A Local Isotropic/Global Orthotropic Finite Element Technique for Modeling the Crush of Wood in Impact Limiters

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INTRODUCTION

Wood is often used as the energy absorbing material in impact limiters, because it begins to crush at low strains, then maintains a near constant crush stress up to nearly 60 percent volume reduction, and then "locks up." Hill (Hill and Joseph, 1974) has performed tests that show that wood is an excellent absorber. However, wood's orthotropic behavior for large crush is difficult to model. In the past, analysts have used isotropic foam-like material models for modeling wood. A new finite element technique is presented in this paper that gives a better model of wood crush than the model currently in use. The orthotropic technique is based on locally isotropic, but globally orthotropic (LIGO) (Attaway, 1988) assumptions in which alternating layers of hard and soft crushable material are used. Each layer is isotropic; however, by alternating hard and soft thin layers, the resulting global behavior is orthotropic.

In the remainder of this paper, the new technique for modeling orthotropic wood crush will be presented. The model is used to predict the crush behavior for different grain orientations of balsa wood. As an example problem, an impact limiter containing balsa wood as the crushable material is analyzed using both an isotropic model and the LIGO model.

ORTHOTROPIC NATURE OF WOOD

Wood's strength varies with grain orientation. To describe the grain orientations, we define a cylindrical coordinate system to coincide with the natural directions of the tree trunk from which the wood was cut. The strength and Young's modulus in the longitudinal direction are much greater than in the tangential and radial directions.

For an impact limiter, the elastic behavior of wood is not as important as its crush behavior because the energy absorbed by elastic deformation is small compared to the total energy absorbed. The emphasis of the analysis that follows will be on wood's inelastic orthotropic crush behavior. Phenomena such as strain rate effects or environmental effects such as temperature and moisture were not considered. Effects from imperfections such as knots, splits, and non-uniform growth also were not considered. Wood's behavior was considered on the "tree ring scale" instead of the cellular scale (Gibson and Ashby, 1988).

FINITE ELEMENT MODEL FOR LARGE CRUSH OF ORTHOTROPIC MATERIAL

The orthotropic nature of wood was introduced by modeling alternating layers of hard and soft crushable materials corresponding to the constituents in the "grain" of the wood. Within each material layer, an isotropic material model was used; however, the inherent directionality of thin layers introduces the desired global anisotropic behavior. This local isotropic, global orthotropic (LIGO) finite element technique was implemented using the transient dynamic finite element code PRONTO2D (Taylor and Flanagan, 1987)

Large deformation wood crush requires a volumetric yield criterion as well as a volumetric flow rule. The "soil and crushable foam" constitutive model from PRONTO2D was used to model each layer. In this model, the volumetric response is not affected by deviatoric response, but deviatoric response can be a function of pressure. The volumetric response is defined using a piecewise linear curve for the volumetric strain versus pressure relation. Thus, any experimental relation for crush may be expressed in terms of the volume strain. The deviatoric part of the response is computed using a conventional plasticity theory with radial return. Only pressure independent perfectly plastic deviatoric behavior is modeled.

Young's modulus for the hard and soft material can be computed once wood's modulus in the hard (parallel to grain) and soft (perpendicular to grain) direction have been measured experimentally. For large crush of wood, Poisson's ratio is small; therefore, a Poisson's ratio of zero was assumed for both the weak and the strong layers.

In the LIGO model, four parameters were used to control the initial crush behavior: i) deviatoric yield stress of the soft layer, ii) volumetric yield pressure of the soft layer, iii) deviatoric yield stress of the hard layer, and iv) volumetric yield pressure of the hard layer.

The balsa wood of interest had a uniaxial crush strength of 195 psi perpendicular to the grain and 820 psi parallel to the grain. In order to match the material properties for balsa wood in the weak direction, the volumetric yield pressure was assumed to be 65 psi and the deviatoric yield stress for the soft layer was assumed to be 190 psi, which was slightly lower than the equivalent yield pressure. The lower deviatoric yield stress was selected to ensure that deviatoric yielding occurred before volumetric yielding. For the average crush strength to be 820 psi, the hard material must have a uniaxial crush of 1450 psi, which corresponds to a crush pressure of 483 psi. The yield stress for the hard layer was assumed to be 1400 psi. For both the hard and soft materials, a plateau of crush stress was defined for volume strains less than 60%. Beyond 60% volume strain, the crush stress was allowed to increase very rapidly.

Crush of LIGO Material at Different Grain Angles

As a test of the LIGO model, the crush of a 5x5 inch square block of balsa wood was simulated by assuming that the sample was confined by three fixed plates, while a fourth confining plate was given a prescribed velocity. Thus, a condition of uniaxial strain confined compression was created. Zero friction was assumed between the plates and the wood.

Six different grain angles were considered: 90°, 64.4°, 45°, 25.6°, 11.3°, and 0°. The unusual orientations of 64.4°, 25.6°, and 11.3° were chosen for meshing convenience. The 0° grain orientation corresponds to the strong direction of wood, which has grain parallel to the direction of crush. The 90° orientation corresponds to the weak direction, which has the grain perpendicular to the crush direction. The 90°, 45°, 11.3°, and 0° orientations will be discussed in detail below.

For loading perpendicular to the grain (90°), alternating layers of soft and hard material were crushed as shown in Figure 1. The corresponding load-deflection curve for the perpendicular loading is also shown in Figure 1. The soft layers crushed uniformly, with an initial crush load at 190 psi. After the soft layers crush to lock-up, the hard layers began to crush. This crush mode caused the load-deflection curve to rise steeply after the lock-up of the soft material, then level out again after the hard layers began to crush. This step observed in perpendicular crush of the LIGO specimen is not seen in wood. Instead, a gradual transition is observed. A more gradual transition may be obtained by adjusting the thickness of the layers or by adjusting the pressure-volume strain relation.

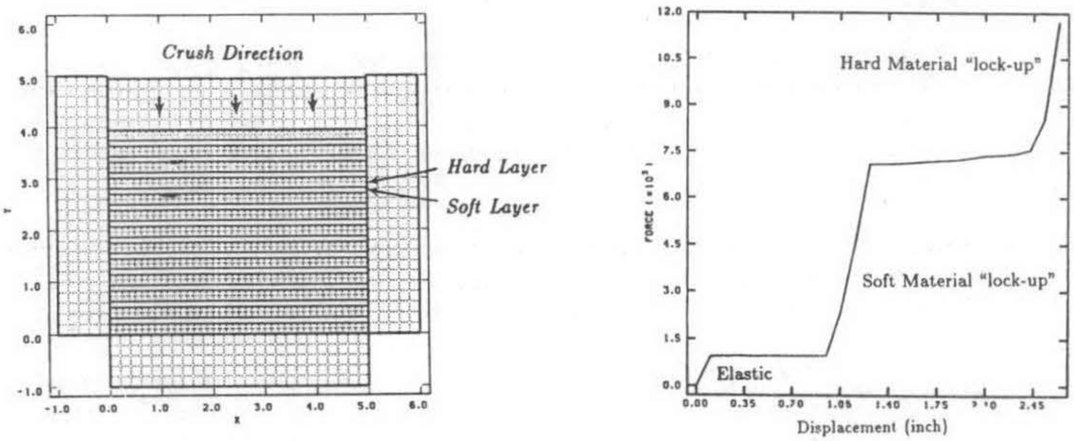

Figure 1: *Deformed shape for loading 90° to the grain and associated load-deflection curve.*

The deformed shape of a specimen that was crushed with loading at a 45° grain angle is shown in Figure 2. The corresponding load-deflection curve is also shown in Figure 2. The crush magnitude was greatest along the diagonal through the center of the sample parallel to the layer orientation. A waviness of the deformation is clearly visible. In the corners where short layers exist, the crush magnitude was smallest.

The deformed shape and load-deflection curve for a sample loaded at 11.3° to the grain is shown in Figure 3. The deformation was very anisotropic and non-uniform (Figure 3). The outer portion of the specimen crushed more than the inner portion. Selective crushing of the soft layers caused bending to occur in the hard layers.

The deformed shape for the crush parallel to grain and the corresponding

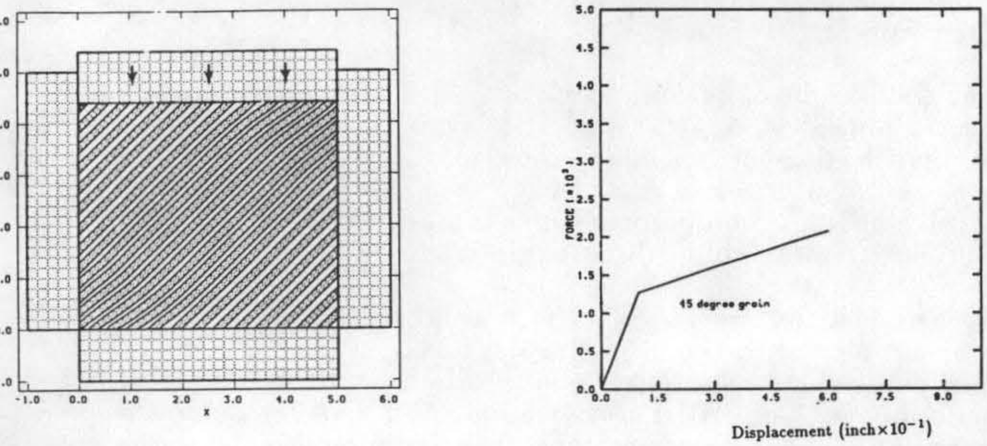

Figure 2: *Deformed shape for loading 45° to the grain and associated load-deflection curve.*

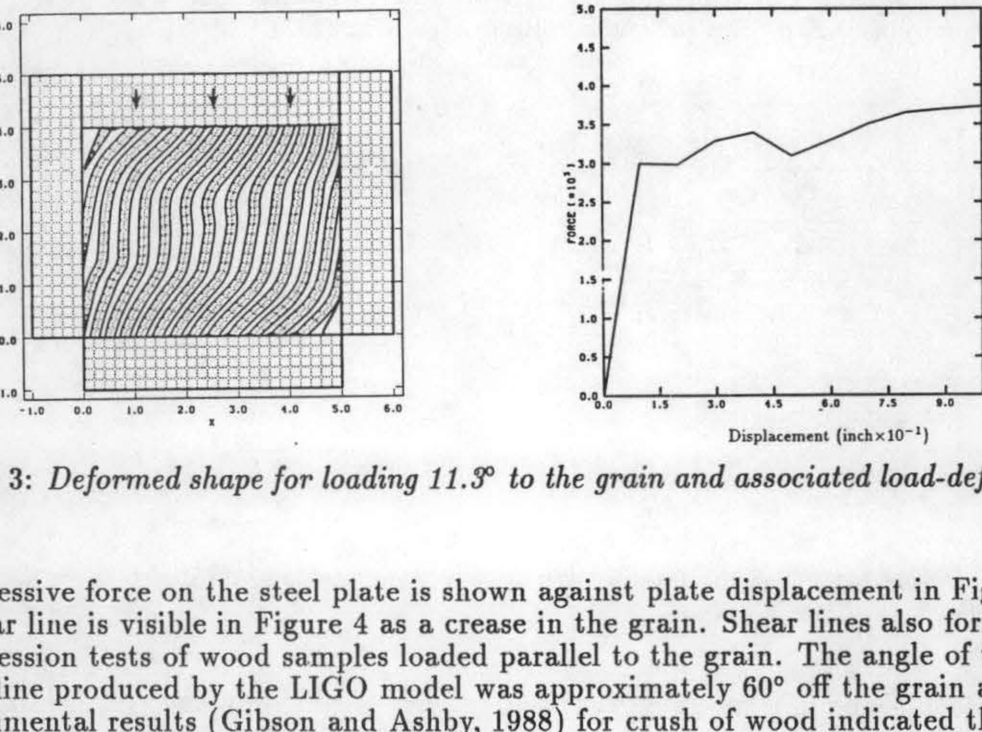

Figure 3: *Deformed shape for loading 11.3° to the grain and associated load-deflection curve.*

compressive force on the steel plate is shown against plate displacement in Figure 4. A shear line is visible in Figure 4 as a crease in the grain. Shear lines also form in compression tests of wood samples loaded parallel to the grain. The angle of the shear line produced by the LIGO model was approximately 60° off the grain angle. Experimental results (Gibson and Ashby, 1988) for crush of wood indicated that shear line angles range between 45° and 65°. Thus, the model results seem to agree with the experimental observations fairly well.

Crush Strength Versus Grain Angle

The present results compare very well with accepted theoretical and empirical models for initial wood crush stress. Empirical formulas for predicting the onset of crushing were developed in the 1920's (Hankinson, 1921). Several theoretical yield criteria for anisotropic materials have also been formulated (Tsai and Hahn, 1980). While a theory exists for the yield or crush stress versus grain angle, the behavior of wood crushed beyond the yield stress is not well understood. Tests on wood crush

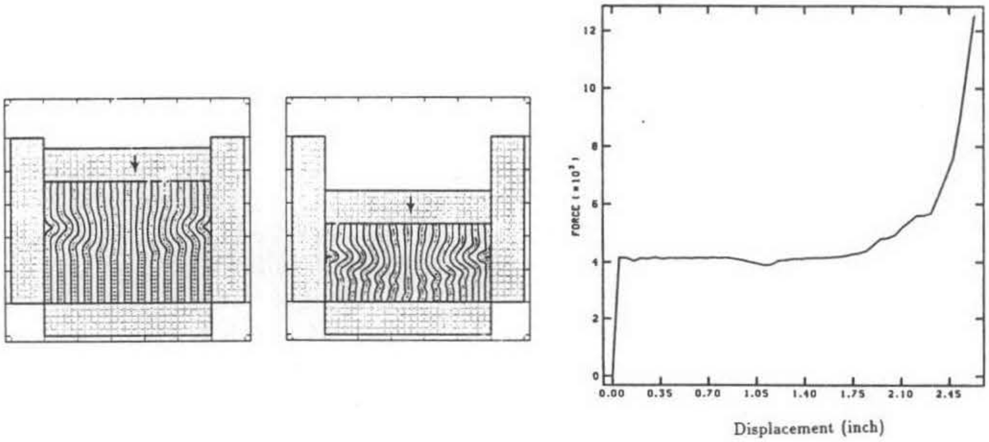

Figure 4: *Deformed shape for loading parallel to the grain and associated load deflection curve.*

parallel to grain and crush perpendicular to grain have been performed, (Joseph and Hill, 1976); however, few data exist for wood crushed at other grain orientations. Shown in Figure 5 is a comparison of the initial crush stress versus grain angle from the LIGO model, from empirical formula for wood, and from a theoretical yield criteria for orthotropic materials. The finite element results matched both the empirical formula and the theoretical criteria very well. Experimental error from compression tests on wood samples will be greater than the difference between the LIGO model and Hankinson's formula.

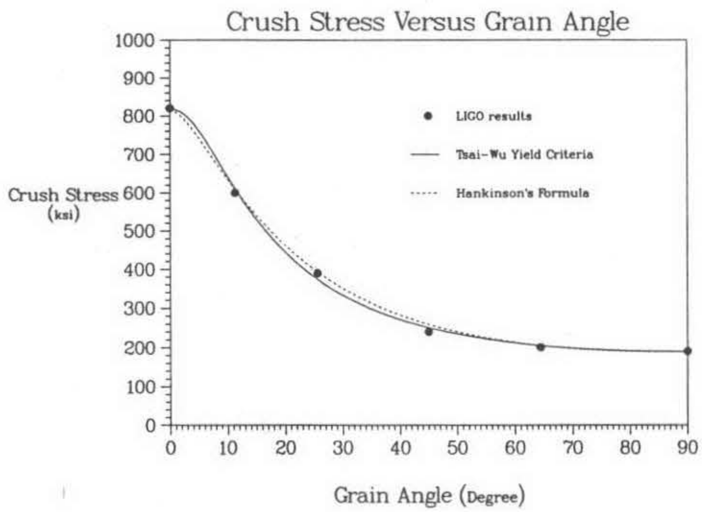

Figure 5: *Comparison of Hankinson's formula and Tsai-Wu yield criteria to the LIGO model.*

CRUSHING OF AN IMPACT LIMITER CONTAINING WOOD AND METAL GUSSETS

A section of an impact limiter that contained wood confined by metal gussets was analyzed to determine how the metal gussets interact with the surrounding wood. The limiter was confined on the top by a non-moving platen and on the bottom by an equivalent mass representing the weight of a transportation cask. An initial velocity of 527 inches per second was given to the metal gusset, wood, and equivalent mass.

First, an isotropic material model was used to model the wood. The "soil and crushable foam" constitutive relation from PRONTO2D was used to model the isotropic material. The isotropic analysis indicated that wood interacted with the gusset by providing lateral support for the gusset as it buckled. This interaction is illustrated by the deformed shape and the load-time curve shown in Figure 6. The high initial force ($0.5 \leq t \leq 2.5$ msec) in the load-time curve was required to initiate the gusset buckle. Once the gusset buckles, the force drops to a lower value ($3.0 \leq t \leq 5.0$ msec). A criticism of the isotropic wood model was that it may provide too much lateral support to the metal gusset.

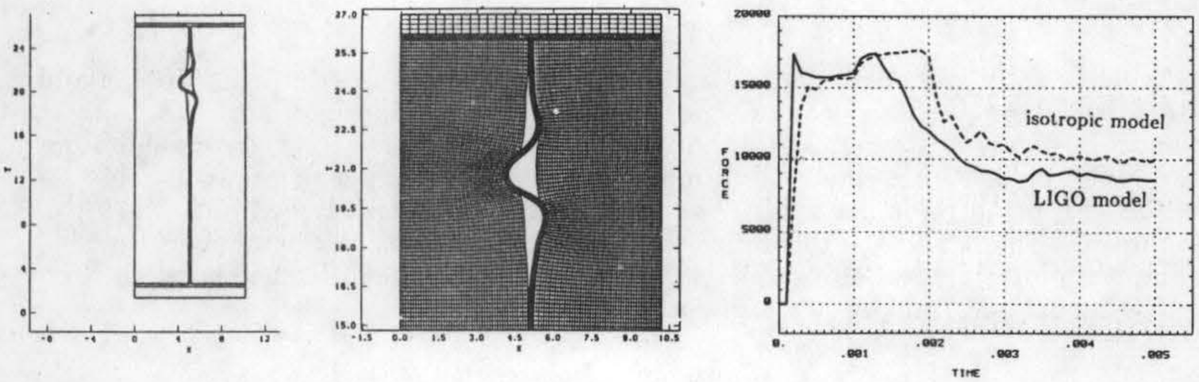

Figure 6: *Deformed shape from isotropic foam / gusset model and associated load versus time curve.*

An orthotropic model of the same system was constructed with the LIGO model using the same boundary conditions and impact velocity as in the isotropic model. Shown in Figure 7 is the deformation that resulted when the LIGO model was used. The associated load-deflection curve is shown in Figure 6. The isotropic and orthotropic load-time curves were very similar until the gusset buckled. After the gusset buckled, the LIGO model predicted less crush force than the isotropic model.

In the LIGO model, a kink in the wood grain formed along the high point in the gusset buckle, indicating that the wood could pull away from the gusset. In the isotropic model, no kink formed, and the foam remained in contact with the gusset as it buckled. Wood grain kinks have been observed in dynamic tests of wood/gusset structures. The isotropic model predicted the highest pressure along the high point of the gusset buckle. The LIGO model predicted low pressure along the high point of the buckle.

The kink generated by the LIGO model was caused by hard material layers buckling. After these layers buckled, the material in the region of the buckle softened due to rotation of the wood grain relative to the primary direction of crush.

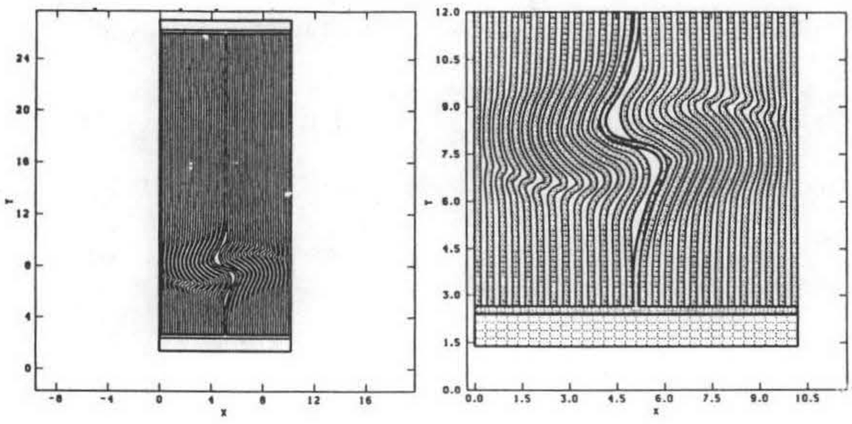

Figure 7: *Deformed shape from the LIGO / gusset model.*

Associated with this geometric softening behavior was a localization of deformation in the softened region.

The magnitude and the duration of the force required to buckle the gusset were approximately the same for both the isotropic and the orthotropic models. Once the gusset buckled, however, the orthotropic model crushed with only 80 percent of the force required to crush the isotropic model due to the wood grain rotation.

CONCLUSIONS

The LIGO (locally isotropic / globally orthotropic) model is capable of capturing many of the phenomena associated with the large crush of orthotropic materials. Crush stresses obtained with the LIGO model for loading at different angles to the grain compared well with Hankinson's empirical formula and with the Tsai-Wu failure criterion for orthotropic materials. Shear lines, which are observed experimentally in tests of wood with loading parallel to the grain, were predicted by the LIGO model.

An impact limiter, containing a wood material and an internal supporting gusset, was modeled with an isotropic model and with the LIGO model for the wood. The isotropic and LIGO models produced different behaviors for large crush. When the LIGO model was used, the metal gusset buckled and rotated the wood grain locally in the vicinity of the gusset buckle. This rotation caused a reduction in wood strength.

REFERENCES

Attaway, S.W., "A Local Isotropic/Global Orthotropic Finite Element Technique for Modeling the Crush of Wood," SAND88-1449, Sandia National Laboratories, Albuquerque, NM (1988)

Gibson, L. J. and Ashby, M.F., *Cellular Solids, Structure and Properties*, Pergamon Press, (1988).

Hill, T.K., Joseph, W.W., "Energy-Absorbing Characteristics of Materials," SAND74-0159, Sandia National Laboratories, Albuquerque, NM, (1974).

Hankinson, R.L., "Investigation of Crushing Strength of Spruce at Various Angles of Grain," U.S. Air Service, Air Service Inform. Cir. III (259), 15 pp. (1921).

Jones, R.M., *Mechanics of Composite Materials*, McGraw-Hill (1975).

Johnson, W., "Historical and Present-day References Concerning Impact on Wood," *Int. J. Impact Eng.*, Vol. 4, No. 3, pp 161-171 (1986).

Joseph, W.W. and Hill, T.K., "Energy-Absorbing Characteristics of California Redwood Subjected to High Strain," SAND76-0087, Sandia National Laboratories, Albuquerque, NM (1976).

Tsai, S.W., Hahn, H.T., *Introduction to Composite Materials*, Technomic, Inc, Westport, CT (1980).

Taylor, L.M., and Flanagan, D.P., "PRONTO2D: A Two-Dimensional Transient Solid Dynamics Program," SAND86-0594, Sandia National Laboratories, Albuquerque, NM (1987).