1-10	6.242	1.5890	.17	5.800	1.6241	.85	.19
E-30-2-20	3.890	1.1231	.07	3.292	0.9934	.08	4.59
E-30-3-10	5.015	1.2818	.09	4.418	1.0565	.18	5.16
E-30-4-15	4.271	1.2844	.08	3.736	1.1413	.12	3.68
E-30-5-20	4.443	1.3228	.06	3.718	1.1084	.05	10.43
F-30-2-20	2.923	0.7397	.04	3.448	0.8400	.07	5.64
F-30-3-15	3.884	0.8569	.05	4.307	1.0431	.32	3.26
F-30-4-15	2.953	0.8167	.08	3.760	1.0001	.22	3.64
F-30-5-10	3.796	0.8282	.08	3.084	0.7087	.19	3.43
G-30-1-20	3.690	1.3797	.26	4.476	1.6315	.15	2.47
G-30-2-20	4.230	2.0028	.35	2.888	1.2837	.07	4.27
G-30-3-10	4.800	1.0474	.10	8.239	1.8250	.66	7.68
G-30-4-15	4.898	1.0587	.34	5.537	1.1595	.28	1.38
G-30-5-15	2.501	0.8300	.03	4.737	1.6307	.13	26.97

APPENDIX C

COMPOSITE COMPRESSION SAMPLE DATA

Sample	M(%)	G	Ex10^5	Ex10^5	% Variation
A-1-0-10	13.1	.451	223.74	217.05	3.08
A-2-0-10	14.9	.406	171.48	178.41	3.88
A-3-0-15	13.6	.422	164.71	179.49	8.23
A-4-0-20	14.6	.417	154.94	171.33	9.57
B-1-0-20	16.0	.464	255.21	231.63	2.77
B-2-0-15	15.9	.445	226.54	207.67	9.09
B-3-0-15	15.8	.394	153.73	191.74	19.82
B-4-0-10	14.3	.449	209.75	219.57	4.47
C-1-0-10	11.6	.392	130.84	143.32	8.71
C-2-0-15	14.2	.380	105.77	112.79	6.22
C-3-0-20	15.8	.406	142.31	140.46	1.31
D-1-0-20	14.5	.500	203.26	170.09	19.50
D-3-0-15	15.9	.476	218.74	238.58	8.32
D-4-0-10	11.2	.497	227.12	219.31	3.56
A-1-30-20	15.9	.425	26.35	30.13	12.55
A-2-30-15	14.3	.425	23.90	24.43	2.16
A-3-30-20	15.2	.405	22.48	26.80	16.12
A-4-30-10	12.8	.410	28.98	45.87	36.82
B-1-30-10	14.2	.441	26.38	31.04	15.01
B-2-30-20	16.6	.405	22.05	23.11	4.59
B-3-30-15	14.5	.430	26.93	28.56	5.71
B-4-30-15	15.5	.402	22.76	24.48	7.03
C-1-30-15	14.1	.396	19.53	26.15	25.32
C-2-30-20	15.2	.443	39.75	41.93	6.20
C-3-30-10	13.2	.435	44.20	42.35	4.37
D-1-30-10	14.2	.451	31.23	44.55	29.90
D-2-30-10	11.0	.477	32.85	39.93	17.73
D-3-30-15	11.9	.510	21.54	25.71	16.22
D-4-30-20	15.8	.479	27.29	27.06	.85

APPENDIX C (Continued)

Sample	M(%)	G	$Ex10^5$	$Ex10^5$	% Variation
A-2-60-15	10.8	.422	6.63	4.61	43.82
A-3-60-10	11.0	.427	7.86	5.24	50.00
A-4-60-20	14.7	.423	16.03	8.38	91.29
B-1-60-10	15.2	.432	4.94	7.15	30.91
B-2-60-15	13.5	.425	4.55	5.05	9.90
B-4-60-15	15.2	.410	5.30	4.27	24.12
C-1-60-10	11.9	.368	3.27	3.83	17.23
C-2-60-10	14.4	.423	5.98	5.20	15.00
C-3-60-15	15.0	.417	4.72	4.19	12.65
C-4-60-20	16.2	.415	4.91	4.91	0
D-2-60-10	11.2	.436	3.70	4.17	11.27
D-3-60-20	14.3	.472	6.43	7.05	8.79
D-4-60-15	13.9	.486	5.70	5.50	3.64
A-1-90-20	13.5	.425	5.38	2.65	101.50
A-2-90-10	11.7	.417	6.35	3.40	86.80
A-3-90-15	12.5	.419	4.76	2.84	67.70
B-1-90-10	11.4	.415	1.84	2.57	28.40
B-3-90-20	16.3	.403	1.45	1.36	6.62
B-4-90-15	15.3	.385	3.81	2.95	29.20
C-1-90-20	16.1	.388	2.63	3.04	23.30
C-2-90-20	14.7	.414	3.82	2.96	29.00
C-3-90-10	14.5	.406	4.59	4.07	12.75
C-4-90-15	15.9	.382	2.57	3.09	16.80
D-1-90-15	11.7	.462	3.28	2.94	11.55
D-2-90-10	11.8	.459	2.68	2.61	2.68
D-3-90-10	10.6	.479	2.02	2.12	4.72
D-4-90-20	14.0	.423	4.13	3.47	19.00

APPENDIX D

COMPOSITE TENSION SAMPLE DATA

Sample	M(%)	G	Ex10^5	Ex10^5	% Variation
E-0-1-10	9.6	.537	182.66	205.11	10.95
E-0-2-15	11.0	.546	226.26	256.76	11.85
E-0-3-20	11.0	.575	237.23	225.58	5.16
E-0-4-20	11.0	.544	269.44	276.26	2.47
E-0-5-15	12.0	.492	269.36	259.15	3.94
F-0-1-15	13.1	.681	327.33	304.26	7.60
F-0-2-10	11.3	.608	220.53	234.69	6.04
F-0-3-20	9.2	.645	289.40	361.14	19.79
F-0-4-10	10.0	.620	296.67	293.60	1.05
F-0-5-20	15.2	.506	319.24	365.02	12.55
G-0-1-10	11.9	.593	207.89	259.44	19.80
G-0-2-15	12.0	.540	265.34	300.30	11.60
G-0-3-15	11.5	.545	242.67	287.88	15.70
G-0-4-10	11.0	.410	180.74	183.40	1.45
G-0-5-20	11.6	.455	179.74	201.02	10.60
E-30-1-10	10.2	.473	27.09	26.50	2.23
E-30-2-20	10.1	.507	38.27	43.23	11.50
E-30-3-10	15.9	.430	37.19	45.15	17.60
E-30-4-15	11.5	.477	34.32	38.60	11.10
E-30-5-20	12.1	.498	33.65	40.15	16.20
F-30-2-20	11.8	.599	59.93	52.72	13.70
F-30-3-15	11.5	.593	51.41	42.41	21.80
F-30-4-15	12.3	.607	54.72	44.68	23.30
F-30-5-10	11.6	.610	53.23	62.25	14.40
G-30-1-20	11.2	.540	31.77	26.86	18.30
G-30-2-20	11.8	.544	21.68	34.10	36.40
G-30-3-10	11.0	.501	41.70	23.92	74.40
G-30-4-15	12.8	.493	42.58	38.91	9.44
G-30-5-15	13.0	.509	54.53	27.75	96.50