NON-SHEAR COMPLIANCES AND ELASTIC CONSTANTS MEASURED FOR THE WOOD OF EIGHT HARDWOOD TREES

BY

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ABSTRACT

NON-SHEAR COMPLIANCES AND ELASTIC CONSTANTS DETERMINED FOR THE WOOD OF EIGHT HARDWOOD TREES

By

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To determine if linear relationships existed between the non-shear compliances of the wood of eight hardwood trees, the non-shear compliances were measured from short columns loaded in compression in the longitudinal, radial, and tangential directions. Significant linear relationships were found between pairs of compliances with the exception of S_{LR} and S_{RR}, and S_{LT} and S_{TT}, for a given direction of loading. S_{ij} relates the strain in the i direction to the applied stress in the j direction. To determine if the property $S_{ij} = S_{ji}$ found in orthotropic materials holds true for wood, specimens from each tree were tested in the longitudinal, radial, and tangential direction. As predicted by the linear orthotropic elastic theory the compliances S_{RT} and S_{TR} were found to be equal. However, the measured values of the compliances S_{LR} and S_{RL}, and S_{LT} and S_{TL} did not behave as predicted by linear orthotropic elastic theory.

TO CAROL

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NOTATION

L, R, T = longitudinal, radial, and tangential.

i = subscript L, R, or T.

j = subscript L, R, or T.

σ_i = stress in the i direction. (psi)

ε_i = strain in the i direction. (in/in)

E_i = modulus of elasticity in the i direction = σ_i/ε_i. (psi)

G_{ij} = shear modulus in the ij plane, $i \neq j$. (psi)

S_{ij} = compliance with strain in the i direction per unit stress in the j direction = ε_i/σ_j. (1/psi)

ν_{ji} = Poisson's ratio of strain in the i direction to that in the j direction for loading in the j direction; $i \neq j$; = $\varepsilon_i/\varepsilon_j$.

INTRODUCTION

The increasing use of computer analysis to solve three-dimensional stress and strain problems encountered in structural design allows more efficient use of many construction materials. To solve three-dimensional stress and strain problems for wood members 12, elastic constants or their related compliances are required. Wood is a highly complex and variable material and an accurate knowledge of all of its elastic parameters is needed for precise design analysis. "Engineers and designers are hesitant to use wood under complex loading in part because of the uncertainty of proper values of its elastic constants" (Gunnerson 1973).

There are two general methods for obtaining values for the elastic constants of wood. The first is direct measurement of the constants, which involves extensive testing of each wood species. The second is to predict the elastic constants from a known physical property. Two of the better documented physical properties of wood are specific gravity, and the modulus of elasticity in the longitudinal direction.

This study is part of a larger project, whose aim is to develop a set of equations relating the various non-shear compliances to the compliance S_{LL}, the inverse of the modulus of elasticity in the L direction (E_L). S_{ij} relates the strain in the i direction to the applied stress in the j direction. Previously (Sliker 1985, 1988, 1989), specimens tested in the longitudinal (L), radial (R), and tangential (T) directions were not matched with respect to tree or species. The objective of this study is to use matched samples to clarify the relationships found by Sliker (1985, 1988, 1989), and Yu (1990), and to test if the property $S_{ij} = S_{ji}$ found in orthotropic materials holds true for wood.

Wood is a cellular, biological material formed by the secondary thickening of woody plants such as trees, shrubs, and vines. Most of the commercially important woods used in the United States come from trees. The term wood as used in this thesis refers only to the wood produced by trees. Wood can be divided into two broad classifications hardwoods, and softwoods. Hardwoods being formed by deciduous trees (dicotyledons of the Angiosperms), and softwoods formed by coniferous trees (conifers of the Gymnosperms). This study deals with the properties of hardwoods.

The wood of hardwoods is composed of four basic types of cells: vessels (or pores), fibers, ray cells, and longitudinal parenchyma. The term pore refers to the appearance of the vessel element in cross-sectional view. The general size, number, and distribution of pores within the growth rings further categorizes hardwoods into two main groups:
ring-porous hardwoods and diffuse-porous hardwoods. In ring-porous hardwoods the large pores are concentrated in the wood formed in the early part of the year (earlywood or springwood) while the pores in the wood formed later in the year (latewood

or summerwood) are generally smaller and less numerous. Ring-porous hardwoods are characterized by distinctive figure on the tangential and radial surfaces. White oak and white ash are examples of ring-porous hardwoods. In other hardwoods the pores are evenly dispersed throughout the growth ring with little noticeable variation between earlywood and latewood; these woods are called diffuse-porous hardwoods. Basswood and cottonwood are two species which fit this category. Some hardwoods do not fit neatly in either the ring-porous or the diffuse-porous category. Black walnut for example tends to form larger pores early in the year with the size gradually tapering off as growth continues forming no definite zones of one size pores. Hardwoods such as black walnut are said to be semi-ring-porous or semi-diffuse-porous.

Variation in the relative proportions of different cell types and sizes is reflected in the wide variation in physical and mechanical properties of the various hardwood species. Within a given species and even within a single tree there is also a wide variation in the cellular makeup of the wood.

When trees are forced out of their normal erect growth pattern abnormal tissue is often formed. In hardwoods this tissue is called tension wood. Tension wood is generally found on the upper side of a leaning trunk or on the upper side of branches though it may also be irregularly distributed through out a tree. Tension wood differs significantly from normal wood in several ways. In tension wood all or part of the secondary cell wall nearest the lumen is replaced by a gelatinous layer composed mainly of cellulose and is loosely attached to the other cell wall layers. The secondary cell wall restricts longitudinal shrinkage; as a result tension wood usually shows excessive longitudinal shrinkage. Mechanical properties can also be affected by tension wood. Tension wood has long ropey fiber bundles which gives the wood a woolly appearance when rough sawn. Another growth factor that can affect the physical and mechanical properties of wood is juvenile wood. Juvenile wood is formed by immature cambial initial cells near the pith of the tree. The length of time that juvenile wood is formed varies from species to species but is generally between 5 and 20 years (Panshin, De Zeeuw 1980). Hardwood fiber cells formed by an immature cambium are generally shorter and thinner walled then mature fiber cells. In addition the cellulose microfibrils of the S_2 layer of the cell wall are formed at a angle to the main axis of cellular orientation, the L direction. All of these factors contribute to juvenile wood's generally lower strength and stability, when compared to wood formed later by mature cambial initials. The physical and mechanical properties of mature wood are most often recorded in tables for structural applications.

Fiber cells provide much of the strength of wood, their distribution and number within a particular piece of wood will have an effect on that piece's physical and mechanical properties. Growth rate can affect the distribution of fiber cells and as a result the mechanical properties of ring-porous hardwoods. In ring-porous hardwoods the width of the earlywood, composed mainly of large vessel cells, does not vary much with growth rate. Consequently fast growing ring-porous hardwoods have a higher proportion of fibrous latewood and will be stronger then a piece of slow growth ring-porous hardwood composed mainly of earlywood which contains a higher proportion of weaker vessel cells.

The normal growth pattern of a tree, upwards from the tips of branches and outward from the pith, forms wood in annual increments of cylindrical shells about the pith. This cylindrical symmetry is reflected in woods physical and mechanical properties. Conventionally wood is treated as having three mutually perpendicular axis of symmetry: one along the main axis of cell orientation called the longitudinal (L) direction, a second in the direction of the rays called the radial (R) direction, and a third tangent to the curvature of the growth rings called the tangential (T) direction. Wood can then be treated mathematically as an orthotropic material for stress analysis.

To fully describe the stress strain relationship in an orthotropic material twelve elastic constants are required. The elastic constants are the modulus of elasticity in the L, R, and T directions, E_L, E_R, and E_T; six Poisson's ratios ν_{LR}, ν_{LT}, ν_{RT}, ν_{RL}, ν_{TR}, and ν_{TL}; and three shear moduli G_{LR}, G_{LT}, and G_{RT}. A matrix equation describing the three dimensional non-shear relationships of stress and strain in an orthotropic material can be described in terms of these elastic constants or their related compliances (Bodig and Jayne, 1982).

$$\begin{vmatrix} \epsilon_L \\ \epsilon_R \\ \epsilon_T \end{vmatrix} = \begin{vmatrix} \frac{1}{E_L} & \frac{-\nu_{RL}}{E_R} & \frac{-\nu_{TL}}{E_T} \\ \frac{-\nu_{LR}}{E_L} & \frac{1}{E_R} & \frac{-\nu_{TR}}{E_T} \\ \frac{-\nu_{LT}}{E_L} & \frac{-\nu_{RT}}{E_R} & \frac{1}{E_T} \end{vmatrix} \begin{vmatrix} \sigma_L \\ \sigma_R \\ \sigma_T \end{vmatrix} = \begin{vmatrix} S_{LL} & S_{LR} & S_{LT} \\ S_{RL} & S_{RR} & S_{RT} \\ S_{TL} & S_{TR} & S_{TT} \end{vmatrix} \begin{vmatrix} \sigma_L \\ \sigma_R \\ \sigma_T \end{vmatrix} \quad (1)$$

Additionally the reciprocal relationship $S_{ij} = S_{ji}$, where i and j equal L, R, or T but $i \neq j$, should exist in orthotropic materials. If the nine non-shear compliances were known or could be accurately estimated and either the stress or strain was known then the other parameter could be solved for. Of the elastic constants only one, E_L, is well documented for the majority of commonly used woods (Sliker 1988).

Electric resistance strain gages have had a long history of use for stress and strain analysis for wood. Radcliffe (1955) described the use of electric resistance strain gages on wood for the determination of elastic constants. Also given were special procedures to be followed in order to maintain the sensitivity and accuracy of the strain gages when used on wood.

Perry (1984) summarized some of the properties of electrical resistance strain gages and their effect on strain measurements. Among the properties which can effect the accuracy of stain measurements on wood are: reinforcement effects of the wire and backing material, transverse sensitivity of the gage, and thermal effects on the gage. When using strain gages on low modulus materials such as wood the relatively stiff backing material found on most commercial strain gages can act to reinforce the weaker substrate. The loops in the strain sensitive wire of many commercial gages can be effected by strains perpendicular to the main axis of measurement. This transverse sensitivity can cause large error in measurements because of the large Poisson effect in wood. While most gages are supplied with a transverse-sensitivity constant which can be used to correct for this, as the test conditions change from those used to calibrate the gage this constant becomes less accurate. Wood is a poor conductor of heat, as a result thermal drift can be a major problem when using electrical resistance strain gages. When used on wood, the gage must not only be compensated for changes in resistance due to temperature change but also for expansion of the wood due to heating and contraction of the wood due drying induced by the heating.

Sliker (1967, and 1971) described the manufacture and use of free filament strain gages in order to overcome some of the problems inherent in commercial gages. He used widely spaced strain sensitive wires bonded directly to the wood substrate with a low modulus nitrocellulose adhesive. The strain sensitive wires were widely spaced to reduce the heat concentration and the related shrinkage and swelling of the wood substrate. The gages were bonded directly to the wood substrate with a low modulus nitrocellulose adhesive without a backing material, which adds stiffness to many commercial gages. By doing this the reinforcing effect of the stiff backings is avoided.

In 1970, Goodman and Bodig tested four wood species in compression and torsion. They obtained values for the orthotropic elastic parameters and compared them to theoretical values. They found agreement between the measured and theoretical values of longitudinal strains when loading at angles within a principle orthotropic plane. However no significant agreement was found for general loading. They concluded that the layered homogeneous structure of wood might lead to behavior not predicted by orthotropic elastic theory. Their results also could not substantiate the assumed symmetry of an orthotropic material. The error involved in measuring some of the smaller Poisson's ratios might have partly accounted for this.

In 1973, Bodig and Goodman reported additional information on estimating the elastic parameters of softwoods and hardwoods. Data used in their analysis came from a number of sources and test methods. Significant exponential relationships were found between density and the various elastic parameters with the exception of Poisson's ratios which were considered to be a constants. Significant relationships were also found between E_L and the other elastic constants with the exception of Poisson's ratios. Using these equations, the moduli of elasticity, and the moduli of rigidity were predicted for most of the commercially important species grown in the United States.

Bucur (1983) used ultrasound to measure the elastic constants of increment cores. The results of the ultrasonic measurements were then compared to measurements made on standard samples loaded in static bending. Significant correlations were found between the elastic constants measured by the ultrasonic method and those determined by static bending test. He concluded that the ultrasonic method could provide a suitable non-destructive quality control test for wood.

Guitard and Amri (1987) used the results of their own research along with bibliographical data to look at the relationship between the elastic and physical characteristics of hardwoods and softwoods. They found significant exponential relationships between specific gravity and the elastic properties hardwoods. As with Bodig and Goodman the data used came from a variety of sources and a variety of test methods.

Sliker (1985, 1988, and 1989) used a variety of softwood and hardwood species in compression test to obtain the non-shear compliances. His research resulted in the following relationships:

	EQUATION	CORRELATION COEF	
1.	$S_{RL} = 0.022*10^{-6} - 0.405\ S_{LL}$	$R^2 = 0.900$	
2.	$S_{TL} = 0.021*10^{-6} - 0.500\ S_{LL}$	$R^2 = 0.925$	
3.	$S_{TR} = 1.260*10^{-6} - 0.887\ S_{RR}$	$R^2 = 0.911$	
4.	$S_{LR} = 0.029*10^{-6} - 0.0483\ S_{RR}$	$R^2 = 0.539$	(2)
5.	$S_{RT} = -0.659*10^{-6} - 0.255\ S_{TT}$	$R^2 = 0.980$	
6.	$S_{LT} = -0.022*10^{-6} - 0.274\ S_{TT}$	$R^2 = 0.980$	

for woods tested at between 9% and 12% moisture content. Units for the compliances S_{ij} are strain (inch per inch) per unit stress (psi).

Sliker (1990) tested specimens at three moisture content levels to determine the affect of moisture content on the relationships between pairs of compliances. Results showed that moisture content has very little effect on the relationship between pairs of compliances.

In 1990, Yu tested matched specimens in compression in the L, R, and T directions with the following results:

	EQUATION	CORRELATION COEF	
1.	$S_{RL} = -0.016*10^{-6} - 0.353\ S_{LL}$	$R^2 = 0.613$	
2.	$S_{TL} = -0.062*10^{-6} - 0.360\ S_{LL}$	$R^2 = 0.566$	
3.	$S_{TR} = 1.224*10^{-6} - 0.967\ S_{RR}$	$R^2 = 0.858$	
4.	$S_{LR} = -0.210*10^{-6} - 0.0143\ S_{RR}$	$R^2 = 0.332$	(3)
5.	$S_{RT} = -0.309*10^{-6} - 0.288\ S_{TT}$	$R^2 = 0.936$	
6.	$S_{LT} = -0.266*10^{-6} - 0.00605\ S_{TT}$	$R^2 = 0.100$	

Units for the compliances S_{ij} are strain (inch per inch) per unit stress (psi). With the exception of the relationship between S_{LT} and S_{TT} the relationship between pairs of compliances did not differ significantly from those determined by Sliker (1985, 1988, 1989). While the reciprocal relationship $S_{TR} = S_{RT}$ was close to its theoretical value, the relationships between S_{LR} and S_{RL}, and S_{LT} and S_{TL} were not, possibly due to the difficulty in measuring S_{LR} and S_{LT}, or to the different viscoelastic responses of wood when loading parallel and perpendicular to the grain.

OBJECTIVES

The objectives of this research are:

1. To determine if linear relationships exist between the non-shear compliances of different hardwood species from loadings in the L, R, and T directions.

2. To test if the property $S_{ij} = S_{ji}$ found in orthotropic materials holds true for wood through the use of matched specimens.

METHODS

MATERIALS

Material was obtained from eight trees representing six species: cottonwood (Populus deltoides S.), basswood (Tilia americana L.)-two trees, white ash (Fraxinus species)-two trees, black cherry (Prunus serotina Ehrh.), hard maple (Acer species), and black walnut (Juglans nigra L.). A single log, having a diameter of over 30 inches, from each of these trees was sawn into 3.25 inch thick planks and kiln dried to between 8% and 14% moisture content. All moisture contents were calculated on an oven-dry basis. A slow drying schedule was chosen to minimize drying defects, no equalization or conditioning was preformed at the end drying schedule. After kiln drying, specimen blanks were cut, from the planks, slightly larger then finished specimen size and conditioned in a room kept at 68°F and 65% relative humidity where they reached an equilibrium moisture content of between 10% and 12%. To avoid juvenile wood only portions of the planks 15 growth rings or more from the center of the tree were used to cut specimen blanks. Tension wood was very noticeable in the cottonwood and basswood samples.

SPECIMEN PREPARATION

Three types of specimens were prepared from the blanks corresponding to the three loading directions (L, R, and T) (Figure 1). Space limitations and strain gage geometry allowed the strain in only one direction perpendicular to the load axis to be measured when loading in the R and T directions. Two separate samples were required to measure the two strains orthogonal to the load axis when loading in the R and T directions. The use of a special strain gage design to measure the small strains in the L direction when loading in the R and T directions made a total of five specimen strain gage types. Two matched specimens of each specimen strain gage type were prepared from each tree. A total of eighty specimens were prepared, 16 L type, 16 R type for each gage arrangement for a total of 32 R type, and 16 T type for each gage arrangement for a total of 32 T type specimens. In each case the specimens were carefully machined to closely approximate truly orthotropic surfaces. On planks where the L direction was difficult to determine a red dye in kerosene was applied and the major direction of flow was used to determine the L-direction (Yu 1990). Longitudinal specimens were 7 inches long by 1.25 inches by 1.25 inches. The 7 inch dimension was in the L direction and the 1.25 inch dimensions were in the R and T directions. Radial and tangential specimens were made by laminating five pieces measuring 1.5 inches by 1.25 inches by 12 inches as described by Sliker

(1985). The 12 inch dimension was in the L direction and the 1.25 inch dimension was in either the R or T direction, depending upon the specimen type to be made. The five pieces were then laminated with polyvinyl acetate adhesive into blanks measuring 1.5 inches by 6.25 inches by 12 inches. Laminates were then machined to a thickness of 1.25 inches, and specimens were made by cutting in the direction of the 6.25 inch dimension at 1.25 inch intervals in the L direction. The ends of the specimens were then squared giving the specimen a final length of about 6 inches. In addition, moisture content and specific gravity were determined for each set of test specimens, and matched samples were fabricated for use in monitoring moisture content during testing. Specific gravity information is listed in Table 1.

Free-filament strain gages bonded to the specimens with nitrocellulose adhesive were used to measures strains during testing (Sliker 1985, 1988, 1989). The two gage types and three gage configurations used are shown in Figure 2. Type A gages were constructed by soldering 4 inch lengths of 1 mil constantan wire, having a resistance of 290 ohms per foot, to 12 mil leads, resulting in a gage resistance of approximately 97 ohms and a gage factor of 2.05 (Sliker 1985). Type B gages were made by soldering 1 inch lengths of 1 mil constantan wire to 12 mil leads (Sliker 1989).

Specimens were prepared for gage attachment by lightly sanding the mounting area to provide a smooth mounting surface. The gage pattern was then drawn on the specimen. A thin coat of nitrocellulose adhesive was applied to the mounting area and allowed to cure for 24 hours, this was done to insure good adhesion of the gage to the porous wood surface. After curing, the mounting area was again lightly sanded. The gages were then placed on the specimens. Finally a second coat of adhesive was applied to attach the gage to the specimen.

The gage arrangement for specimens to be loaded in the L direction is shown in Figure 3. A type A-1 gage was used for measuring longitudinal strains. This U-shaped gage was formed by pivoting the center of a type A gage 180 degrees around a straight pin creating a gage length of 2 inches (Sliker 1967, 1985). Similarly, a type A-2 gage was used for measuring strains in the R and T directions. This gage was formed by making three 180 degree turns with a type A gage around straight pins creating a 1 inch gage length (Sliker 1985). When pivoting a gage around a straight pin, it is advantageous to give the straight pin a slight slant away from the direction in which the gage is laid out (Sliker 1967). This allows the strain gage wire to easily slide down the pin when tension is applied insuring close contact with the wood surface during adhesion. To compensate for any bending caused by eccentric loading of the specimens matching gages on opposite faces were connected in series, any increase in strain due to bending on one side would be compensated for by a decrease in strain on the opposite side (Sliker 1989).

Gages for measuring strains when loading in the R and T directions were mounted only on the middle layer of the five layer laminate. One reason for doing this was to eliminate any differences which might exist between layers when measuring strains parallel and perpendicular to the load axis. In addition, gages should be mounted away from the ends of compression specimens as there is some horizontal shear between the specimen and the test apparatus. According to Goodman and Bodig (1970) this horizontal shear dissipates about one inch from the ends of the specimen. Specimen strain gage types used for loading in the R and T directions are shown in Figure 4 and Figure 5 respectively.

Two types of strain gages were used to measure the strains in specimens loaded in the R and T directions. A type A-2 gage was used to measure the strains parallel to the load axis when loading in the R and T directions. A type A-2 gage was also used to measures strains in the R and T directions when loading in the T and R directions respectively. Type B-1 gages were used to measure the longitudinal strains when loading in the R and T directions. Type B-1 gages are formed by mounting four type B gages parallel to each other on the specimen and then connecting them in series with 12 mil constantan wire. Type B-1 gages were mounted so that all the strain sensitive material was oriented in the L direction because of the small strains measured in the L direction (Sliker 1989). Strains perpendicular to the L axis might be picked up perpendicular to the gage axis by end loops in the other types of gages used, which could lead to large errors. Gages mounted on opposite faces were connected in series in order to compensate for any specimen bending which might occur during loading (Sliker 1989).

TESTING PROCEDURES

All testing was performed in a room maintained at 68°F and 65% relative humidity where specimens reached an equilibrium at between 10% and 12% moisture content. Before testing a specimen, the cross sectional area of the specimen was measured, and the matched sample was weighed in order to determine the moisture content of the test specimen. Testing was done by loading specimens mounted in a compression cage (Figure 6). In order to maintain equal pressure on the end of the specimens, ball bearings were used to allow the top and bottom bearing blocks to rotate freely (Bodig and Goodman 1969). In addition, loose fitting guides were used to keep the specimen centered on the bearings (Sliker 1989).

Loads were applied in the L direction by an Instron model 4206 testing machine with the crosshead speed set at .005 inches/minute (Figure 7). The compression cage was connected to the crossheads at the top and bottom by universal joints.

Strain measurements were made with a Measurements Group's model 3800 Wide Range Strain Indicator for each pair of gages oriented in a given direction. Readings were taken of the load and the strains in the L, R, and T directions at intervals of 50 microstrain in the L direction to a maximum of 600 microstrain.

When loading in the R and T directions, the compression cage was suspended from a steel frame by a universal joint and weights applied to a hanger suspended from the bottom of the cage through another universal joint (Figure 8). The load was applied by placing 10 pound weights on the hanger in succession until 100 pounds had been loaded. The total time of loading was kept under 2 minutes in order to limit any effect creep might have on the strain. Time of loading was not considered as critical for specimens loaded in the longitudinal direction, as there is very little apparent relationship between strain rate and E_L at the stress levels tested (Sliker 1973). To measure the small strains in the L direction when loading in the R and T directions, the sensitivity of the strain indicator was increased by setting the gage factor from 2.05 to 0.205, which allowed measurements of strain down to 0.1 microstrain. Shielded cables connected the gages in the L direction to the strain indicator in order to minimize the noise to signal ratio (Sliker 1989). Readings of the load and the strains parallel and perpendicular to the load were recorded at zero load and at 10 pound intervals until a maximum load of 100 pounds was reached.

STATISTICAL PROCEDURES

The compliance S_{ij} can be calculated by multiplying the slope of the strain versus load line of a specimen by the cross-sectional area of the specimen. Least squares regression analysis of the strain and load data collected during testing was used to determine the slopes needed to calculate the compliances S_{LL}, S_{RL}, S_{TL}, S_{RR}, S_{TR}, S_{LR}, S_{TT}, S_{LR}, and S_{LT}. The moduli of elasticity E_L, E_R, and E_T were calculated by regression analysis as the slope of the stress versus strain line, where the stress and strain are in the same direction. Poisson's ratios were calculated as the slope of the strain perpendicular to the load axis versus the strain parallel to the load axis line. To conform with more traditional practices the signs of the compliances and moduli of elasticity are reversed, ie S_{LL}, S_{RR}, S_{TT}, E_L, E_R, and E_T are shown as positive even though they were determined from compressive strains. While the elastic limits of wood differ significantly in tension and compression the moduli of elasticity are approximately equal (Kollmann and Cote 1968).

If linear relationship are to be found between pairs of compliances it must first be determined if the compliances vary from tree to tree. An analysis of variance was preformed on each compliance, modulus of elasticity, and Poisson's ratio in order to determine if they varied among the trees tested.

In addition a Fisher's protected least significant difference (FPLSD) analysis was preformed on the compliances and elastic constants that were found to differ significantly from tree to tree. This procedure was used to determine if the trees tested could be divided into groups which did not significantly differ from each other in a particular compliance or constant tested.

Once all the compliances were found to differ among the trees tested, regression analysis was used to determine the best fit linear equation describing the relationships between pairs of compliances for a given direction of loading (L, R, or T). An analysis of variance (ANOVA) was done on each equation in order to determine its significance. Additionally a t-test was preformed on the constant and slope coefficients in each equation to determine if they varied significantly from zero.

For equations that were found to be significant and where the intercept coefficient is significant, predictive equations were obtained for Poisson's ratio by dividing both sides of the equation by the compliance S_{jj}. Poisson's ratio can be determined by the quotient of compliances S_{ij}/S_{jj}. For non-significant equations and equations where the intercept did not differ significantly from zero this term would be a constant and the best estimate of Poisson's ratio would be the average value determined during testing.

T-tests were then performed to determine if the equations found to be significant in this study differed significantly from equation (2) developed by Sliker (1985, 1988, and 1989), and the equation (3) determined by Yu (1991). A t-test was also used to test if the reciprocal relationship $S_{ij} = S_{ji}$ of orthotropic materials held true for the eight trees tested. Regression analysis was then used on the reciprocal relationships S_{LR} and S_{RL}, S_{LT} and S_{TL}, and S_{RT} and S_{TR}, in order to determine if linear relationships existed between the compliances. An ANOVA was preformed to determine the significance of the equation and a t-test preformed to determine if the constant and slopes varied significantly from their theoretical values.

RESULTS

The compliances, moduli of elasticity, and Poisson's ratios calculated from test data are presented in Tables 2 through 19. Also listed in Tables 2 through 19 are the mean values and coefficients of variability (CV) for the measured values of the constants for each tree tested. The CV ranged from a low of 0.074 % for the compliance S_{TL} measured for BA2 to a high of 31.5 % for Poisson's ratio measured for WA2, with the average value being 4.75%. The analysis of variances between trees for each constant are also presented in Tables 2 through 19.

The analysis of variance showed that the compliances S_{LL}, S_{RL}, S_{TL}, S_{RR}, S_{TR}, S_{LR}, S_{TT}, S_{RT}, and S_{LT} varied significantly between trees at the 99% level. The modulus of elasticity E_L, E_R, and E_T along with the υ_{RL}, υ_{TR}, and υ_{TL} also showed significant variance between trees at the 99% level. υ_{RT} varied between trees at the 95% level, and υ_{LR} and υ_{LT} were not found to differ between the trees tested even at the 50% level. The results of the FPLSD analysis are presented in Tables 20 through 24. The FPLSD analysis of the compliance S_{LL} showed the following groups of trees did not differ from each other at the 95% level: WAL and BC1, BC1 and BA2, WA1 WA2 BA1 and COT1, WA2 BA1 COT1 and HM1. Similar groupings were found for the other constants.

Since all the compliances significantly differed between the trees tested, the following linear equations were developed describing the relationship between pairs of compliances:

	EQUATION	CORRELATION COEF
1.	$S_{RL} = 0.0299*10^{-6} - 0.429\ S_{LL}$	$R^2 = 0.928$
2.	$S_{TL} = 0.0152*10^{-6} - 0.461\ S_{LL}$	$R^2 = 0.921$
3.	$S_{TR} = 1.79*10^{-6} - 1.15\ S_{RR}$	$R^2 = 0.962$
4.	$S_{LR} = -0.247*10^{-6} - 0.00767\ S_{RR}$	$R^2 = 0.124$ (4)
5.	$S_{RT} = 0.089*10^{-6} - 0.338\ S_{TT}$	$R^2 = 0.971$
6.	$S_{LT} = -0.291*10^{-6} - 0.00648\ S_{TT}$	$R^2 = 0.359$

Units for the compliances S_{ij} are strain (inch per inch) per unit stress (psi). Plots of the regression lines and compliances are given in Figures 9 through 14. The analysis of variance and the results of the t-test of the constants for the above equations are shown in Table 25. Equations 1, 2, 3, and 5 in Table 25 were found to be significant at the 99% level. Equation 6 of Table 25 was significant at the 75% level and equation 4 of Table 25 was not found to be significant at the 75% level. The slopes of the equations 1, 2, 3, and 5 Table 25 were found to be significant at the 99% level. The slope of the equation 6 Table 25 was significant at the 80% level and the slope of the equation 4 Table 25 was significant at the 40% level. Intercept coefficients of equations 4, and 6 Table 25 were found to be significant at the 99% level. The intercept of the equation 3 Table 25 was significant at the 98% level. The intercepts of equations 1, 2, and 5 Table 25 were not found to be significant at the 90% level.

As Poissons's ratio can be written as the ratio of compliances, the significance of intercepts in the equations 3, 4, and 6 Table 25 allows the use of these equations to create predictive equations for υ_{RT}, υ_{RL}, and υ_{TL}. By dividing both sides of equation 3 Table 25 by S_{RR} it becomes:

$$S_{TR}/S_{RR} = 1.79*10^{-6}/S_{RR} - 1.15 = \upsilon_{RT}.$$

Equations 4 and 6 were found to be non-significant as a result the validity of this procedure on these equations is questionable. A better estimate of υ_{RL} and υ_{TL} would be their average values of 0.597 and 0.0375 respectively. The intercepts of the equations 1, 2 and 5 in Table 25 were not found to be significant. The best estimation of the υ_{LR}, υ_{LT}, and υ_{TR} would then be their average values of 0.376, 0.438, and 0.332 respectively.

The results of the t-test comparing the equations found in this study with those developed by Sliker (1985, 1988, and 1989) and Yu (1990), are shown in Table 26. Only equation 3 in Table 26 $S_{TR} = f(S_{RR})$ was found to differ at the 80% level from the equations developed by Sliker. The other equations did not differ significantly from Sliker's at the 90 % level. Similarly equation 3 in Table 26 was the only equation found to differ from those found by Yu (1990) at the 80% level.

The t-test (Table 27) of the reciprocal compliances found that the compliances S_{RT} and S_{TR} did not differ significantly from each other. Since the compliances S_{RT} and S_{TR} do not differ significantly from each other equations 3 and 5 of equation (3) can be combined to form a an equation relating compliance S_{RR} to the compliance S_{TT}. The resulting equation is:

$$S_{RR} = 1.479*10^{-6} + 0.294\ S_{TT}$$

The results of the t-test comparing the slope of this equation to the slope of the equation developed by Sliker (1988) are found in Table 28. No significant difference was found between the slopes of the two equations. The compliances S_{LR} and S_{RL} differed from each other at the 99% level, the compliances S_{LT} and S_{TL} also differed from each other at the 99% level.

The results of the regression analysis of the reciprocal compliances $S_{ij} = f(S_{ji})$ are as follows:

	Equation	Coefficient of corr.	
1.	$S_{LR} = -0.0866*10^{-6} + 0.912\ S_{RL}$	$R^2 = 0.565$	
2.	$S_{LT} = -0.285*10^{-6} + 0.329\ S_{TL}$	$R^2 = 0.051$	(5)
3.	$S_{RT} = -0.279*10^{-6} + 0.895\ S_{TR}$	$R^2 = 0.952$	

Plots of the regression line and the compliances along with the theoretical line are shown in Figures 15 through 17. The results of the ANOVA (Table 29) show that equations 1 and 3 of equation (5) are significant at the 95% level. Equation 2 was not significant at the 75% level. The results of the t-test (Table 29) of the regression coefficients show that the constants in equations 1 and 3 of equation (4) do not differ significantly from the theoretical value of 0. The constant of equation 2 does differ from the theoretical value at the 90% level. In addition the slope of equation 1 does not differ significantly for the predicted value of 1. The slopes of equations 2 and 3 do differ from the predicted values at the 50% level.

SUMMARY AND CONCLUSION

Matched specimens taken from eight trees representing six hardwood species were tested in compression in the L, R, and T directions. All testing was done in a room maintained at 68°F and 60% relative humidity, where the specimens had equalized at between 10% and 12% moisture content. Strains parallel and perpendicular to the load axis were recorded. The non-shear compliances were calculated from the strain readings parallel and perpendicular to the load axis per unit stress in the loading direction (L, R, or T). From this information the following conclusions were made.

1. The CV of the measured values of the constants and compliances varied from 0.074% to 31.5% with the average being 4.75%. WA2 samples tended to have a higher CV then the other samples tested. White ash being a ring-porous hardwood has a less homogenous cross-sectional structure then the other, diffuse-porous or semi-diffuse-porous, species tested. The differing properties of the earlywood and latewood of white ash may partly explain the large CV observed.

2. The wood from the eight trees examined differed significantly in their measured compliances and moduli of elasticity, but not in their Poissons ratio's, when specimens were loaded in the L direction. The woods examined also differed significantly in their compliances, moduli of elasticity, and Poissons ratio's when specimens were loaded in the R and T directions. The relationship between creep and the rate of loading in the R, and T directions may partly explain the significant differences between the Poisson's ratios when loading in the R and T directions.

3. Linear equations relating pairs of compliances were developed. The equations are as follows:

	EQUATION	CORRELATION COEF
1.	$S_{RL} = 0.0299*10^{-6} - 0.429\ S_{LL}$	$R^2 = 0.928$
2.	$S_{TL} = 0.0152*10^{-6} - 0.461\ S_{LL}$	$R^2 = 0.921$
3.	$S_{TR} = 1.79*10^{-6} - 1.15\ S_{RR}$	$R^2 = 0.962$
4.	$S_{LR} = -0.247*10^{-6} - 0.00767\ S_{RR}$	$R^2 = 0.124$
5.	$S_{RT} = 0.089*10^{-6} - 0.338\ S_{TT}$	$R^2 = 0.971$
6.	$S_{LT} = -0.291*10^{-6} - 0.00648\ S_{TT}$	$R^2 = 0.359$

The equations relating S_{RL} and S_{LL}, S_{TL} and S_{LL}, S_{TR} and S_{RR}, and S_{RT} and S_{TT}, were significant at the 90% level, however, the equations relating S_{LR} and S_{RR}, and S_{LT} and S_{TT} were not. The difficulty in measuring the smaller compliances, S_{LR} and

S_{LT} may have partly contributed to the lack of significance in these equations. The effect of loading rate on the viscoelastic behavior in the R and T directions may also have contributed to the lack of linear relationships. Because of the small number of samples used more testing may be required to clarify these relationships.

4. The intercept of the linear equations relating S_{LR} and S_{RR}, S_{LT} and S_{TT}, and S_{TR} and S_{RR} were significant. Poisson's ratio can be written as the ratio of compliances following predictive equations were developed:

1. $\nu_{RT} = 1.79*10^{-6} / S_{RR} - 1.15$
2. $\nu_{RL} = -0.00767*10^{-6} / S_{RR} - 0.247$
3. $\nu_{TL} = -0.00648*10^{-6} / S_{TT} - 0.291$

The intercepts of the equations relating S_{RL} and S_{LL}, S_{TL} and S_{LL}, and S_{RT} and S_{TT} were not significant. Thus the ratio between the compliances becomes a constant. The best estimate of ν_{LR}, ν_{LT}, and ν_{TR} would be their average values of 0.376, 0.438, and 0.332 respectively.

5. The equations relating the compliances S_{RL} and S_{LL}, S_{TL} and S_{LL}, S_{LR} and S_{RR}, S_{RT} and S_{TT}, and S_{LT} and S_{TT} did not differ significantly from those developed by Sliker (1985, 1988, 1989), and Yu (1990). This suggests that the

relationships between pairs of compliances found in this study may exist for a broader range of species then tested.

6. As predicted by orthotropic theory the compliances S_{RT} and S_{TR} were found not to differ from each other. The equations relating S_{RT} and S_{RR}, and S_{TR} and S_{TT}, can be combined and a predictive equation relating S_{RR} and S_{TT} can be produced:

$$S_{RR} = 1.479*10^{-6} + 0.294\ S_{TT}$$

This equation is not significantly different from the equation found by Sliker (1988). The compliances S_{TL} and S_{LT}, and S_{RL} and S_{LR} were found to differ from each other. The difficulty in measuring the smaller compliances may partially explain this difference. The different viscoelastic behavior of wood in the L, R, and T direction, and the effect of rate of loading on the viscoelastic behavior in the R and T directions may lead to behavior not predicted by linear orthotropic elastic theory.

7. Linear equations were developed relating the compliances S_{LR} and S_{RL}, S_{LT} and S_{TL}, and S_{RT} and S_{TR}.

1. $S_{LR} = -0.886*10^{-6} + 0.917\ S_{RL}$
2. $S_{LT} = -0.285*10^{-6} + 0.329\ S_{TL}$
3. $S_{RT} = -0.277*10^{-6} + 0.895\ S_{TR}$

Equations 1 and 3 were found to be significant. Equation 2 was not found to be significant at the 90% level. The intercept and slope of the equation relating S_{LR} and S_{RL} did not differ significantly from those predicted by linear orthotropic elastic theory. The intercept of the equation relating S_{RT} and S_{TR} also did not differ significantly from its theoretical value. However, the slope of the equation did differ significantly from its predicted value. The highly linear relationship between these two compliances may partly explain the significance of this difference. Both the intercept and the slope of the equation relating S_{LT} and S_{TL} differed significantly from the values predicted by orthotropic elastic theory.

8. The existence of linear relationships between compliances can provide engineers and designers with an easier method of applying orthotropic theory in the design of wood structures.

9. Several sources of potential error were present in the manufacturing and testing of specimens and need to be taken into account when interpreting the results. During the manufacturing of specimens tension wood was observed in the cottonwood and both of the basswood logs. The extent to which this tension wood affected the strain measurements is unknown, and it should be considered as a possible error source. Human error in mounting the gages on the specimens may have allowed some of the gages to be mounted slightly off axis. This would result in transverse sensitivity errors in the strain readings. The different viscoelastic properties of wood in the L, R, and T directions would introduce varying degrees of error based on variations in the loading rate. The alternating current used in the lighting and other electrical equipment in the testing laboratory can cause an interference in the electrical signals passing through the cables connecting the specimen and the strain indicators. Human error must also be considered as various people were involved in the loading of test specimens and the recording of strain levels. While in most cases these error were negligible, some of the smaller measurements, such as those used to determine S_{LR} and S_{LT}, the error involved would be proportionally larger.

The results of this testing can not substantiate the symmetry condition of an orthotropic material. While this may partially be explained by the difficulty in measuring the compliances S_{LR} and S_{LT}, and the different viscoelastic behaviors of wood in the L, R, and T directions may lead to behavior not predicted by linear orthotropic elastic theory. The small number of sample tested in this study make firm conclusions about the orthotropic behavior of wood difficult. In order to clarify the relationships between compliances additional testing on a broader range of species needs to be undertaken. Additionally, testing needs to be done on the viscoelastic behavior of wood and its effect on the relationship between compliances.

Table 1. Oven dry specific gravities measured for specimens made from the eight trees tested.

SPECIES*	Specific gravity at 0 % MC
COTTONWOOD (*Populus deltoides S.*) (COT2)	0.48
BASSWOOD (*Tilia americana L.*) (BA1)	0.49
BASSWOOD (*Tilia americana L.*) (BA2)	0.42
WHITE ASH (*Fraxinus species*) (WA1)	0.63
WHITE ASH (*Fraxinus species*) (WA2)	0.61
BLACK CHERRY (*Prunus serotina Ehrh.*) (BC1)	0.65
HARD MAPLE (*Acer species*) (HM1)	0.75
BLACK WALNUT (*Juglans nigra L.*) (WAL)	0.54

* The number after the abbreviation of the species designates the log from which specimens were taken.

Table 2. Estimate of variability between individual measurements of the compliance S_{LL}.

SPECIMEN #	S_{LL} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-L1	$0.543*10^{-6}$	0.520	0.0314	5.783	10.89
COT2-L2	0.498				10.93
BA1-L1	0.526	0.522	0.0060	1.139	10.20
BA1-L2	0.518				10.20
BA2-L1	0.676	0.674	0.0028	0.409	10.11
BA2-L2	0.672				10.05
WA1-L1	0.519	0.545	0.0376	7.250	11.67
WA1-L2	0.572				11.67
WA2-L1	0.487	0.540	0.0752	15.454	11.08
WA2-L2	0.593				11.09
BC1-L1	0.722	0.702	0.0276	3.829	11.33
BC1-L3	0.683				11.33
HM1-L1	0.461	0.462	0.0016	0.339	11.91
HM1-L2	0.463				11.91
WAL-L1	0.756	0.756	0.0001	0.020	10.68
WAL-L2	0.755				10.68

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.1548	0.0221	20.02	<.001
ERROR	8	0.0088	0.0011		
TOTAL	15	0.1636			

Table 3. Estimate of variability between individual measurements of the compliance S_{RL}.

SPECIMEN #	S_{RL} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-L1	$-0.186*10^{-6}$	-0.181	0.0064	3.518	
10.89 COT2-L2	-0.177				
10.93					
BA1-L1	-0.174	-0.189	0.0211	11.158	10.20
BA1-L2	-0.204				10.20
BA2-L1	-0.261	-0.244	0.0246	10.079	10.11
BA2-L2	-0.226				10.05
WA1-L1	-0.168	-0.186	0.0252	13.542	11.67
WA1-L2	-0.204				11.67
WA2-L2	-0.185	-0.218	0.0460	21.103	11.08
WA2-L2	-0.250				11.09
BC1-L1	-0.293	-0.276	0.0239	8.664	11.33
BC1-L3	-0.259				11.33
HM1-L1	-0.176	-0.185	0.0119	6.445	11.91
HM1-L2	-0.193				11.91
WAL-L1	-0.293	-0.298	0.0073	2.448	10.68
WAL-L2	-0.303				10.68

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.02921	0.004173	7.20	<.005
ERROR	8	0.00464	0.000580		
TOTAL	15	0.03385			

Table 4. Estimate of variability between individual measurements of the compliance S_{TL}.

SPECIMEN #	S_{TL} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-L1	$-0.209*10^{-6}$	-0.213	0.0067	3.143	
10.89					
COT2-L2	-0.218				10.93
BA1-L1	-0.245	-0.207	0.0547	2.457	10.20
BA1-L2	-0.168				10.20
BA2-L1	-0.279	-0.280	0.0008	0.296	10.11
BA2-L2	-0.280				10.05
WA1-L1	-0.221	-0.233	0.0168	7.188	11.67
WA1-L2	-0.245				11.67
WA2-L2	-0.229	-0.244	0.0217	8.869	11.08
WA2-L2	-0.259				11.09
BC1-L1	-0.320	-0.301	0.0273	9.067	11.33
BC1-L3	-0.282				11.33
HM1-L1	-0.218	-0.220	0.0029	1.334	11.91
HM1-L2	-0.222				11.91
WAL-L1	-0.339	-0.346	0.0110	3.168	10.68
WAL-L2	-0.354				10.68

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.03398	0.004855	8.47	< 0.005
ERROR	8	0.00459	0.000573		
TOTAL	15	0.03857			

Table 5. Estimate of variability between individual measurements of the modulus of elasticity E_L.

SPECIMEN #	E_L (psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-L1	1843000	1924500	115258	5.989	10.89
COT2-L2	2006000				10.93
BA1-L1	1899000	1933500	48790	2.523	10.20
BA1-L2	1968000				10.20
BA2-L1	1479000	1483500	6364	0.429	10.11
BA2-L2	1488000				10.05
WA1-L1	1923000	1836000	123037	6.701	11.67
WA1-L2	1749000				11.67
WA2-L2	2055000	1870500	260922	13.949	11.08
WA2-L2	1686000				11.09
BC1-L1	1385000	1424500	55861	3.921	11.33
BC1-L3	1464000				11.33
HM1-L1	2170000	2164500	7778	0.359	11.91
HM1-L2	2159000				11.91
WAL-L1	1323000	1323500	707	0.053	10.68
WAL-L2	1324000				10.68

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	$1.233*10^{12}$	$1.762*10^{11}$	13.8	< 0.001
ERROR	8	$1.021*10^{11}$	$1.276*10^{10}$		
TOTAL	15	$1.335*10^{12}$			

Table 6. Estimate of variability between individual measurements of the Poisson's ratio υ_{LR}.

SPECIMEN #	υ_{LR}	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-L1	0.303	0.329	0.0368	11.200	10.89
COT2-L2	0.355				10.93
BA1-L1	0.331	0.367	0.0501	13.663	10.20
BA1-L2	0.402				10.20
BA2-L1	0.386	0.362	0.0350	9.665	10.11
BA2-L2	0.337				10.05
WA1-L1	0.324	0.340	0.0226	6.658	11.67
WA1-L2	0.356				11.67
WA2-L2	0.381	0.402	0.0292	7.276	11.08
WA2-L2	0.422				11.09
BC1-L1	0.405	0.392	0.0186	4.739	11.33
BC1-L3	0.379				11.33
HM1-L1	0.383	0.400	0.0244	6.103	11.91
HM1-L2	0.417				11.91
WAL-L1	0.387	0.394	0.0097	2.472	10.68
WAL-L2	0.401				10.68

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.008260	0.001180	1.53	> 0.25
ERROR	8	0.006159	0.000770		
TOTAL	15	0.014420			

Table 7. Estimate of variability between individual measurements of the Poisson's ratio υ_{LT}

SPECIMEN #	υ_{LT}	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-L1	0.385	0.442	0.0799	18.100	10.89
COT2-L2	0.498				10.93
BA1-L1	0.466	0.398	0.0956	24.008	10.20
BA1-L2	0.331				10.20
BA2-L1	0.413	0.415	0.0029	0.702	10.11
BA2-L2	0.417				10.05
WA1-L1	0.426	0.427	0.0013	0.301	11.67
WA1-L2	0.428				11.67
WA2-L2	0.470	0.454	0.0231	5.099	11.08
WA2-L2	0.438				11.09
BC1-L1	0.444	0.428	0.0220	5.140	11.33
BC1-L3	0.413				11.33
HM1-L1	0.473	0.476	0.0044	0.922	11.91
HM1-L2	0.479				11.91
WAL-L1	0.448	0.459	0.0146	3.192	10.68
WAL-L2	0.469				10.68

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.00886	0.00127	0.60	> 0.25
ERROR	8	0.01674	0.00209		
TOTAL	15	0.02560			

Table 8. Estimate of variability between individual measurements of the compliance S_{RR}.

SPECIMEN #	S_{RR} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-R1	$5.831*10^{-6}$	5.739	0.166	2.892	10.99
COT2-R2	5.907				10.99
COT2-R3	5.689				10.99
COT2-R4	5.530				10.99
BA1-R1	8.132	8.068	0.125	1.549	10.32
BA1-R2	7.882				10.21
BA1-R3	8.143				10.26
BA1-R4	8.115				10.28
BA2-R1	9.639	10.006	0.628	6.276	10.14
BA2-R2	9.340				10.15
BA2-R3	10.334				10.17
BA2-R4	10.711				10.17
WA1-R1	3.842	4.118	0.239	5.804	11.72
WA1-R2	3.995				11.72
WA1-R3	4.293				11.72
WA1-R4	4.341				11.74
WA2-R1	3.413	4.675	0.873	18.674	11.19
WA2-R2	5.024				11.12
WA2-R3	4.853				11.15
WA2-R4	5.409				11.15
BC1-R1	3.464	3.558	0.065	1.827	11.38
BC1-R2	3.565				11.38
BC1-R3	3.609				11.39
BC1-R4	3.593				11.39
HM1-R1	3.233	3.266	0.039	1.194	11.97
HM1-R2	3.232				11.97
HM1-R3	3.303				11.98
HM1-R4	3.295				11.98
WAL-R3	3.902	3.776	0.091	2.410	10.66
WAL-R4	3.773				10.60
WAL-R1	3.687				10.67
WAL-R2	3.743				10.67

Table 8 (cont'd)

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	164.817	23.545	148.28	< .001
ERROR	24	3.811	0.159		
TOTAL	31	168.628			

Table 9. Estimate of variability between individual measurements of the compliance S_{TR}.

SPECIMEN #	S_{TR} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-R1	$-5.365*10^{-6}$	-5.344	0.0303	0.567	
10.99					
COT2-R2	-5.322				10.99
BA1-R1	-6.333	-6.387	0.0764	1.195	10.32
BA1-R2	-6.441				10.32
BA2-R1	-9.592	-9.745	0.2171	2.228	10.14
BA2-R2	-9.899				10.15
WA1-R1	-2.336	-2.428	0.1297	5.345	11.72
WA1-R2	-2.519				11.72
WA2-R1	-3.118	-3.018	0.1416	4.690	11.19
WA2-R2	-2.918				11.12
BC1-R1	-2.369	-2.443	0.1045	4.277	11.38
BC1-R2	-2.516				11.38
HM1-R1	-2.275	-2.293	0.0264	1.152	11.97
HM1-R2	-2.312				11.97
WAL-R3	-2.272	-2.285	0.0183	0.800	10.66
WAL-R4	-2.298				10.60

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	103.4366	14.7767	1198.08	< 0.001
ERROR	8	0.0987	0.0123		
TOTAL	15	103.5353			

Table 10. Estimate of variability between individual measurements of the modulus of elasticity E_R.

SPECIMEN #	E_R (psi)	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-R1	171000	174250	5377	3.086	10.99
COT2-R2	169000				10.99
COT2-R3	176000				10.99
COT2-R4	181000				10.99
BA1-R1	123000	124000	2000	1.613	10.32
BA1-R2	127000				10.21
BA1-R3	123000				10.26
BA1-R4	123000				10.28
BA2-R1	104000	100250	6397	6.381	10.14
BA2-R2	107000				10.15
BA2-R3	97000				10.17
BA2-R4	93000				10.17
WA1-R1	260000	243250	14221	5.846	11.72
WA1-R2	250000				11.72
WA1-R3	233000				11.72
WA1-R4	230000				11.74
WA2-R1	293000	220500	49197	22.311	11.19
WA2-R2	199000				11.12
WA2-R3	206000				11.15
WA2-R4	184000				11.15
BC1-R1	287000	280500	4509	1.607	11.38
BC1-R2	280000				11.38
BC1-R3	277000				11.39
BC1-R4	278000				11.39
HM1-R1	309000	306000	3464	1.132	11.97
HM1-R2	309000				11.97
HM1-R3	303000				11.98
HM1-R4	303000				11.98
WAL-R3	256000	264750	6344	2.396	10.66
WAL-R4	265000				10.60
WAL-R1	271000				10.67
WAL-R2	267000				10.67

Table 10 (cont'd)

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	$1.559*10^{11}$	$2.227*10^{10}$	64.35	$< .001$
ERROR	24	$8.307*10^{9}$	$3.461*10^{8}$		
TOTAL	31	$1.642*10^{11}$			

Table 11. Estimate of variability between individual measurements of the Poisson's ratio υ_{RT}.

SPECIMEN #	υ_{RT}	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-R1	0.920	0.911	0.0135	1.487	10.99
COT2-R2	0.901				10.99
BA1-R1	0.779	0.798	0.0274	3.435	10.32
BA1-R2	0.818				10.21
BA2-R1	0.995	1.027	0.0457	4.451	10.14
BA2-R2	1.060				10.15
WA1-R1	0.614	0.622	0.0119	1.917	11.72
WA1-R2	0.631				11.72
WA2-R1	0.914	0.747	0.2355	31.510	11.19
WA2-R2	0.581				11.12
BC1-R1	0.684	0.695	0.0156	2.245	11.38
BC1-R2	0.706				11.38
HM1-R1	0.704	0.709	0.0080	1.135	11.97
HM1-R2	0.715				11.97
WAL-R3	0.582	0.596	0.0189	3.166	10.66
WAL-R4	0.609				10.66

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.29700	0.4243	5.72	< 0.025
ERROR	8	0.05931	0.00741		
TOTAL	15	0.35631			

Table 12. Estimate of variability between individual measurements of the compliance S_{LR}.

SPECIMEN #	S_{LR} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-R3	$-0.233*10^{-6}$	-0.245	0.0168	6.831	
10.99					
COT2-R4	-0.257				10.99
BA1-R3	-0.260	-0.264	0.0056	2.113	10.26
BA1-R4	-0.268				10.28
BA2-R3	-0.353	-0.361	0.0106	2.936	10.17
BA2-R4	-0.368				10.17
WA1-R3	-0.218	-0.219	0.0010	0.472	11.72
WA1-R4	-0.219				11.74
WA2-R3	-0.339	-0.344	0.0075	2.187	11.15
WA2-R4	-0.349				11.15
BC1-R3	-0.340	-0.310	0.0419	13.505	11.39
BC1-R4	-0.281				11.39
HM1-R3	-0.230	-0.234	0.0051	2.199	11.98
HM1-R4	-0.237				11.98
WAL-R1	-0.341	-0.337	0.0062	1.836	10.67
WAL-R2	-0.333				10.67

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.04303	0.006147	21.57	< 0.001
ERROR	8	0.00228	0.000285		
TOTAL	15	0.04531			

Table 13. Estimate of variability between individual measurements of the Poisson's ratio υ_{RL}.

SPECIMEN #	υ_{RL}	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-R3	0.0410	0.044	0.0039	8.810	10.99
COT2-R4	0.0465				10.99
BA1-R3	0.0320	0.033	0.0008	2.370	10.26
BA1-R4	0.0331				10.28
BA2-R3	0.0341	0.035	0.0019	5.224	10.17
BA2-R4	0.0368				10.17
WA1-R3	0.0508	0.051	0.0002	0.321	11.72
WA1-R4	0.0506				11.74
WA2-R3	0.0698	0.067	0.0039	5.835	11.15
WA2-R4	0.0643				11.15
BC1-R3	0.0942	0.086	0.0114	13.195	11.39
BC1-R4	0.0781				11.39
HM1-R3	0.0697	0.071	0.0017	2.365	11.98
HM1-R4	0.0721				11.98
WAL-R1	0.0926	0.091	0.0026	2.914	10.67
WAL-R2	0.0889				10.65

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.007181	0.001026	48.56	< 0.001
ERROR	8	0.000169	0.000021		
TOTAL	15	0.007350			

Table 14. Estimate of variability between individual measurements of the compliance S_{TT}.

SPECIMEN #	S_{TT} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC%
COT2-T1	$17.217*10^{-6}$	17.836	0.507	2.842	10.99
COT2-T2	17.636				11.00
COT2-T3	18.321				10.89
COT2-T4	18.171				10.98
BA1-T1	21.213	20.853	0.861	4.129	10.16
BA1-T2	21.787				10.16
BA1-T3	20.648				10.24
BA1-T4	19.765				10.21
BA2-T3	23.062	22.323	1.355	6.070	10.14
BA2-T4	23.840				10.14
BA2-T1	21.434				10.11
BA2-T2	20.956				10.08
WA1-T1	6.278	6.438	0.113	1.755	11.72
WA1-T2	6.439				11.72
WA1-T3	6.522				11.65
WA1-T4	6.515				11.70
WA2-T1	7.186	7.137	0.169	2.638	11.14
WA2-T2	7.163				11.20
WA2-T3	6.900				11.10
WA2-T4	7.297				11.10
BC1-T1	8.282	8.156	0.202	2.477	11.42
BC1-T2	8.245				11.42
BC1-T4	7.854				11.30
BC1-T8	8.243				11.30
HM1-T1	5.934	6.109	0.143	2.341	12.00
HM1-T2	6.215				11.96
HM1-T3	6.235				11.88
HM1-T4	6.051				11.88
WAL-T3	8.107	8.353	0.216	2.586	10.65
WAL-T4	8.292				10.65
WAL-T1	8.627				10.59
WAL-T2	8.388				10.59

Table 14 (cont'd)

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	1344.760	192.109	515.23	< .001
ERROR	24	8.949	0.373		
TOTAL	31	1353.709			

Table 15. Estimate of variability between individual measurements of the compliance S_{RT}.

SPECIMEN #	S_{RT} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-T1	$-5.044*10^{-6}$	-5.031	0.0183	0.365	10.99
COT2-T2	-5.018				11.00
BA1-T1	-7.147	-7.182	0.0502	0.699	10.16
BA1-T2	-7.218				10.16
BA2-T3	-8.386	-8.390	0.0063	0.074	10.14
BA2-T4	-8.395				10.14
WA1-T1	-2.152	-2.168	0.0231	1.066	11.72
WA1-T2	-2.184				11.72
WA2-T1	-2.722	-2.729	0.0102	0.375	11.14
WA2-T2	-2.736				11.20
BC1-T1	-2.341	-2.330	0.0166	0.711	11.42
BC1-T2	-2.318				11.42
HM1-T1	-2.069	-2.153	0.1193	5.541	12.00
HM1-T2	-2.237				11.96
WAL-T3	-2.668	-2.628	0.0564	2.147	10.65
WAL-T4	-2.588				10.65

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	86.9541	12.4220	4713.00	< 0.001
ERROR	8	0.0211	0.0026		
TOTAL	15	86.9752			

Table 16. Estimate of variability between individual measurements of the modulus of elasticity E_T.

SPECIMEN #	E_T (psi)	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-T1	57900	56050	1533	2.735	10.99
COT2-T2	56700				11.00
COT2-T3	54600				10.89
COT2-T4	55000				10.98
BA1-T1	47100	48000	2012	4.192	10.16
BA1-T2	45900				10.16
BA1-T3	48400				10.24
BA1-T4	50600				10.21
BA2-T3	43400	44900	2707	6.029	10.14
BA2-T4	41900				10.14
BA2-T1	46600				10.11
BA2-T2	47700				10.08
WA1-T1	159300	155350	2783	1.791	11.72
WA1-T2	155300				11.72
WA1-T3	153300				11.65
WA1-T4	153500				11.70
WA2-T1	139200	140175	3351	2.391	11.14
WA2-T2	139600				11.20
WA2-T3	144900				11.10
WA2-T4	137000				11.10
BC1-T1	120700	122650	3113	2.538	11.42
BC1-T2	121300				11.42
BC1-T4	127300				11.30
BC1-T8	121300				11.30
HM1-T1	168500	163725	3860	2.358	12.00
HM1-T2	160900				11.96
HM1-T3	160300				11.88
HM1-T4	165200				11.88
WAL-T3	123300	119750	3080	2.572	10.65
WAL-T4	120600				10.65
WAL-T1	115900				10.59
WAL-T2	119200				10.59

Table 16 (cont'd)

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	$6.797*10^{10}$	$9.710*10^{9}$	1163.53	$< .001$
ERROR	24	$2.003*10^{8}$	$8.345*10^{6}$		
TOTAL	31	$6.817*10^{10}$			

Table 17. Estimate of variability between individual measurements of the Poisson's ratio υ_{TR}.

SPECIMEN #	υ_{TR}	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-T1	0.292	0.288	0.0053	1.837	10.99
COT2-T2	0.285				11.00
BA1-T1	0.337	0.334	0.0040	1.185	10.16
BA1-T2	0.331				10.16
BA2-T3	0.364	0.358	0.0081	2.270	10.14
BA2-T4	0.352				10.14
WA1-T1	0.343	0.341	0.0025	0.730	11.72
WA1-T2	0.339				11.72
WA2-T1	0.379	0.380	0.0023	0.606	11.14
WA2-T2	0.382				11.20
BC1-T1	0.283	0.282	0.0011	0.389	11.42
BC1-T2	0.281				11.42
HM1-T1	0.349	0.354	0.0080	2.267	12.00
HM1-T2	0.360				11.96
WAL-T3	0.329	0.321	0.0120	3.734	10.65
WAL-T4	0.312				10.65

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.01629	0.002327	55.73	< 0.001
ERROR	8	0.00033	0.000042		
TOTAL	15	0.01662			

Table 18. Estimate of variability between individual measurements of the compliance S_{LT}.

SPECIMEN #	S_{LT} (1/psi)	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-T3	$-0.322*10^{-6}$	-0.343	0.0286	8.343	10.89
COT2-T4	-0.363				10.98
BA1-T3	-0.420	-0.411	0.0135	3.289	10.24
BA1-T4	-0.401				10.21
BA2-T1	-0.487	-0.486	0.0008	0.170	10.11
BA2-T2	-0.486				10.08
WA1-T3	-0.422	-0.413	0.0137	3.323	11.65
WA1-T4	-0.403				11.70
WA2-T3	-0.266	-0.281	0.0204	7.254	11.10
WA2-T4	-0.295				11.10
BC1-T4	-0.377	-0.384	0.0091	2.380	11.30
BC1-T8	-0.390				11.30
HM1-T3	-0.284	-0.270	0.0195	7.202	11.88
HM1-T4	-0.257				11.88
WAL-T1	-0.360	-0.363	0.0045	1.235	10.59
WAL-T2	-0.367				10.59

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.071795	0.010256	39.15	< 0.001
ERROR	8	0.002096	0.000262		
TOTAL	15	0.073891			

Table 19. Estimate of variability between individual measurements of the Poisson's ratio υ_{TL}.

SPECIMEN #	υ_{TL}	MEAN	STANDARD DEVIATION	CV %	MC %
COT2-T3	0.0176	0.019	0.0017	8.961	10.89
COT2-T4	0.0200				10.98
BA1-T3	0.0203	0.020	0.0000	0.174	10.24
BA1-T4	0.0203				10.21
BA2-T1	0.0227	0.023	0.0003	1.449	10.11
BA2-T2	0.0232				10.08
WA1-T3	0.0647	0.063	0.0021	3.240	11.65
WA1-T4	0.0618				11.70
WA2-T3	0.0386	0.040	0.0013	3.273	11.10
WA2-T4	0.0405				11.10
BC1-T4	0.0480	0.048	0.0005	1.008	11.30
BC1-T8	0.0474				11.30
HM1-T3	0.0456	0.044	0.0022	5.063	11.88
HM1-T4	0.0424				11.88
WAL-T1	0.0417	0.043	0.0014	3.244	10.59
WAL-T2	0.0437				10.59

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
TREES	7	0.0034224	0.0004889	223.51	< 0.001
ERROR	8	0.0000175	0.0000022		
TOTAL	15	0.0034399			

Table 20. Fisher's protected least significant difference test of the mean values of the compliances and modulus of elasticity for specimens loaded in the L direction.

TREE	S_{LL} (1/psi)		TREE	E_L (psi)	
WAL	$0.7555*10^{-6}$	A *	HM 1	2164500	A
BC 1	0.7025	AB	BA 1	1933500	AB
BA 2	0.6740	B	COT 1	1924500	AB
WA 1	0.5455	C	WA 2	1870500	B
WA 2	0.5400	CD	WA 1	1836000	B
BA 1	0.5220	CD	BA 2	1483500	C
COT 1	0.5205	CD	BC 1	1424500	C
HM 1	0.4620	D	WAL	1323500	C
FPLSD = 0.0707			FPLSD = 240718		

TREE	S_{RL} (1/psi)		TREE	S_{TL} (1/psi)	
COT 1	$-0.1815*10^{-6}$	A	BA 1	$-0.2065*10^{-6}$	A
HM 1	-0.1845	A	COT 1	-0.2135	A
WA 1	-0.1860	A	HM 1	-0.2200	A
BA 1	-0.1890	A	WA 1	-0.2330	AB
WA 2	-0.2175	AB	WA 2	-0.2440	AB
BA 2	-0.2435	BC	BA 2	-0.2795	BC
BC 1	-0.2760	CD	BA 1	-0.3010	BCD
WAL	-0.2980	D	WAL	-0.3465	D
FPLSD = 0.0513			FPLSD = 0.0510		

* means with the same letter within the same column are not significantly different from each other at the 95% probability level.

Table 21. Fisher's protected least significant difference test of the mean values of the compliances, modulus of elasticity, and Poisson's ratio for specimens loaded in the R direction and with the lateral strain measured in the T direction.

TREE	S_{RR} (1/psi)		TREE	E_R (psi)	
BA 2	9.4900*10^{-6}	A *	HM 1	309000	A
BA 1	8.0070	B	BC 1	284500	AB
COT 1	5.8690	C	WAL	260500	AB
WA 2	4.2190	D	WA 1	255000	B
WA 1	3.9180	DE	WA 2	246000	B
WAL	3.8380	DE	COT 1	170000	C
BC 1	3.5150	DE	BA 1	125000	CD
HM 1	3.2330	E	BA 2	105500	D
FPLSD = 0.8915			FPLSD = 50896		

TREE	S_{TR} (1/psi)		TREE	υ_{RT}	
WAL	-2.2850*10^{-6}	A	BA 2	1.0275	A
HM 1	-2.2935	A	COT 1	0.9105	AB
WA 1	-2.4385	A	BA 1	0.7985	BC
BC 1	-2.4425	A	WA 2	0.7475	BCD
WA 2	-3.0180	B	HM 1	0.7095	CD
COT 1	-5.3435	C	BC 1	0.6950	CD
BA 1	-6.3870	D	WA 1	0.6225	CD
BA 2	-9.7455	E	WAL	0.5955	D
FPLSD = 0.2363			FPLSD = 0.1834		

* means with the same letter within the same column are not significantly different from each other at the 95% probability level.

Table 22. Fisher's protected least significant difference test of the mean values of the compliances, modulus of elasticity, and Poisson's ratio for specimens loaded in the R direction and with the lateral strain measured in the L direction.

TREE	S_{RR} (1/psi)		TREE	E_R (psi)	
BA 2	$10.5230*10^{-6}$	A *	HM 1	303000	A
BA 1	8.1290	B	BC 1	277500	B
COT 1	5.6090	C	WAL	269000	B
WA 2	5.1310	D	WA 1	231500	C
WA 1	4.3170	E	WA 2	195000	D
WAL	3.7150	FG	COT 1	178500	E
BC 1	3.6010	GH	BA 1	123000	F
HM 1	3.2990	H	BA 2	95000	G
FPLSD = 0.3703			FPLSD = 12505		

TREE	S_{LR} (1/psi)		TREE	υ_{RL}	
WA 1	$-0.2185*10^{-6}$	A	WAL	0.0910	A
HM 1	-0.2335	AB	BC 1	0.0860	A
COT 1	-0.2450	AB	HM 1	0.0710	B
BA 1	-0.2640	B	WA 2	0.0670	B
BC 1	-0.3105	C	WA 1	0.0510	C
WAL	-0.3370	CD	COT 1	0.0435	CD
WA 2	-0.3440	CD	BA 2	0.0340	DE
BA 2	-0.3605	D	BA 1	0.0325	E
FPLSD = 0.0360			FPLSD = 0.0098		

* means with the same letter within the same column are not significantly different from each other at the 95% probability level.

Table 23. Fisher's protected least significant difference test of the mean values of the compliances, modulus of elasticity, and Poisson's ratio for specimens loaded in the T direction and with the lateral strain measured in the R direction.

TREE	S_{TT} (1/psi)		TREE	E_T (psi)	
BA2	$23.4510*10^{-6}$	A *	HM 1	164700	A
BA 1	21.5000	B	WA 1	157300	B
COT 1	17.4260	C	WA 2	139400	C
BC 1	8.2640	D	WAL	121950	D
WAL	8.2000	D	BC 1	121000	D
WA 2	7.1740	E	COT 1	57300	E
WA 1	6.3590	F	BA 1	46500	F
HM 1	6.0750	F	BA 2	42650	F
FPLSD = 0.5959			FPLSD = 4961		

TREE	S_{RT} (1/psi)		TREE	υ_{TR}	
HM 1	$-2.1530*10^{-6}$	A	WA 2	0.3805	A
WA 1	-2.1680	A	BA 2	0.3580	B
BC 1	-2.3295	B	HM 1	0.3545	BC
WAL	-2.6280	C	WA 1	0.3410	CD
WA 2	-2.7290	C	BA 1	0.3340	DE
COT 1	-5.0310	D	WAL	0.3205	E
BA 1	-7.1825	E	COT 1	0.2885	F
BA 2	-8.3905	G	BC 1	0.2820	F
FPLSD = 0.1095			FPLSD = 0.0138		

* means with the same letter within the same column are not significantly different from each other at the 95% probability level.

Table 24. Fisher's protected least significant difference test of the mean values of the compliances, modulus of elasticity, and Poisson's ratio for specimens loaded in the R direction and with the lateral strain measured in the L direction.

TREE	S_{TT} (1/psi)		TREE	E_T (psi)	
BA 2	$21.1950*10^{-6}$	A *	HM 1	162750	A
BA 1	20.2070	B	WA 1	153400	B
COT 1	18.2460	C	WA 2	140950	C
WAL	8.5070	D	BC 1	124300	D
BC 1	8.0490	D	WAL	117550	F
WA 2	7.0990	E	COT 1	54800	G
WA 1	6.5180	EF	BA 1	49500	GH
HM 1	6.1440	F	BA 2	47150	H
FPLSD = 0.6375			FPLSD = 6294		

TREE	S_{LT} (1/psi)		TREE	υ_{TL}	
HM 1	$-0.2705*10^{-6}$	A	WA 1	0.0635	A
WA 2	-0.2805	A	BC 1	0.0475	B
COT 1	-0.3425	B	HM 1	0.0440	C
WAL	-0.3635	BC	WAL	0.0430	C
BC 1	-0.3835	CD	WA 2	0.0395	D
BA 1	-0.4105	DE	BA 2	0.0230	E
WA 1	-0.4125	E	BA 1	0.0200	EF
BA 2	-0.4865	F	COT 1	0.0190	F
FPLSD = 0.0345			FPLSD = 0.0032		

* means with the same letter within the same column are not significantly different from each other at the 95% probability level.

Table 25. Analysis of variance and statistics of slope and intercept constants for the compliance equations.

EQUATION #1 $S_{RL}{}^{*} = 0.0299*10^{-6} - 0.429\ S_{LL}$

PREDICTOR	COEF	ST DEV	T-RATIO	P
CONSTANT	$0.0299*10^{-6}$	$0.0291*10^{-6}$	1.03	< 0.4
SLOPE	-0.429	0.04896	-8.77	< 0.002

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
REGRESSION	1	10.013549	0.013549	76.98	< 0.001
ERROR	6	0.001057	0.000176		
TOTAL	7	0.014606			

EQUATION #2 $S_{TL} = 0.0152*10^{-6} - 0.461\ S_{LL}$

PREDICTOR	COEF	ST DEV	T-RATIO	P
CONSTANT	$0.0152*10^{-6}$	$0.03285*10^{-6}$	0.46	< 0.6
SLOPE	-0.461	0.05523	-8.35	< 0.002

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
REGRESSION	1	0.015645	0.015645	69.84	< 0.001
ERROR	6	0.001346	0.000224		
TOTAL	7	0.016991			

* Units for the compliances S_{ij} are strain (inch/inch) per unit stress (psi).

Table 25 (cont'd)

EQUATION #3 $S_{TR}{}^{*} = 1.79*10^{-6} - 1.15\ S_{RR}$

PREDICTOR	COEF	ST DEV	T-RATIO	P
CONSTANT	$1.79*10^{-6}$	$0.5287*10^{-6}$	3.38	< 0.02
SLOPE	-1.15	0.09286	-12.35	< 0.002

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
REGRESSION	1	49.766	49.766	152.19	< 0.001
ERROR	6	1.959	0.327		
TOTAL	7	51.726			

EQUATION #4 $S_{LR} = -0.247*10^{-6} - 0.00767\ S_{RR}$

PREDICTOR	COEF	ST DEV	T-RATIO	P
CONSTANT	$-0.247*10^{-6}$	$0.05021*10^{-6}$	-4.91	< 0.001
SLOPE	-0.00767	0.008327	-0.92	< 0.6

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
REGRESSION	1	0.00262	0.00262	0.85	> 0.25
ERROR	6	0.018852	0.003142		
TOTAL	7	0.021515			

* Units for the compliances S_{ij} are strain (inch/inch) per unit stress (psi).

Table 25 (cont'd)

EQUATION #5 $S_{RT}^{*} = 0.089*10^{-6} - 0.338\ S_{TT}$

PREDICTOR	COEF	ST DEV	T-RATIO	P
CONSTANT	$0.089*10^{-6}$	$0.3332*10^{-6}$	0.27	< 0.8
SLOPE	-0.338	0.02371	-14.27	< 0.001

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
REGRESSION	1	42.233	42.233	204.02	< 0.001
ERROR	6	1.244	0.207		
TOTAL	7	43.477			

EQUATION #6 $S_{LT} = -0.291*10^{-6} - 0.00648\ S_{TT}$

PREDICTOR	COEF	ST DEV	T-RATIO	P
CONSTANT	$-0.291*10^{-6}$	$0.04771*10^{-6}$	-6.10	< 0.001
SLOPE	-0.00648	0.003534	-1.83	< 0.2

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	P
REGRESSION	1	0.012889	0.012889	3.36	< 0.25
ERROR	6	0.023009	0.003835		
TOTAL	7	0.035897			

* Units for the compliances S_{ij} are strain (inch/inch) per unit stress (psi).

Table 26. Statistical analysis of the differences between the slopes of compliance equations developed in this study and those developed by Sliker, and Yu.

EQUATION #1 $S_{RL} = f(S_{LL})$

	SLOPE	T	DF	T 80%	T 90%
WEIGEL	-0.429				
SLIKER	-0.429	-0.193	22	1.321	1.717
YU	-0.353	-0.551	13	1.350	1.771

EQUATION #2 $S_{TL} = f(S_{LL})$

	SLOPE	T	DF	T 80%	T 90%
WEIGEL	-0.461				
SLIKER	-0.500	0.402	22	1.321	1.717
YU	-0.360	0.889	13	1.350	1.771

EQUATION #3 $S_{TR} = f(S_{RR})$

	SLOPE	T	DF	T 80%	T 90%
WEIGEL	-1.150				
SLIKER	-0.887	2.414	15	1.341	1.753
YU	-0.967	1.613	13	1.350	1.771

Table 26 (cont'd)

EQUATION #4 $S_{RT} = f(S_{TT})$

	SLOPE	T	DF	T 80%	T 90%
WEIGEL	-0.338				
SLIKER	-0.255	0.526	13	1.350	1.771
YU	-0.288	0.332	13	1.350	1.771

Table 27. Comparison of the reciprocal compliances.

H_o $S_{RT} = S_{TR}$

COMPLIANCE	n	MEAN	ST DEV
S_{RT}	16	$-4.08*10^{-6}$	$2.41*10^{-6}$
S_{TR}	16	$-4.24*10^{-6}$	$2.63*10^{-6}$
t = 0.19	DF = 29.8	P = 0.85	

H_o $S_{RL} = S_{LR}$

COMPLIANCE	n	MEAN	ST DEV
S_{RL}	16	$-0.222*10^{-6}$	$0.0475*10^{-6}$
S_{LR}	16	$-0.2891*10^{-6}$	$0.055*10^{-6}$
t = 3.70	DF = 29.4	P = 0.0009	

H_o $S_{RL} = S_{LR}$

COMPLIANCE	n	MEAN	ST DEV
S_{TL}	16	$-0.2555*10^{-6}$	$0.0507*10^{-6}$
S_{LT}	16	$-0.3688*10^{-6}$	$0.0702*10^{-6}$
t = 5.23	DF = 27.3	P < 0.0001	

Table 28. Statistical analysis of the difference between the slope of the equation relating S_{RR} and S_{TT} developed in this study and the equation developed by Sliker (1988).

	SLOPE	T	DF	T 80%	T 90%
WEIGEL	0.293				
SLIKER	0.291	-0.066	13	1.350	1.771

Table 29. Analysis of variance of the regression equation relating reciprocal compliances and t-test comparing equations determined in this study with their theoretical values.

Equation 1. $S_{LR}^{*} = -0.886*10^{-6} + 0.917\ S_{RL}$

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.012156	0.012156	7.792	< 0.05
Error	6	0.009359	0.00156		
Total	7	0.021515			

t- test comparing predicted values and theoretical values

Predictor	Coef	Theoretical value	T	$T_{.25}$	$T_{.1}$
Constant	$0.0886*10^{-6}$	0	-1.1721	0.718	
1.440 Slope	0.917	1	-0.268	0.718	
1.440					

Table 29 (cont'd)

Equation 2. $S_{LT} = -0.285*10^{-6} + 0.329\ S_{TL}$

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.001842	0.001842	0.325	> 0.25
Error	6	0.034055	0.005676		
Total	7	0.035897			

t- test comparing predicted values and theoretical values

Predictor	Coef	Theoretical value	T	$T_{.25}$	$T_{.1}$
Constant	$-0.285*10^{-6}$	0	-1.8968	0.718	1.440
Slope	0.329	1	-1.160	0.718	1.440

* Units for the compliances S_{ij} are strain (inch/inch) per unit stress (psi).

Table 29 (cont'd)

Equation 3. $S_{RT}^{*} = -0.279*10^{-6} + 0.895\ S_{TR}$

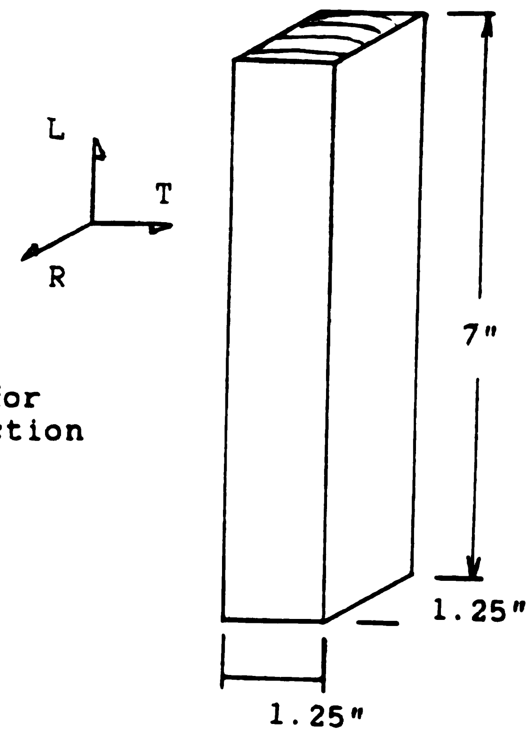
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	41.402	41.402	119.659	< 0.001
Error	6	2.075	0.08177		
Total	7	43.477			

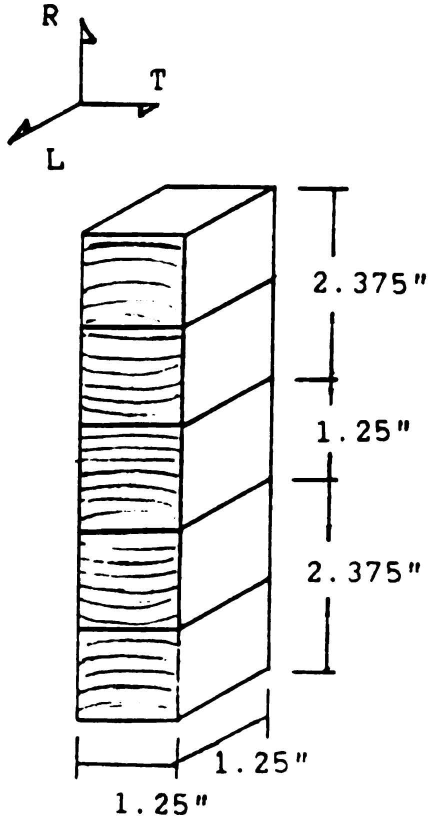
t- test comparing predicted values and theoretical values

Predictor	Coef	Theoretical value	T	$T_{.25}$	$T_{.1}$
Constant	$-0.279*10^{-6}$	0	-0.7037	0.718	1.440
Slope	0.895	1	-1.298	0.718	1.440

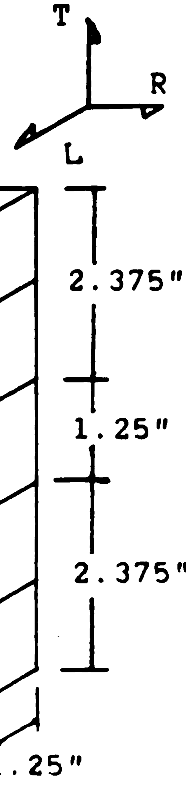
* Units for the compliances S_{ij} are strain (inch/inch) per unit stress (psi).



L type specimen used for
loading in the L direction

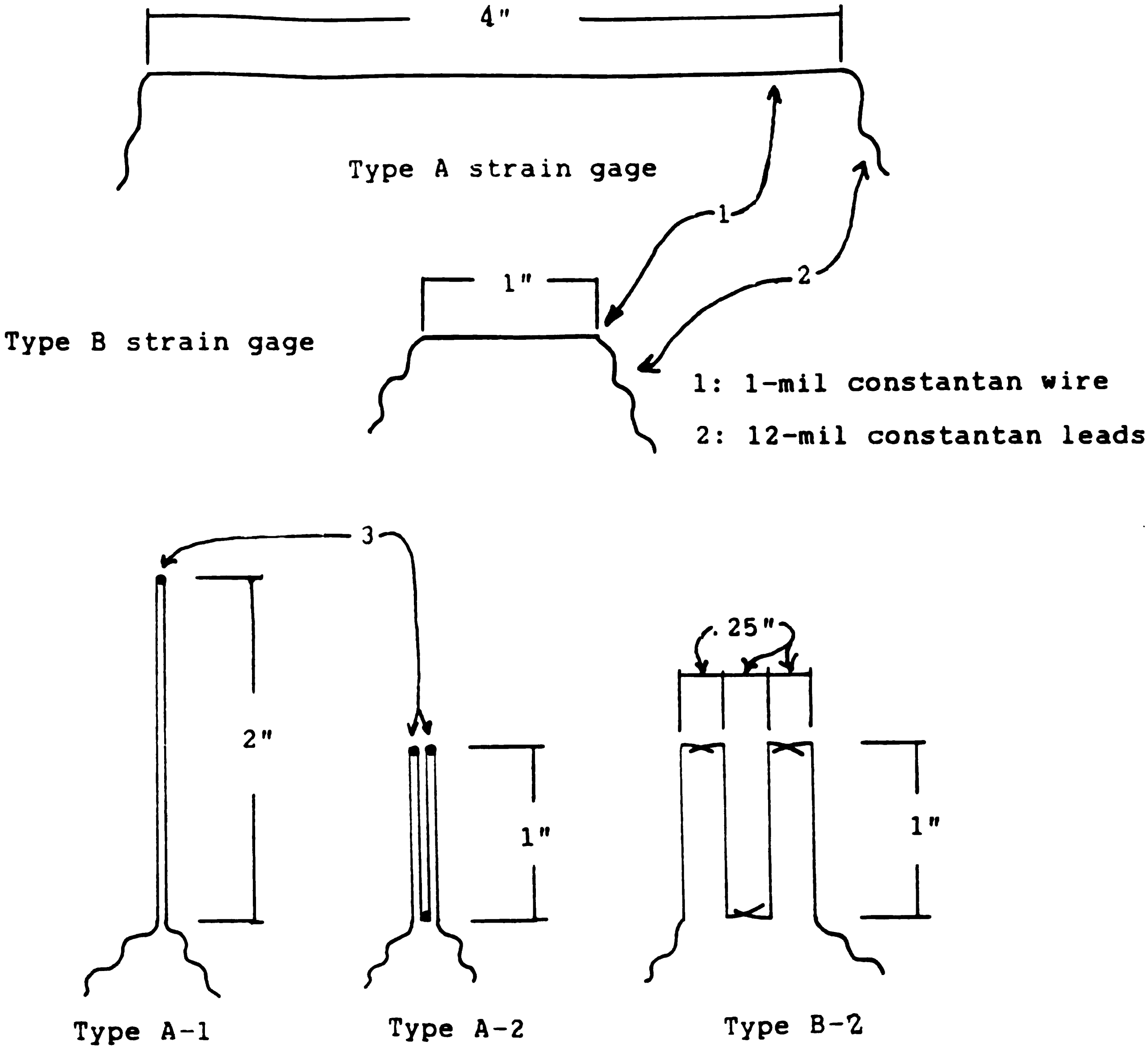


R type specimen used for
loading in the R direction



T type specimen used for
loading in the T direction

Figure 1. Compression samples.

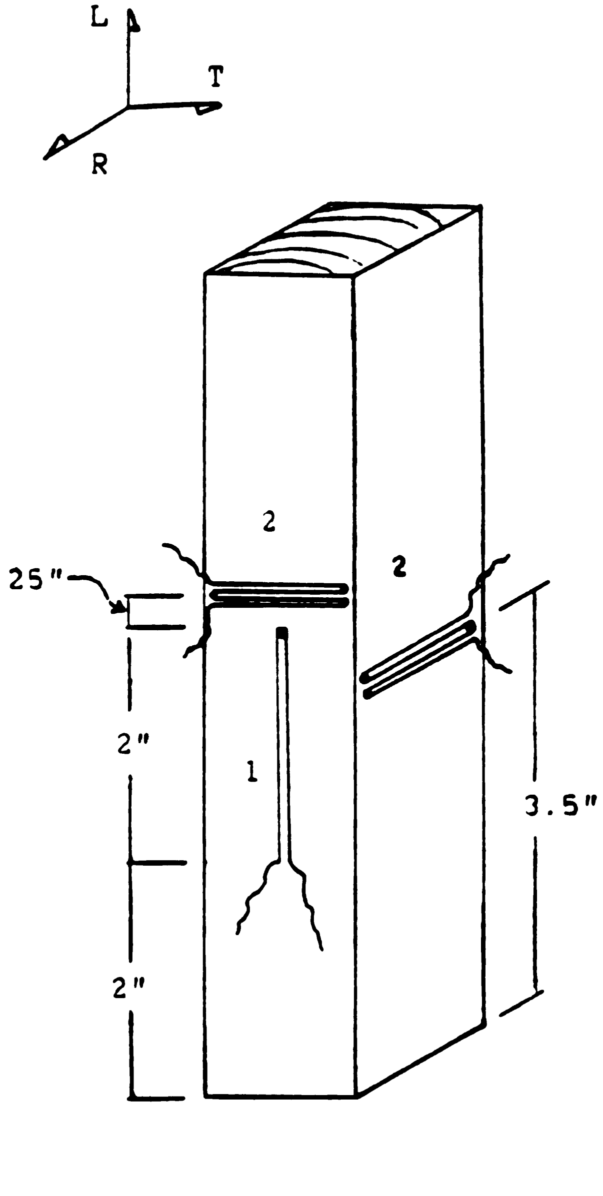


Type A-1 gage used for measuring strains in the L direction when loading in the L direction.

Type A-2 gage used for measuring strains in the R and T directions.

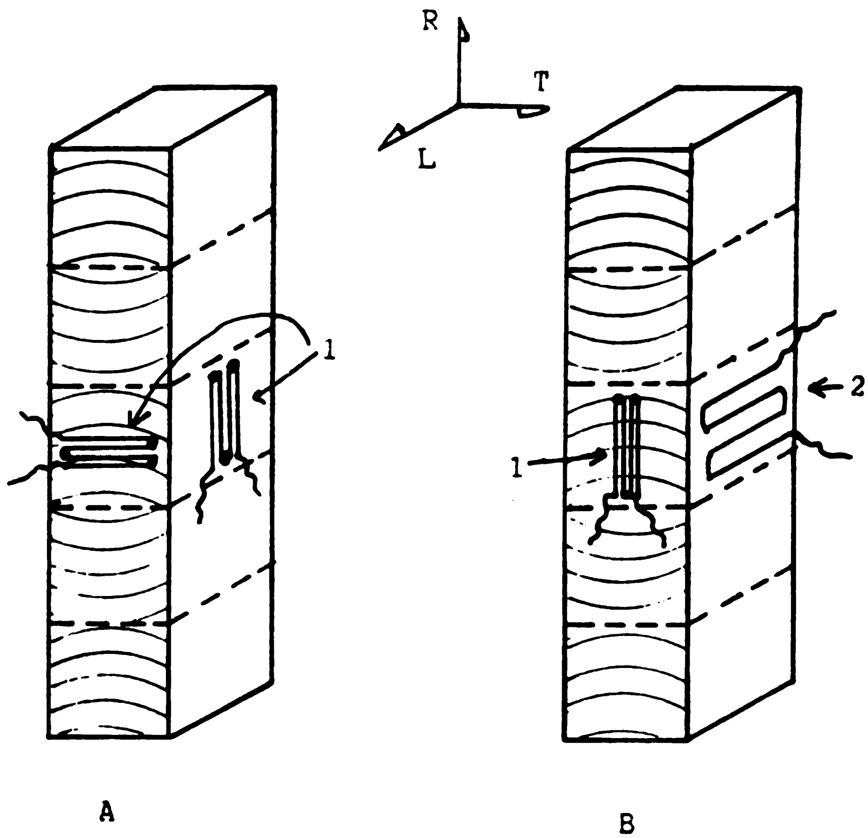
Type B-2 gage used for measuring strains in the L direction when loading in the R and T directions.

Figure 2. Gage types and configurations.



1: Type A-1 gage
2: Type A-2 gage

Figure 3. Gage arrangement for measuring strains when loading in the L direction.

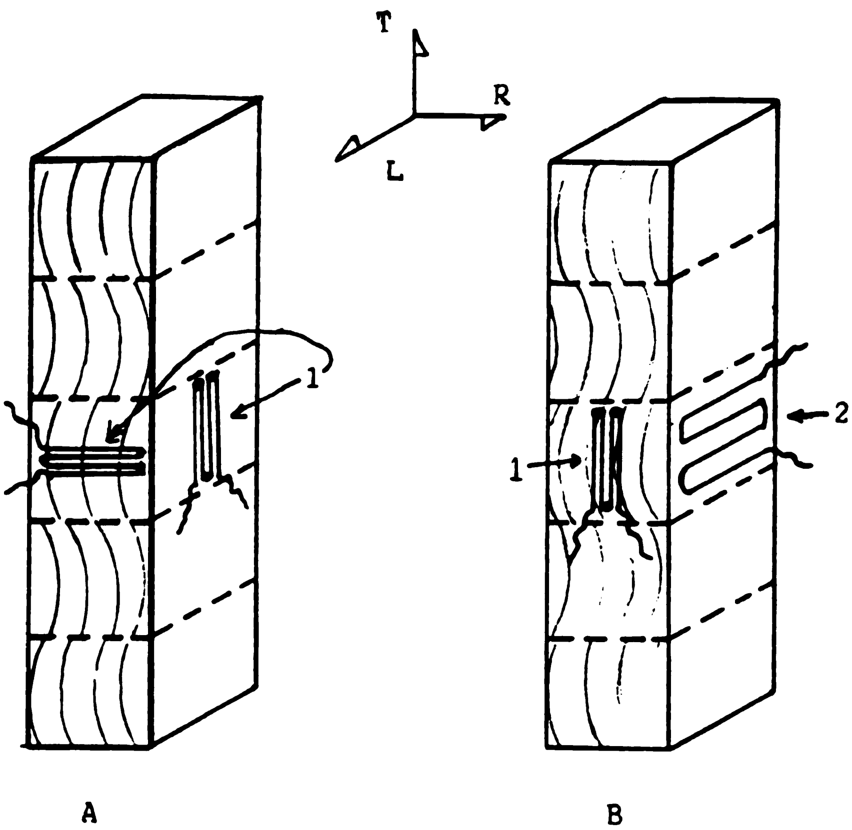


1: Type A-2 gage
2: Type B-1 gage

A: Used to measure strains in the R and T directions when loading in the R direction.

B: Used to measure strains in the R and L directions when loading in the R direction.

Figure 4. Gage arrangements for measuring strains when loading in the R direction.



1: Type A-2 gage
2: Type B-1 gage

A: Used to measure strains in the T and R directions when loading in the T direction.

B: Used to measure strains in the T and L directions when loading in the T direction.

Figure 5. Gage arrangements for measuring strains when loading in the T direction.

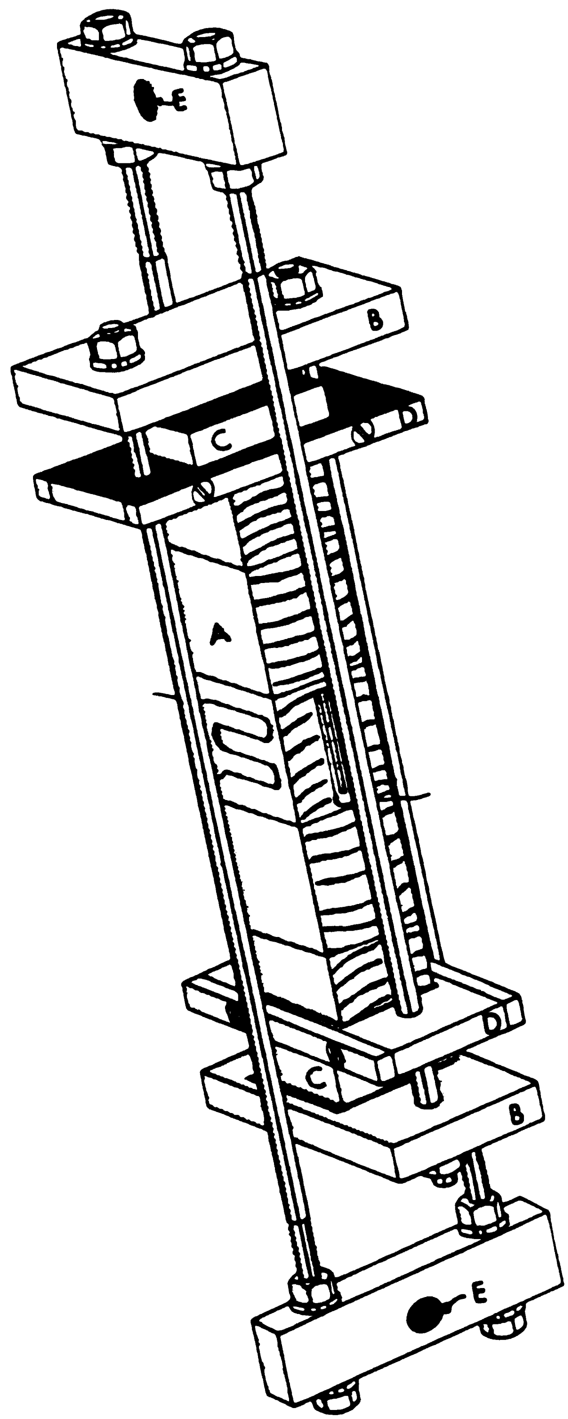


Figure 6. Test specimen A in the compression cage. B is end block. C is end bearing block. D is centering guide. E is hole for metal dowel connection to universal joint. Ball bearing is centered between B and C at each end (Sliker 1989).

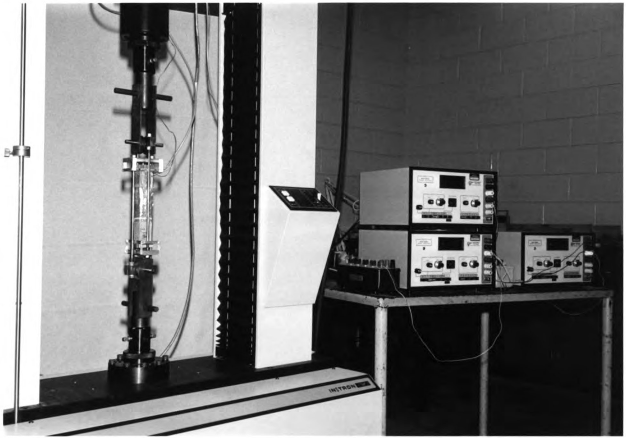


Figure 7. Compression cage connected to Instron crossheads for loading in the L direction.

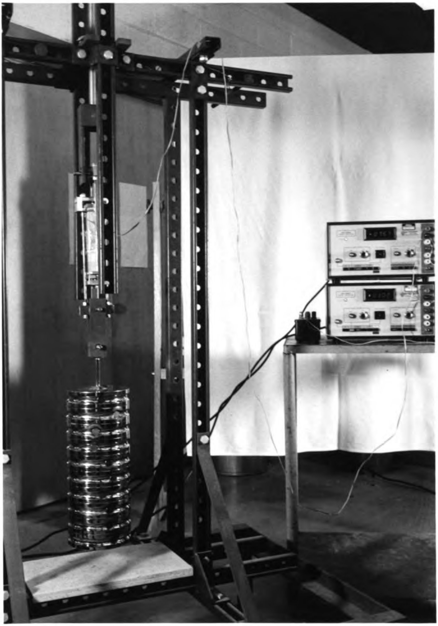
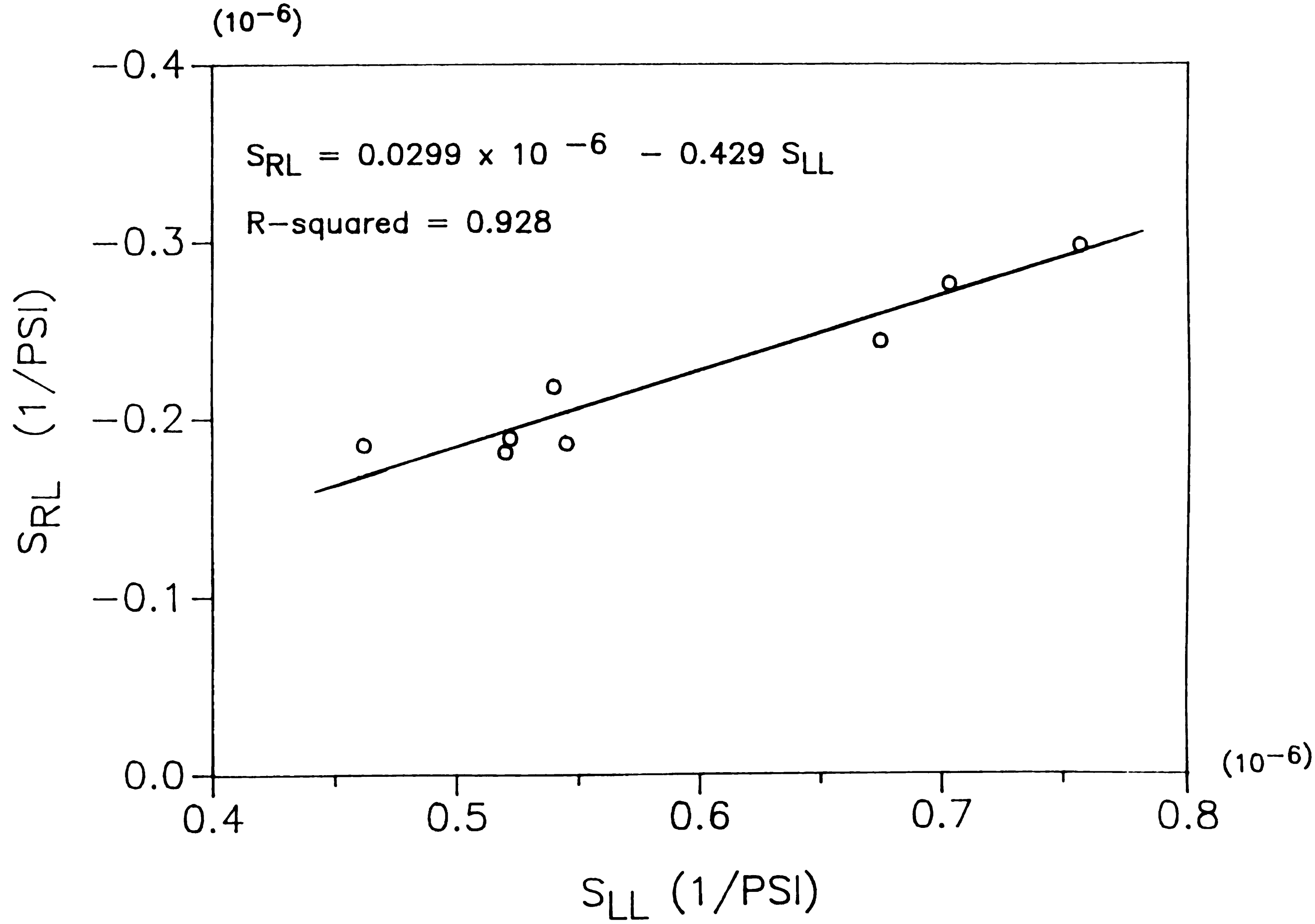
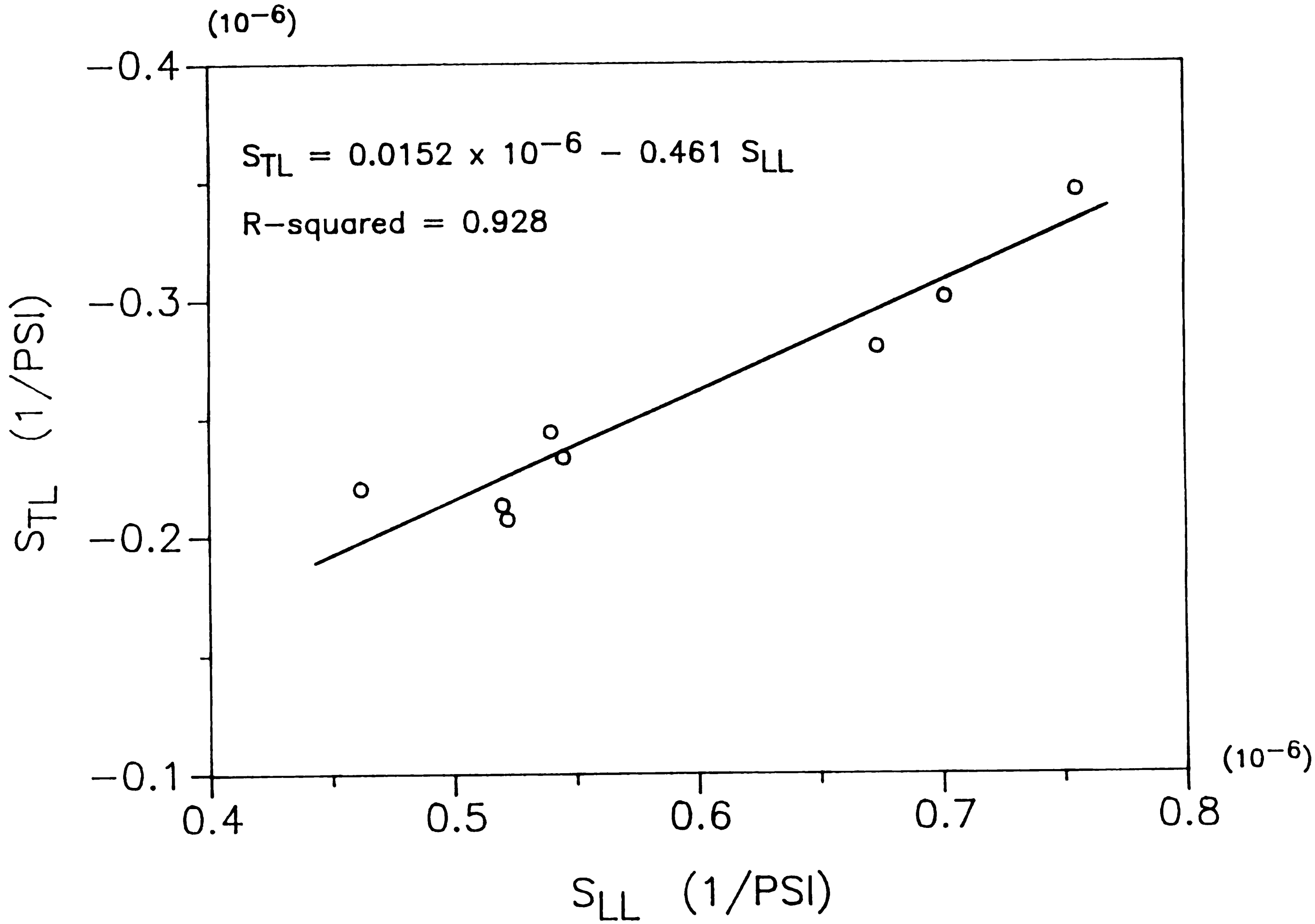


Figure 8. Compression cage mounted on steel frame for loading the R and T directions



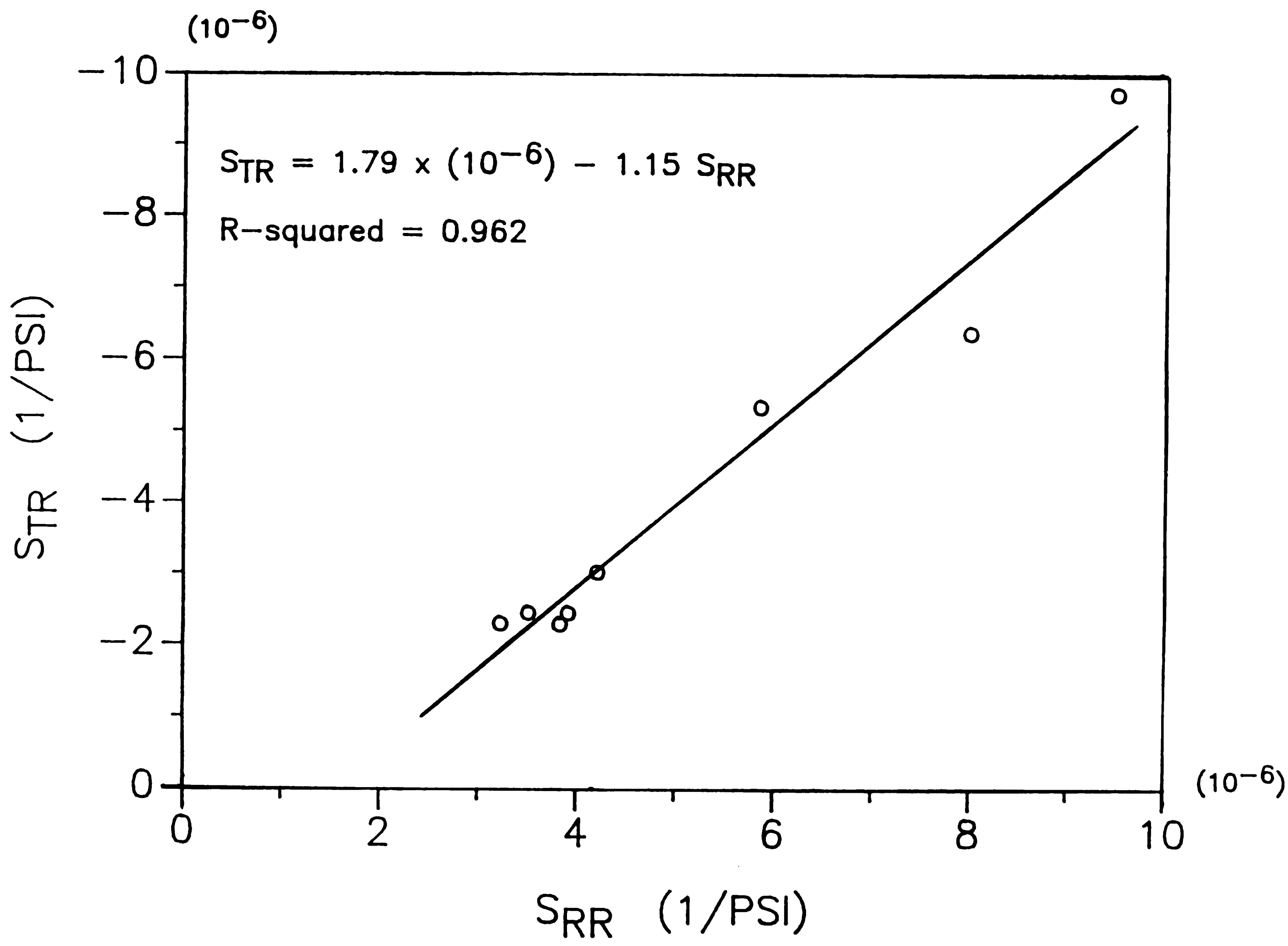
Each point represents the average measurement of two matched specimens.

Figure 9. Compliance S_{RL} plotted as a function of the compliance S_{LL} for the eight trees tested.



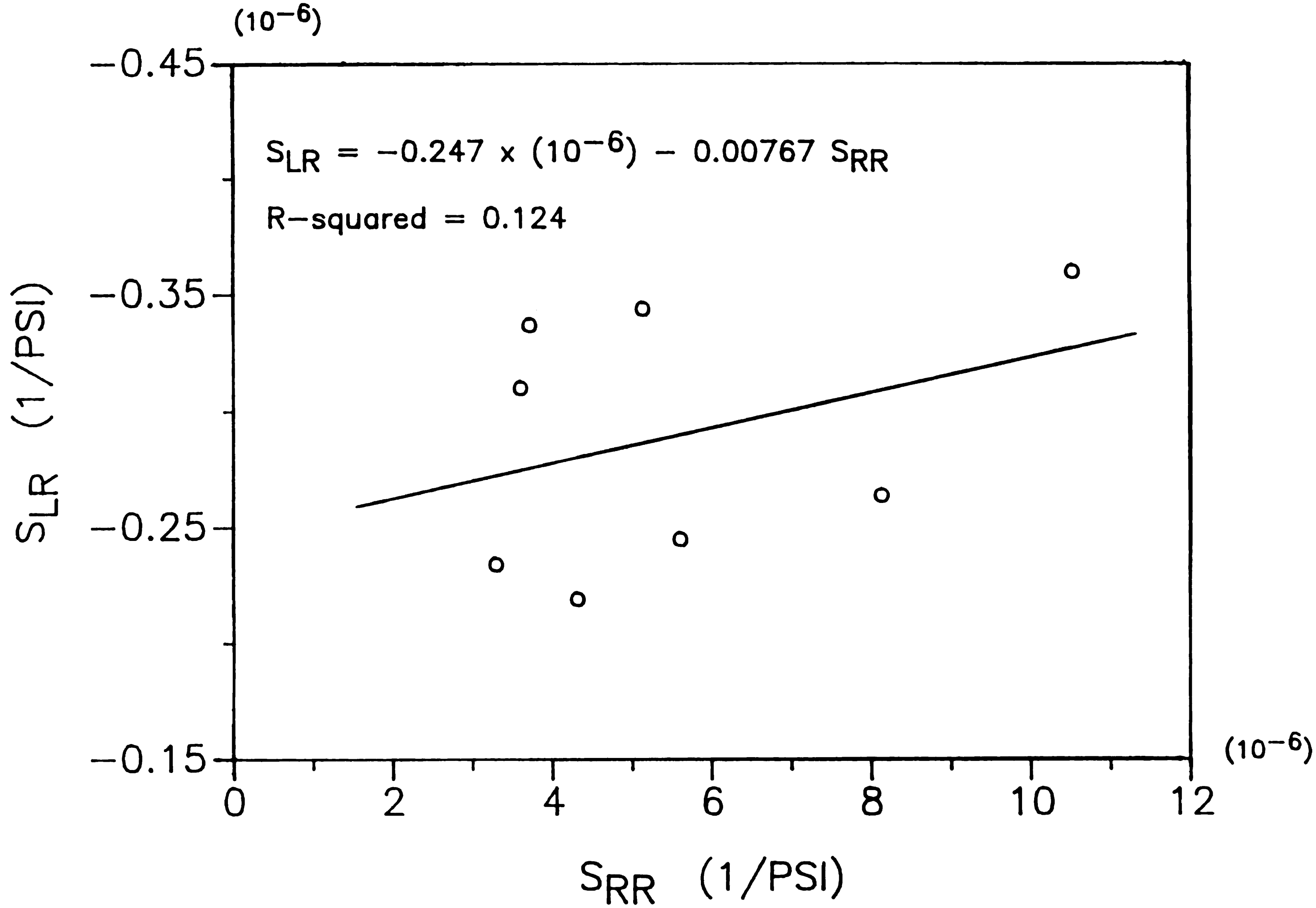
Each point represents the average measurement of two matched specimens.

Figure 10. Compliance S_{TL} plotted as a function of the compliance S_{LL} for the eight trees tested.



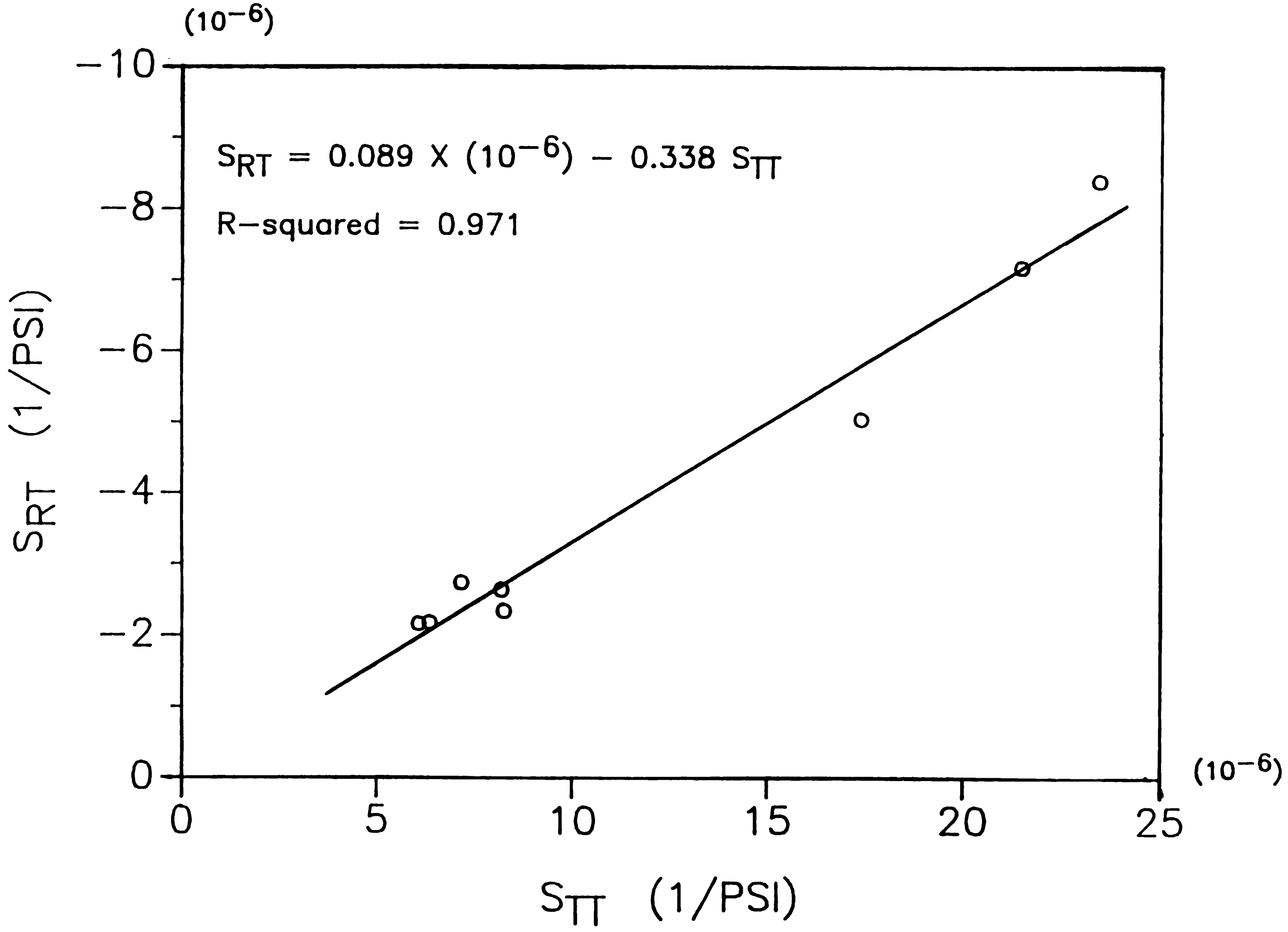
Each point represents the average measurement of two matched specimens.

Figure 11. Compliance S_{TR} plotted as a function of the compliance S_{RR} for the eight trees tested.



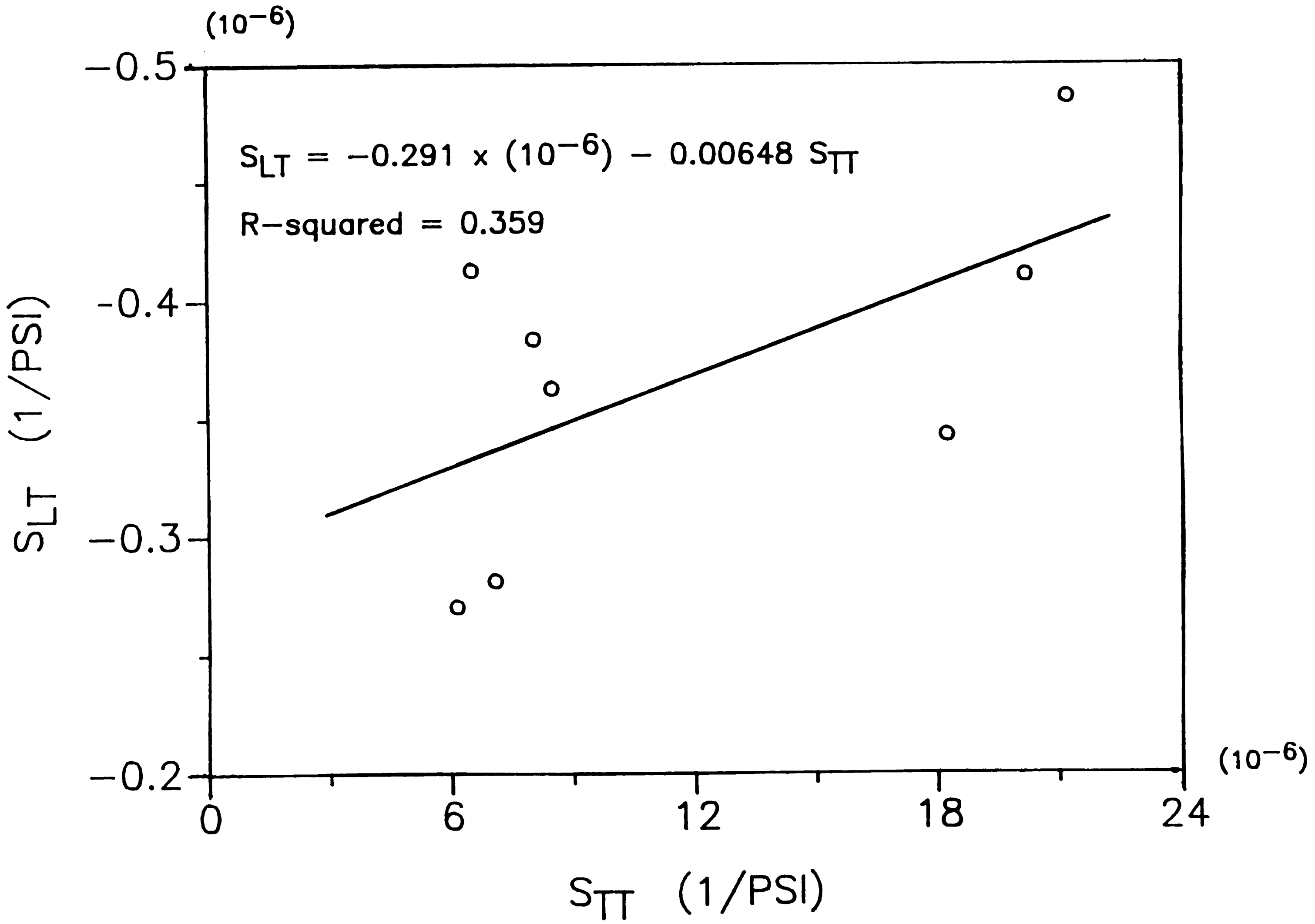
Each point represents the average measurement of two matched specimens.

Figure 12. Compliance S_{LR} plotted as a function of the compliance S_{RR} for the eight trees tested.



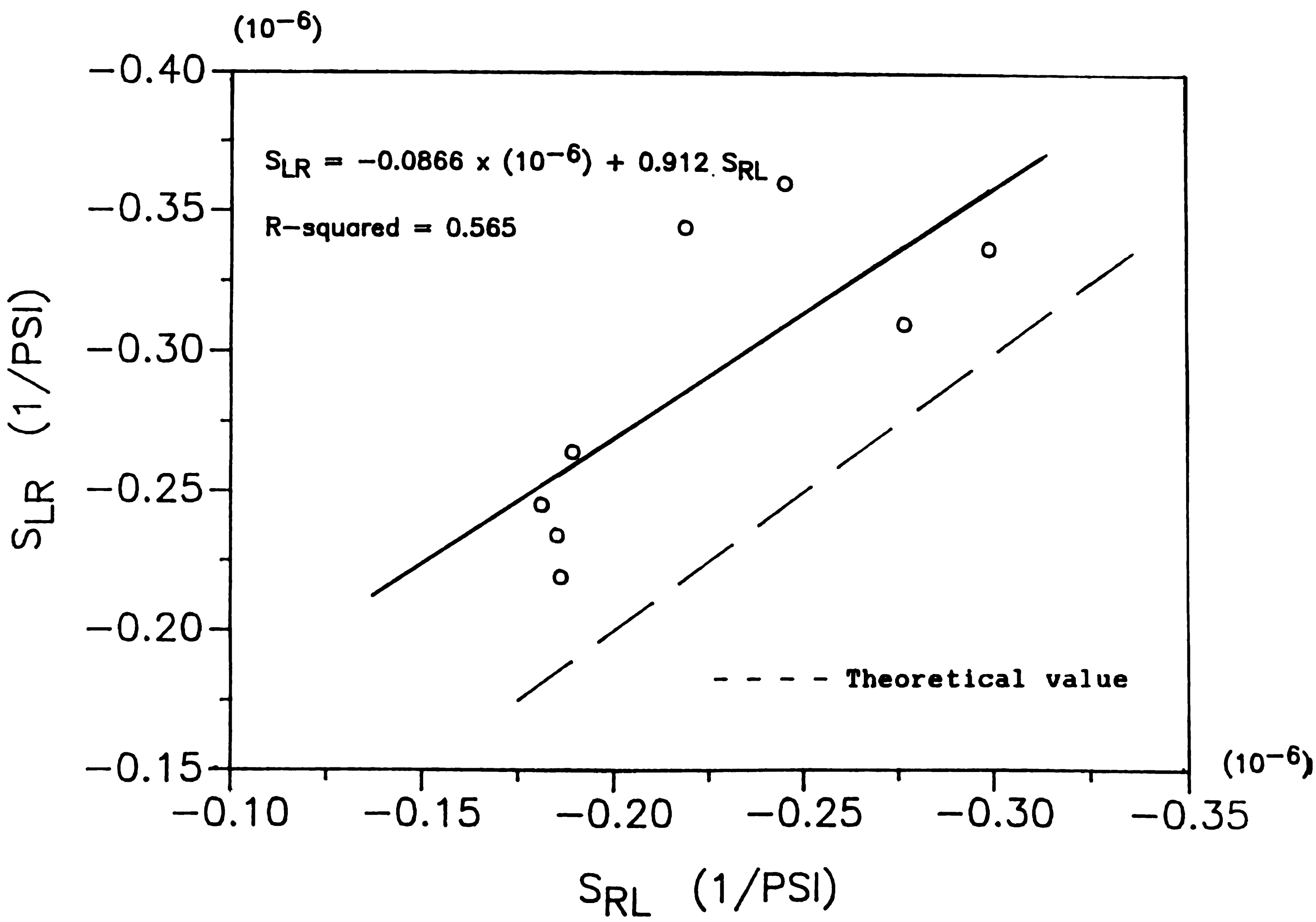
Each point represents the average measurement of two matched specimens.

Figure 13. Compliance S_{RT} plotted as a function of the compliance S_{TT} for the eight trees tested.



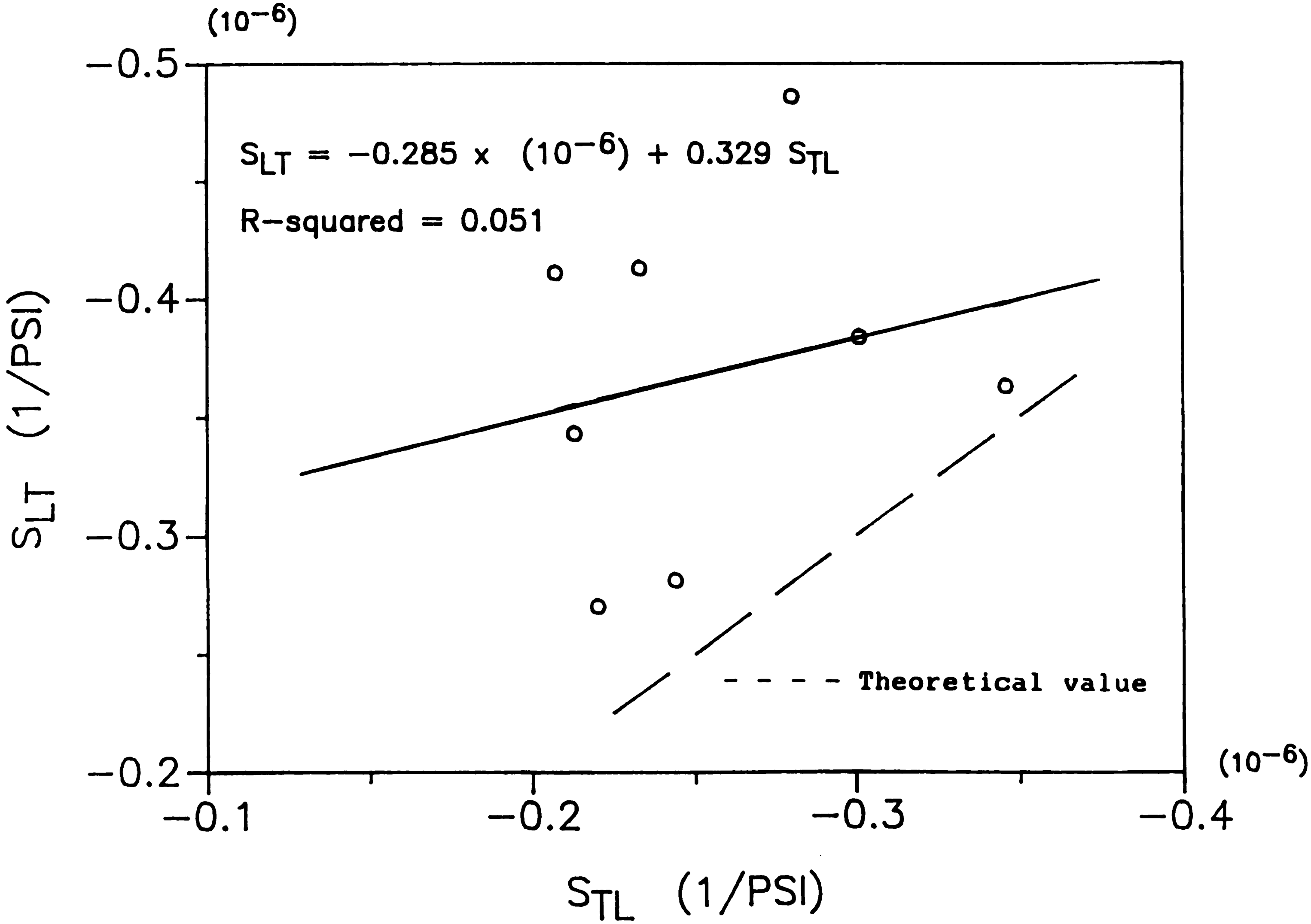
Each point represents the average measurement of two matched specimens.

Figure 14. Compliance S_{LT} plotted as a function of the compliance S_{TT} for the eight trees tested.



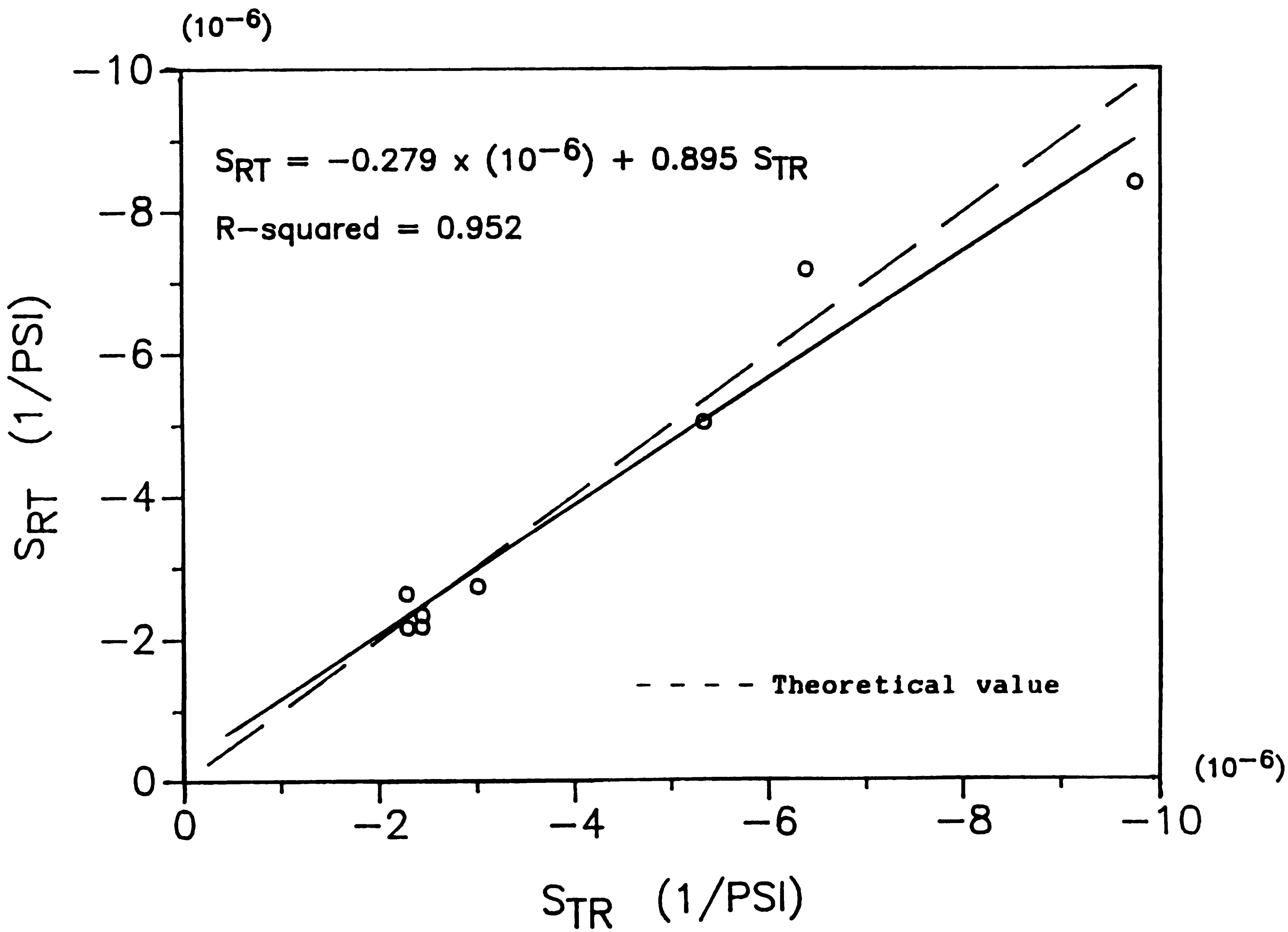
Each point represents the average measurement of two matched specimens.

Figure 15. Compliance S_{LR} plotted as a function of the compliance S_{RL} for the eight trees tested.



Each point represents the average measurement of two matched specimens.

Figure 16. Compliance S_{LT} plotted as a function of the compliance S_{TL} for the eight trees tested.



Each point represents the average measurement of two matched specimens.

Figure 17. Compliance S_{RT} plotted as a function of the compliance S_{TR} for the eight trees tested.

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