FINITE ELEMENT FRACTURE PREDICTION FOR WOOD WITH KNOTS AND CROSS GRAIN

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ABSTRACT

A finite element/fracture mechanics model has been developed to predict the tension behavior of structural wood members containing defects. The computer code STARWX presented here is used in a preliminary investigation of the effect of global cross grain on the strength of structural wood members with knots. The results indicate a more severe stress condition for the member with global cross grain as compared to the straight grain member.

A method of strength prediction is presented that, unlike other methods, simulates the progressive fracture/failure process in wood, which leads to the ultimate load-carrying capacity of the member. Program STARWX is employed to predict the failure of a wood member containing a knot and global cross grain in a case for which actual test data are available. The member ultimate strength predicted was within 15% of the strength determined by the test.

Keywords: Finite elements, fracture prediction, wood with defects.

INTRODUCTION

The inherent anisotropy, inhomogeneity, and occurrence of cracks in wood emphasize the complexity of wood as a structural material and the importance of developing methods of predicting its behavior under load. Recent research efforts have resulted in a finite element/fracture mechanics numerical algorithm capable of describing the anisotropic, inhomogeneous nature of lumber by modeling knots, the associated grain deviations, and crack growth which is evident in wood as the failure process progresses toward the ultimate load-carrying capacity (Cramer and Goodman 1983, 1986; Dabholkar 1980). The code predicts stress and strain values for any location in a piece of lumber under axial load. In addition, the stress intensity factors are predicted if a crack is present. The numerical algorithm developed in this research allows simulation of the progressive failure of lumber pieces containing defects.

The research presented in this paper extends the capabilities of a previously developed code (Cramer and Goodman 1986) to allow modeling of the progressive cracking and failure process in solid wood including the effects of global cross grain. The numerical predictions presented are compared with the results of experiments on failure of wood containing knots and global cross grain.

STARWX, A CODE FOR WOOD CONTAINING DEFECTS

The model presented here combines orthotropic finite element analysis with a technique for predicting the grain deviation around knots. The model is contained in the computer program entitled STARWX (Zandbergs 1985). Its overall capabilities are discussed below.

A major strength-reducing effect of knots is the associated grain deviation. Program STARWX accounts for this grain distortion by utilizing the flow-grain analogy (Phillips et al. 1981) whereby grain line shapes are simulated using fluid mechanics equations for streamlines about an elliptical cylinder in laminar cross flow. Figure 1 shows a finite element mesh approximation of a wood member containing a knot and cross grain. The mesh was generated by program STARWX and models a member with global grain angle, α. The simulated grain pattern is symmetrical about the longitudinal (L) and transverse (T) axes. The grain angle for each element is calculated by averaging the angle of the two longitudinal (parallel to L) sides of the element with respect to the edge of the mesh. Grain angles predicted by the flow-grain analogy were compared with actual measured values (Phillips et al. 1981) for Douglas-fir and lodgepole pine with various knot sizes. The comparison showed the flow-grain analogy to be quite accurate in predicting local grain angles.

The current code allows the simulated knot to be moved to any position across the width of the finite element mesh as long as the center of the knot remains within the boundaries of the mesh. Also, the global grain angle as defined in Fig. 1 can vary from 0 to 15 degrees. This combination of knot locations and grain angles allows for analysis of a wide range of problems.

Program STARWX automatically generates the load and displacement boundary conditions depicted in Fig. 1. As will be discussed in more detail later, a uniform stress is simulated to closely approximate a particular set of test conditions (Anthony 1986) so that comparison of numerical and experimental results can be made.

Program STARWX utilizes a finite element/fracture mechanics code (Cramer and Goodman 1986) that employs three orthotropic element types: 8 node quadrilateral, 6 node triangular, and 8 node hybrid singular quadrilateral elements to model the stress singularity at the crack tip. Excluding the crack tip elements, all elements are standard quadratic isoparametric elements (Zienkiewicz 1977). The hybrid singular elements include fracture mechanics displacement equations directly in their formulation. As a result, the stress intensity factors are determined directly in the solution process. These elements were developed from linear elastic fracture mechanics concepts by Atluri et al. (1974).

The element stresses that are provided by the code are the perpendicular-to-grain, parallel-to-grain, and shear components. In addition, the mode I and mode II stress intensity factors are provided if a crack is present. These values are automatically compared to failure criteria in a post-processing routine to predict crack initiation and propagation. As will be discussed later, program STARWX incorporates the maximum stress theory (Boresi et al. 1978) to predict crack initiation and Wu's criteria (Wu 1967) for mixed mode fracture.

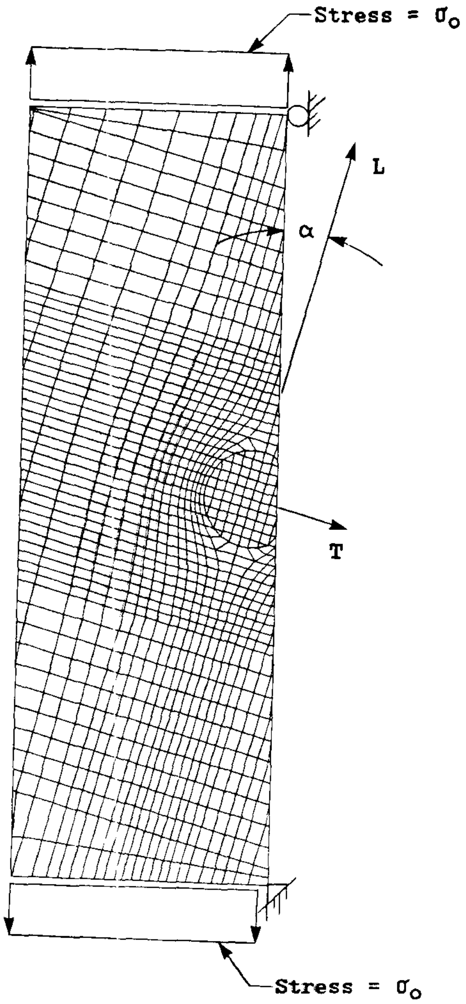


FIG. 1. Finite element mesh approximation for edge-knot member with global grain angle α, generated by Program STARWX.

Element stresses calculated from nodal displacements in the global coordinate system can be transformed to the local element coordinate system by consideration of the grain angle associated with that element yielding the element stresses parallel-to-grain, perpendicular-to-grain, and shear. Since linear elastic behavior is assumed, the load necessary to cause initial failure can be calculated by comparing element stresses with the small specimen clear wood strengths via the failure criteria. When cracks are present, the stress intensity factors are calculated and compared to fracture criteria in an analogous manner to determine what load is required to cause the crack to propagate. The results of these comparisons are presented through a "Failure Summary," which indicates the location of the next failure and directs the user to take the next step in the failure modeling process.

Program STARWX was designed for use with the CDC CYBER 205 Supercomputer. The high speed cost-effective performance of the CYBER 205 was an integral part of the code development.

STRENGTH AND FAILURE PREDICTION

Extensive experimental research has been performed in order to provide a data base for verification and development of the numerical model. Recently Douglas-fir members of ¼- × 4-inch cross section with 14 inches in length between the grips were tested in axial tension (Anthony 1986). Pin and lever specimen grips were employed to approximate a uniform applied stress. Hardwood strips were glued to the specimen to reinforce the area surrounding the pins to prevent shear failure of the test specimen at the pins.

Strength and fracture properties utilized in this study were measured or predicted (Anthony 1986) for the experimental case being modeled. The mode I-LT critical stress intensity factor ($K_{IC\text{-}LT}$) was predicted on the basis of specific gravity and moisture content (Petterson and Bodig 1983). Other properties were measured (Anthony 1986):

$$\begin{aligned} \sigma_{Lult} &= 19{,}500 \text{ psi} \\ \sigma_{Tult} &= 398 \text{ psi} \\ \tau_{LTult} &= 1{,}300 \text{ psi} \\ K_{IC\text{-}LT} &= 314 \text{ psi} \sqrt{\text{in}} \\ K_{IIC\text{-}LT} &= 1{,}360 \text{ psi} \sqrt{\text{in}} \end{aligned}$$

Elastic properties of wood utilized in this study were predicted (Anthony 1986). The longitudinal modulus of elasticity (E_L) and tangential modulus of elasticity (E_T) were predicted on the basis of specific gravity and moisture content (Petterson and Bodig 1983). Other elastic properties were estimated based on average data (Bodig and Jayne 1982; Bodig and Goodman 1973).

$$\begin{aligned} E_L &= 1{,}830{,}000 \text{ psi} \\ E_T &= 127{,}000 \text{ psi} \\ \nu_{LT} &= 0.42 \\ G_{LT} &= 109{,}500 \text{ psi} \end{aligned}$$

Knotwood elastic properties were estimated based on work by Pugel (1980) to be:

$$\begin{aligned} E_R &= 50{,}000 \text{ psi} \\ E_T &= 50{,}000 \text{ psi} \\ \nu_{RT} &= 0.47 \\ G_{RT} &= 38{,}000 \text{ psi} \end{aligned}$$

To predict the location of the initial failure of the material, the maximum stress theory was incorporated into the finite element/fracture mechanics analysis (Cramer and Goodman 1986). By the maximum stress theory, failure occurs when:

$$\begin{aligned} \sigma_L/\sigma_{Lult} &= 1, \text{ or} \\ \sigma_T/\sigma_{Tult} &= 1, \text{ or} \\ \tau_{LT}/\tau_{LTult} &= 1, \end{aligned} \tag{1}$$

where the numerators represent the calculated stresses parallel-to-grain (σ_L), tangential (σ_T), and shear (τ_{LT}), respectively. The denominators correspond to small

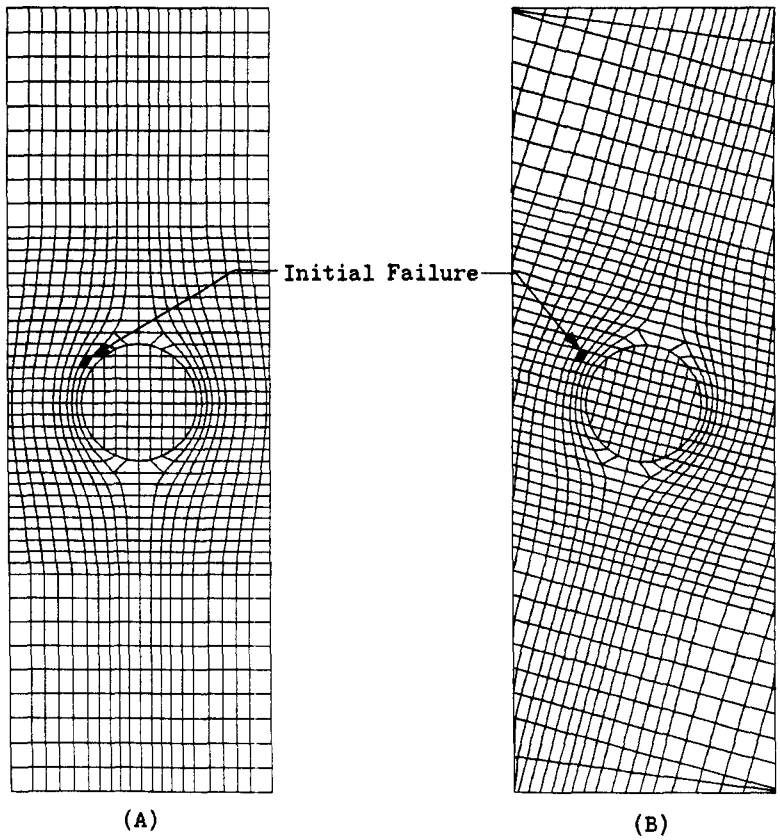


FIG. 2. Program STARWX predicted initial failure to occur due to shear stress at the location indicated.

clear wood specimen ultimate strengths. Boresi et al. (1978) indicate that the maximum stress theory is generally applicable to brittle materials.

To predict mixed mode fracture, program STARWX incorporates Wu's criteria (Wu 1967), which states that crack propagation occurs if:

$$(K_I/K_{IC}) + ({}_{II}/K_{IIC})^2 > 1 \quad (2)$$

However, as research on mixed mode fracture of wood progresses, other models of mixed mode fracture could be easily incorporated.

Figure 2A shows a finite element mesh generated by program STARWX to model a wood member containing a 1¾-inch diameter center-knot and straight global grain. The knot size, width, and length of the member represent average dimensions for the specimens tested by Anthony (1986) containing single knots and global cross grain. The model predicted initial failure to occur due to shear stress in the element (number 625) indicated on the figure at an applied load of 2,852 pounds. Figure 2B shows a finite element mesh for a wood member also containing a 1¾-inch diameter center-knot but having a global grain angle of 15 degrees. The program STARWX analysis predicted initial failure to occur due to shear stress in the element (number 596) indicated on the figure at an applied load of 2,286 pounds. For the member with global cross grain the predicted load at initial failure was 20 percent lower than that for the member with straight global grain. These results are consisitent with the test data (Wilson 1921; McGowan 1968), which show global cross grain to be a severe strength reducing defect. However, initial failure is not an indication of the ultimate load carrying capacity.

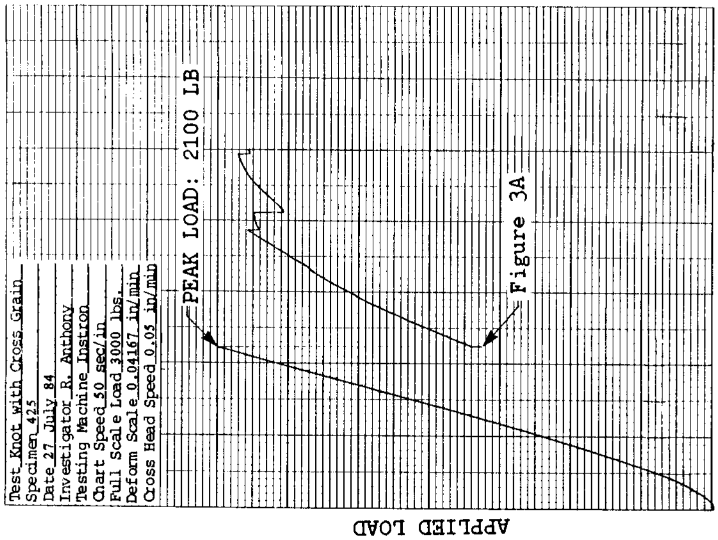
Program STARWX was employed to simulate the failure process of a test specimen. As will be demonstrated, the failure is simulated as a multistep process initiated by formation of a crack at the position of the initial failure. This crack is likely to propagate along a grain line, and other cracks may form as the failure progresses. The ultimate load-carrying capacity of the member is realized when the member can no longer sustain an increase in the applied load. Essential to modeling such a process is accounting for the presence and propagation of cracks.

A complete description of the procedure followed for the fracture mechanics analysis is found in Zandbergs (1985). Briefly, however, the values of K_I and K_{II} are computed at a particular load level from the finite element analysis. If Eq. (2) indicates that fracture continues, the crack is extended and new values of K_I and K_{II} are computed for the new crack size and the process is repeated. If Eq. (2) indicates that the crack stops propagating, the program STARWX analysis indicates via the maximum stress theory (Eq. 1) where a new crack will initiate. This process of crack initiation and propagation continues until the member cannot sustain an increase in the applied load.

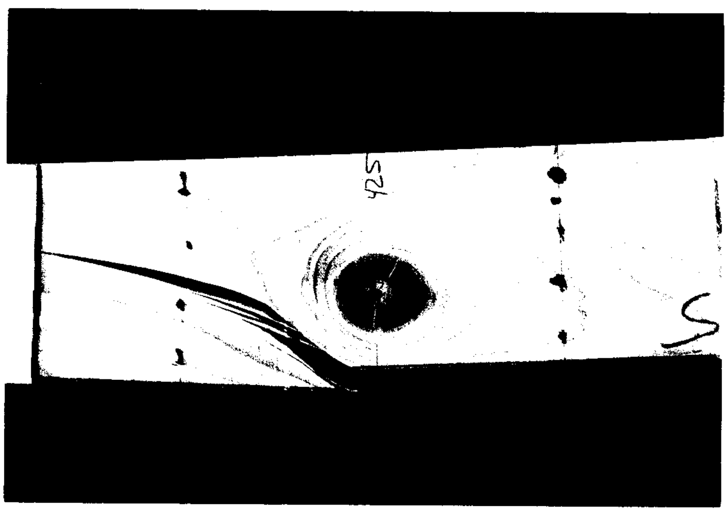
A recent experimental study by Anthony (1986) provided data for comparison to the predictions of the STARWX code. Figure 3A is a photograph of a specimen selected from Anthony's work. The photograph shows the specimen just after reaching its peak load carrying condition. The four ink spots located approximately two knot diameters from the knot center line on either side of the knot, indicate where the local grain angle was measured. These values, measured using a wide-field microscope fitted with a protractor eyepiece, were averaged to give the global grain angle for use with the model. Figure 3B is the experimental Load-Deformation curve. After the initial setting of the specimen grips, linear behavior was observed up to the point of failure at a load of 2,100 pounds. At this point a crack initiated on the edge of the member and propagated abruptly up to the top of the specimen (Fig. 3A). Additional cracking took place as indicated by the experimental load record but another peak load was not obtained.

Figures 4A through C are finite element meshes of the specimen selected from Anthony's (1986) work showing the simulation of the failure process. Displacements calculated by program STARWX were multiplied, giving the exaggerated deformed shape shown in the figure. The model predicted initial failure to occur perpendicular-to-grain at an applied load of 2,425 pounds in the element (number 594) indicated on the figure. A crack was introduced into the finite element mesh to relieve the stress concentration there, and it propagated along the grain line as directed by the fracture mechanics analysis.

For this specimen, the model shows excellent qualitative agreement with the test results. Comparison of Figs. 3 and 4 shows that the model predicted initial failure to occur in a location very near the location of failure in the actual specimen. Figure 4 gives the predicted load at each stage of the program STARWX analysis. The figure shows that the predicted peak load-carrying capacity of the member was realized just prior to initial failure (Fig. 4A) and that the crack propagates



(B)



(A)

FIG. 3. Failure of test specimen (after Anthony 1986).

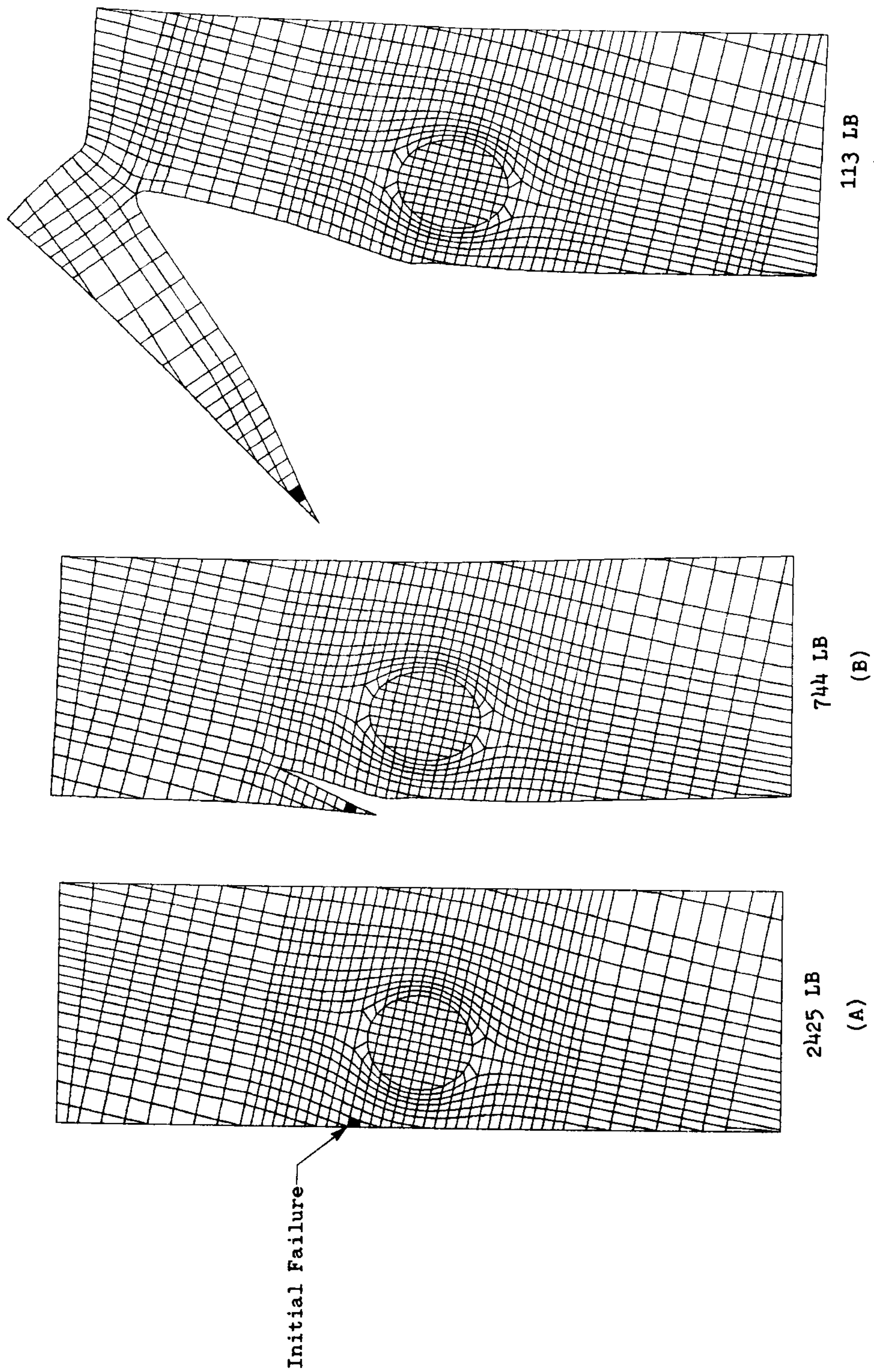


FIG. 4. Progressive failure of Anthony's (1986) specimen as predicted by Program STARWX.

abruptly matching the test results (Fig. 3B). In addition, the strength predicted by the model was only 15% higher than the actual test strength which constitutes reasonably good quantitative agreement.

In comparing Fig. 3 to 4, it is important to note that Fig. 4 presents the simulation of the rapid drop in load from the peak load condition. For the actual test, the load dropped from a peak of 2,100 pounds, due to the initial cracking shown in Fig. 3A, to about 1,000 pounds, after which the load began to increase. However, in the simulation, the load drops from a peak of 2,425 pounds down to about 100 pounds. The minimum loads in these two cases are quite different. In the actual test the specimen ends were reinforced by hardwood strips glued onto the specimen, but the finite element model used in the simulation does not account for the effect of these strips. The strips serve to stop the propagating crack in the actual test and make the minimum load much larger than that predicted by the finite element simulation.

CONCLUSIONS

Program STARWX, as presented in this paper, provides a detailed simulation method of predicting the tension behavior of structural wood members with defects. The algorithm has been applied and the results have been reported here.

The model was employed in a preliminary effort to predict the effect of global cross grain on the strength behavior of a wood member containing a center-knot. The results of the analyses agree with experimental data, indicating that a more severe stress condition exists for the member with global cross grain than for the member with straight global rain.

Program STARWX was employed to simulate the failure of an actual test specimen with a knot and global grain angle of 11 degrees. Excellent qualitative agreement was found between the model and test results. The predicted ultimate strength was 15% higher than the test strength, but the simulated load behavior after the ultimate load was reached did not agree well with the experimental result.

Program STARWX represents a significant advancement in the development of methods for predicting the tension behavior of wood members with defects. With further research the algorithm may be useful in developing improved methods of strength prediction.

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