MODELING THE EFFECT OF OUT-OF-PLANE FIBER ORIENTATION IN LUMBER SPECIMENS

Douglas C. Stahl and *Steven M. Cramer*

Research Assistant and Assistant Professor
Department of Civil and Environmental Engineering
University of Wisconsin–Madison
Madison, WI 53706

and

Kent McDonald

Research Wood Scientist
USDA, Forest Service
Forest Products Laboratory[1]
Madison, WI 53705

(Received March 1989)

ABSTRACT

A method is presented to account for the effect of three-dimensional fiber orientations near knots in a two-dimensional lumber tensile strength prediction model. Data we have collected show that grain angles dive from 15 to 90 degrees out of the wide face plane of flat-grained lumber within a region of about one knot radius from the visual edge of a knot. The diving nature of the grain angles is accounted for in a two-dimensional model, called GASPP+, by transforming a three-dimensional material compliance matrix, and extracting the appropriate coefficients for use in a two-dimensional compliance matrix. Failure criteria are modified to reflect the decreased strength associated with nonzero dive angles. These modifications led to accurate tensile behavior predictions, as evidenced by load-displacement plots and ultimate load measurements of lumber specimens. It is shown that consideration of dive angles is important in predicting the tensile strength and failure mode of thin lumber specimens. Lumber specimen thickness and the manner of loading influence the magnitude of the dive effect on strength.

Keywords: Fiber orientation, lumber tensile strength, fracture, finite elements.

INTRODUCTION

To ensure that lumber continues to be a viable option as a structural material, methods must be developed to predict more accurately its behavior, especially its ultimate strength. By eliminating some of the uncertainty in present grading procedures, boards that are predicted to have higher strengths can be assigned those strengths with confidence. Sawn lumber could be used more efficiently; this would open up some applications where sawn lumber is presently not an option because of economic or purely structural reasons.

The behavior of defect-containing sawn lumber is extremely complex even under simple loading conditions. The board with a knot and associated grain deviations is an orthotropic material with variable orientation of orthotropic axes, with material properties that vary with location, with discontinuities and associated stress concentrations, and with the potential for multiple failure modes

[1] The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

even on the local level. Not surprisingly, most behavior prediction schemes avoid such complications and use empirical relationships between some easily measured property and the desired behavioral characteristic. The current machine stress-rated (MSR) and common visual grading procedures are examples of applied empirical relationships. The accuracy of these methods is inherently limited by any deficiencies in the relationships they depend on. Closed-form elasticity solutions for the stress field in idealized lumber specimens have been proposed (Green 1945: Tang 1984) but involve too many assumptions and simplifications to be a practical alternative to empirical strength prediction methods. A different approach is required to develop a reliable strength prediction scheme.

Several researchers have recognized the importance of fiber orientation, or grain angle, on structural behavior, and have attempted to use this as the basis for strength prediction schemes. Because of the highly orthotropic nature of wood, a modest angle between the fiber orientation and principal stress direction can have a marked effect on both stiffness and strength. Tests reveal that the tensile strength of a block of clear southern pine with an angle of 12 degrees between the fiber orientation and the applied load has only about half the strength of a similar block with the load applied in line with fibers (Pugel 1986). An implication of this is that the grain deviations that commonly occur around knots and other growth defects affect the structural performance of lumber. Bechtel and Allen developed an empirical procedure that uses measurements of surface grain angles—which describe fiber orientation in the plane of the wide face of a board—to locate a cross section of minimum strength and predict the tensile strength of the board (Bechtel and Allen 1987). This scheme performed well in a preliminary verification and awaits further development. Cramer and others (Cramer and Goodman 1986; Cramer et al. 1988; Cramer and McDonald 1989) have pursued a more theoretical approach and developed a strength prediction scheme that uses surface grain angles as the basis for a finite element model of knot-containing lumber. This model is applied in a step-wise process that simulates the sequence of "local failures" and the resulting accumulation of damage that leads to ultimate failure. This procedure has been used to accurately predict the ultimate tensile strength and effective stiffness of knot-containing 2 by 4 boards and smaller lumber specimens (Cramer and McDonald 1989; Cramer et al. 1988).

While these two strength prediction methods are unique in that they address the grain structure of wood surrounding knots, they are limited to consideration of surface grain angles in the wide-face plane of boards. We will present data that show that the orientation of wood fibers near knots involves *all three* board dimensions. Furthermore, an examination of lumber specimens tested to failure in tension indicates that dive angles—which describe fiber orientation out of the plane of the wide face—can affect the failure process (Badreddine 1988; Anthony and Bodig 1988). If out-of-plane fiber orientations do play a significant role in determining the mode of failure and the strength of lumber specimens subject to tension, they should be considered in new strength prediction methods.

Because of the complex arrangement of fibers near a knot, it is extremely difficult by experimental means to distinguish between the individual effects of surface angle components and dive angle components (in and out of the wide-face plane of a board, respectively). Our approach to this problem has been to enhance the theoretical strength prediction method developed by Cramer and others to in-