ELASTIC CONSTANTS FOR HARDWOODS MEASURED FROM PLATE AND TENSION TESTS

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ABSTRACT

Measurements of shear moduli G_{LR} and G_{LT}, Young's moduli E_L, E_R, and E_T, and Poisson's ratios ν_{LT} and ν_{LR} were made at approximately 12% moisture content from material cut from 18 eastern hardwood logs. Shear moduli calculated from off-axis tension tests with angle of load to the L-axis of 20° were slightly larger than those from plate tests. E_R values determined from off-axis tensile tests closely approximated those determined from tensile tests in the R direction. Poisson's ratios for basswood, cottonwood, and soft maple were negative (strains parallel and perpendicular to the load direction were both positive) in the LT plane for loadings at 20° to the L direction. Some significant correlations were found between the reciprocals of elastic constants and the reciprocals of density at test, also between the reciprocals of shear moduli and the reciprocals of Young's moduli E_R and E_T. There was less variability in measurements made in the LR plane than in the LT plane.

Keywords: Density, hardwoods, plate twisting tests, Poisson's ratio, shear modulus, tensile tests, Young's modulus.

NOTATION

- 1 = subscript for direction parallel to load axis
- 2 = subscript for direction perpendicular to load axis
- i = subscript l, L, R, or T
- A = cross-sectional area of specimen
- D_t = density at test moisture content
- E_i = Young's modulus in the i direction (σ_i/ϵ_i)
- $(E)_i$ = Young's modulus in the i direction from off-axis tensile test (Equations 2 and 3)
- G_{LR} = shear modulus in the LR plane (plate test)
- G_{LT} = shear modulus in the LT plane (plate test)
- $(G)_{LR}$ = shear modulus in the LR plane (off-axis tension test)
- $(G)_{LT}$ = shear modulus in the LT plane (off-axis tension test)
- L, R, T = longitudinal, radial, and tangential axes
- M_A = ϵ_A/σ_1, $M_B = \epsilon_B/\sigma_1$, $M_C = \epsilon_C/\sigma_1$
- P = axial load parallel to specimen length
- α = angle in degrees between longitudinal direction L and direction of load P
- ϵ_i = strain in i direction
- ϵ_1, ϵ_2 = strains parallel and perpendicular to the load axis

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$\epsilon_A, \epsilon_B, \epsilon_C$ = strains at 0°, 45°, and 90° to direction of load P in off-axis tension test
ν_{12} = M_C/M_A from off-axis tension test $(-\epsilon_2/\epsilon_1)$
ν'_{12} = Poisson's ratio calculated from Equation 7
ν_{LR} = $-\epsilon_R/\epsilon_L$
ν_{LT} = $-\epsilon_T/\epsilon_L$
σ_i = P/A
ζ_p = angle between the direction of maximum principal strain and the axial load P

INTRODUCTION

A project investigating the mechanical properties of eastern hardwoods is being conducted at Michigan State University. In previous work, relationships between elastic constants other than those for shear were investigated (Yu 1990; Weigel 1991). The current study looks at two ways to measure Young's moduli and the shear moduli G_{LR} and G_{LT}. Equations relating elastic constants to density and to each other are being sought. The testing technique also provides information about the Poisson's ratio ν_{12} for specimens loaded at an angle to the L direction in the LR and LT planes. Mature wood as opposed to juvenile wood was used for the experiments to help simplify the analysis. Juvenile wood could be a topic for another study.

Two methods for measuring shear moduli are by the use of plates and by the use of off-axis tension specimens. Plates are frequently tested by the method described in ASTM D3044-76 (American Society for Testing and Materials 1989), which is designated for plywood plate testing but has also been used for solid wood. A major difficulty with the test for solid wood is making the plates. Off-axis tensile specimens are frequently used to measure shear modulus in synthetic composites such as glass filament composites (Greszczuk 1969). The technique has also been used with wood (Ebrahimi and Sliker 1981; Schuldt 1972; Zhang and Sliker 1991). One of the more practical angles to use between the L direction and the load axis is 20°. According to Zhang and Sliker (1991), this angle produces a value for shear modulus that most closely approximates that from a plate test. Schuldt (1972) arrived at this same angle by finite element analysis. Zhang and Sliker found a tension specimen to be better than a compression specimen for measuring shear moduli. They also found that the maximum strain in off-axis tension specimens occurred somewhere in the range of 20 to 35 degrees with the load axis.

Poisson's ratios can have greatly different values for specimens loaded at an angle to the grain than for those loaded parallel or perpendicular. When a wood specimen is loaded in the L, R, or T directions, the strain perpendicular to the load axis will be opposite in sign to that parallel to it; i.e., for a tension test in the LT plane, Poisson's ratio $\nu_{LT} = -\epsilon_T/\epsilon_L$ and is treated as being a positive Poisson's ratio. However, it is possible for some woods loaded at an angle to the grain to have a negative Poisson's ratio where the strains parallel and perpendicular to the load axis both have the same sign; i.e., $-\nu_{12} = \epsilon_1/\epsilon_2$. This was shown for spruce loaded at various angles to the grain in the LT plane in a publication by Stavsky and Hoff (1969). In the paper by Zhang and Sliker, there was a basswood sample loaded at an angle to the grain of 20° in the LT plane that had a negative Poisson's ratio.

There are numerous studies showing strong correlations between Young's moduli and also shear moduli with specific gravity or density. Many of the regression equations are of the exponential type, although linear regressions seem to work almost as well according to Bodig and Goodman (1973). Good correlation often depends on having a wide range of densities or specific gravities to work with. A large range of densities can be obtained by using data from species grown all over the world since some tropical woods are either lighter or denser than our native U.S. species. Bodig and Goodman (1973), Guitard (1987), and Kellogg and Ifju (1962) combined data for species from many countries. Correlation coefficients (R) in Bodig and Goodman's article for equations relating Young's moduli and shear moduli to density are between 0.915 and 0.988, while coefficients of variation (CV) for the regressions are between 11% and 30%. Most researchers have separated hardwoods from softwoods in their analyses.

Elastic constants can also be predictors for other elastic constants. There are some good examples of this in Bodig and Goodman's 1973 paper, which gives equations for E_R, E_T, G_{LR}, and G_{LT} as functions of E_L. There are also equations in which E_R and E_T are the independent variables. Correlation coefficients R for all of their equations of this type for hardwoods were greater than 0.900. Density was equal to or better as a predictor for elastic constants than were the elastic constants themselves judging by the magnitude of the correlation coefficients and the CVs. None of the previously mentioned publications shows very strong associations between Poisson's ratios and density or the other elastic constants.

The objectives of this research were to compare the shear moduli G_{LR} and G_{LT}, the three Young's moduli (E_L, E_R, and E_T), and the Poisson's ratios ν_{LR} and ν_{LT} obtained by different test methods; and to look for relationships between pairs of elastic constants and between elastic constants and density.

PROCEDURE

The goal of the testing was to measure shear moduli by means of a standard plate test and then to measure Young's moduli, Poisson's ratios, and shear moduli from tension specimens cut from the plates. Half of the plates were to have their broad surfaces LR planes and half were to have their broad surfaces LT planes. Relationships among the various elastic constants determined by the plate and tension tests would be examined.

The source of the test material was 18 eastern hardwood logs that were 30 or more inches in diameter. Species were selected to provide a range of densities and elastic constants. Selection was also based on a wood's reputation for straightness of grain; i.e., woods like sycamore and elm were not included because of their interlocking grain. In most instances, each species was represented by two logs from different trees. A list of the species and their densities as taken from test panels is given in Table 1. The 18 logs were squared and then live-sawn into 3½-inch thick boards that were 12 to 24 inches wide and 8 to 12 feet long.

Equilibrium moisture content desired for test material was 12%. Drying of the green or partially air-dried boards took place in a small dry kiln that could handle only a limited amount of material at a time. A slow kiln schedule taking about 30 days was employed so that some boards were air-drying while the others were in the kiln. Fast drying species like cottonwood often were at a low moisture content before there was an opportunity to put them in the kiln. A problem was encountered with some oak boards that were left to air-dry for a long time in that they honeycombed before they could be put into the kiln. This happened with flatsawn boards of white oak A.

As a preliminary step to making 14-inch by 14-inch by ½-inch plates, blanks one-inch thick by 6 to 8 inches in the R or T direction by 18 inches in the L direction were cut from sections of the large dried boards. Frequently, only one blank could be cut from an 18-inch section of the approximately 3¼-inch thick kiln-dried boards because of slope in grain. However, all blanks for a given plate came from the same board. In most cases, enough blanks were cut from each log to make a plate with its broad surfaces in the LR plane and one with its broad surfaces in the LT plane. Cutting straight-grained blanks with representative radial and tangential faces was a three-dimensional problem, which could not be met with black cherry B in the LR plane. The flow of a drop of dye was used to find the L direction when it was not obvious. Since the blanks in the LR plane had to come from quartersawn boards and those in the LT plane from flatsawn boards, they were not necessarily well matched as to wood properties such as being from the same growth rings.