THICKNESS EFFECT IN WOOD – STATISTICAL OR STRUCTURAL?

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ABSTRACT

Testing and modelling was carried out for Compact Tension (CT) specimens in an attempt to clarify the importance of size of specimen effects on opening fracture mode I properties of spruce. The experimental part of the investigation was carried out on wood in green and 12 percent Moisture Content (MC) conditions in two wood weakest directions RL and TL. Here R denotes radial, T tangential and L longitudinal directions relative to the tree stem. Standard CT specimen dimensions were modified to avoid possible ligament and width size effects on the measured properties. Subsequent to the experimental part, finite element computations were performed to estimate fracture toughness and energy release rates, while the total fracture energy was computed separately. Testing results revealed no clear evidence of size effects. If size effects exist they are masked by inherent variability in fracture properties. Therefore, the question of a statistical thickness effect needs to be considered as opposed to a structural size effect. The authors found that discrete finite element lattices were capable of accurately mimicking experimental load-deformation responses and damage patterns in CT specimens. Lattice fracture models take into account the statistical variation in element stiffness and strength properties using Monte Carlo simulation, and thereby describe the local heterogeneities inherent to wood. The analysis is performed in 3-D with the removal of failed elements as they reach randomly prescribed strength values. It is thereby possible to numerically follow progressive evolution of fracture as well as damage patterns. The lattice fracture model has proven superior to other non-linear fracture models due to its theoretical postulates having physical validity.

1 INTRODUCTION

Fracture mechanics is well established as a routine tool for analysing behaviour of brittle and quasi-ductile homogeneous materials. However, appropriateness of various fracture mechanics techniques for wood is not fully elucidated, reflecting that damage mechanisms are influenced by visco-elastic anisotropy and loading conditions. Under load, damage accumulates due to presence of existing micro-defects, and depends on an interplay of existing micro-defects, the wood structure, moisture history, rate of loading and current environment [1, 2]. Initiation of fracture can be defined in terms of model parameters (pseudo properties), but the instability that leads to complete fracture is largely dependent on loading parameters (load or displacement control, geometry of the specimen and loading points) rather then just material properties. In many cases, crack propagation is not 'self-similar', i.e. relative geometry of the load and specimen change with crack growth. The nominal tensile strength of structural wood components generally exhibits a size-effect. If failure occurs only after large stable crack growth, which is the objective of good design, the size effect should be due to the global release of stored strain energy caused by large fracture. The energy consumed is expected to be proportional to the structural size, whereas the energy released by the fracture is proportional to structure size squared. This is valid for components geometrically similar in two dimensions. Weibull-type statistical size effects [3] due to randomness of material strength is often accounted for in design of wood structures, but its effect should be insignificant for failures occurring after large stable crack growth. The thickness effect in cracked specimens loaded in opening fracture (mode I) was chosen for the study presented herein based on the assumption that, crack propagation parameters can be dependent on the specimen geometry which governs the width of the crack front.

2 LITERATURE REVIEW

It is commonly accepted that there exists an influence of specimen geometry on fracture toughness in the opening mode, K_{Ic}, and other modes. Specifically K_{Ic} is considered sensitive to the crack front width that usually corresponds to the thickness of test specimens used to characterise fracture toughness, or the volume resisting crack propagation. It has also been suggested that the extent of statistical variation in the 'fracture size-effect' might be insignificant compared with inherent variability in K_{Ic} within a wood species or between test methods [4]. Recognizing that fracture toughness decreases with increasing specimen size, Barrett [5] characterized the cumulative distribution for K_{Ic} for Douglas-fir lumber. He used the weakest link theory to explain and represent the size-effect, even though heterogeneities are well structured. In Single End Notched (SEN) specimens K_{Ic} decreased significantly between specimen thickness (t) = 12 to 50 mm, but little between t = 50 and 140 mm.

Bostrom [7] tested CT specimens to estimate the influence of thickness (t = 10, 20, 30, 40 mm) and ligament length on fracture properties of dry Scots pine. He reported that the scatter for K_{Ic} was greater than for total fracture energy, G_f. Total fracture energy per unit facture plane increased with ligament length, which was an indication of the presence of a size-effect. Boatright and Garrett [8] performed experimental analysis of the thickness effect in South-African pine on SEN specimens loaded in tension and four-point bending, in TL, RL and LT directions. The range of thickness was from 1 to 45 mm. Cracks were observed to tunnel into the specimen under both static and dynamic loading, and strains were lower at the edges of the specimens than in the interior. Stanzl-Tschegg et al [9] investigated the effects of specimen thickness (*t*) and ligament length (*w*) on G_f via wedge splitting of CT specimens. Fracture in the TL direction was assumed perfectly brittle and based on total energy results it was concluded that no size-effect exists beyond t = 30 mm and w = 70 mm. The increase in G_f with ligament length is greater than the increase in K_{Ic} (60 percent grater). The increase in G_f with thickness is also greater than the increase in K_{Ic}. It is speculated by the present authors that the dimensions t = 30 mm and w = 70 mm represented the maximum dimensions over which incremental toughening could be mobilized.

3 EXPERIMENTAL STUDY

Eastern Canadian Spruce logs, between 350 and 450 mm diameter, were cut from the University of New Brunswick wood lot in Fredericton. Lumber 50 x 250 mm and 120 x 120 mm in cross-section was cut from saturated (green) sapwood with rather uniform growth ring structure. This facilitated preparation of small specimens for characterising RL and TL fracturing directions in green or dry conditions. Specimen thicknesses used were 20, 40, 60 and 120 mm. There were six and fifteen test replications for green and dried specimens respectively. For green wood, the average density was ρ = 346 kg/m^3 (COV = 18 percent) and average moisture content 57 percent (COV = 41 percent). For 'dry' wood the average ρ was 437 kg/m^3 (COV = 9,6 percent) and average moisture content 12 percent (minimal variability). Density measurements were based on oven dry weight and volume at the test moisture content.

The ASTM guideline for metal CT specimens was the basis for specimen proportioning, but a slightly modified geometry was employed because of an expected influence of ligament length. Crack Mouth Opening Displacement (CMOD) and Crack Opening Displacements (CODs) were measured, Fig. 1. Load was measured using an Instron 10 kN load-cell.

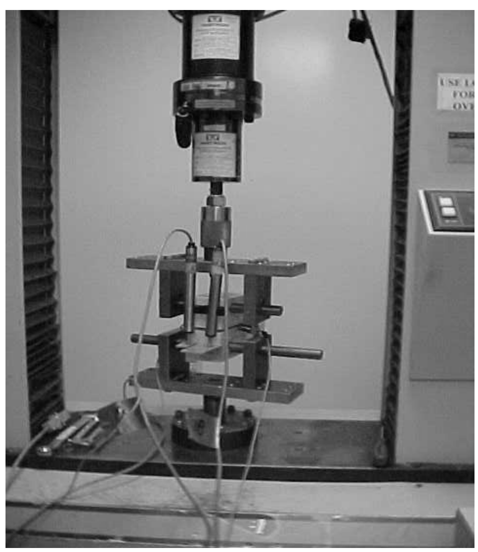
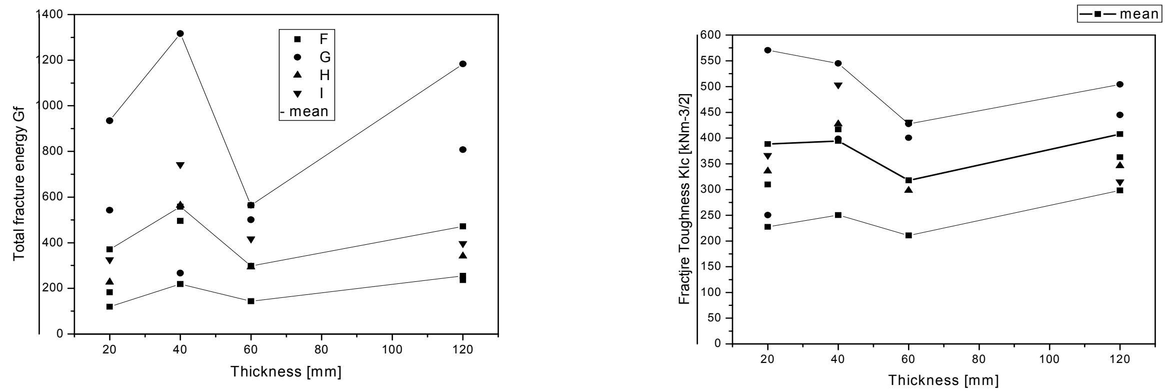


Fig. 1 Test set-up

For green wood the average G_f for the RL direction increased with specimen thickness up to t = 60 mm, but decreased slightly for t = 120 mm. There was a transition to instability at t = 120 mm, so any decrease should be accepted with caution. By contrast, mean values of G_f for the TL direction decreased up to t = 60 mm, and then increased for t = 120 mm. Average K_{Ic} for green wood in the RL and TL directions also exhibited thickness dependence, i.e. decreased up to t = 60 mm and increased for t = 120 mm.

For dry wood (12 percent MC), in the RL direction average K_{Ic} has its highest value at t = 20mm, while in the TL direction the maximum mean value is at t = 40 mm. In the RL direction the average energy release rate has its highest value at t = 20 mm. In the TL direction both average fracture toughness and total fracture energy had a peak at t = 40 mm. Figs. 2a and 2b show typical results. There is no evidence of a clear effect of specimen dimensions on either toughness or total energy release rate that can be distinguishable from inherent variability in those properties.



(a) *(b)*

Fig. 2 Results for dry wood – TL direction –individual, mean, min and max values shown
a) Total fracture energy, G_f, b) Fracture toughness, K_{Ic}

It is clear from the results that there exists no significant structural size effect, and the trends are not unique for different loading directions. This implies the existence of statistical thickness effect. It can be speculated that there is no distinct transition from plane stress to plain stress conditions, as is typical for ductile materials like steel. The inherent wood ultrastructure definitely influences the results, and more so for the RL direction than the TL direction. This is attributed to unavoidable curvature of the growth rings. Ultrastructure was most uniform for the TL direction. It is anticipated that only detailed finite element analysis that uses cylindrical coordinates and includes curvature of the growth rings would reveal the differences in the internal stresses that account for the different results in two test directions. It is clear that different thickness specimens sampled the ultrastructure of the wood differently, on the level of growth rings and transitions from latewood to earlywood. The supposition is that statistical effects have physically based explanations.

4 LATTICE FRACTURE FINITE ELEMENT MODEL

Lattice network finite element models are tools that integrate morphology-based modelling strategies with experimental techniques to represent microstructural properties of wood or other structural materials [10]. The material is discretised into a 3-D network of longitudinal beam elements and transverse and diagonal spring elements, in a way representing the wood cells and microstructural connections between them [11]. The micro-level heterogeneity is implemented via Monte-Carlo simulation that reflects statistical distributions of strength and stiffness of network components. The procedure reproduces inherent disorder of the heterogeneous wood morphology.

Compact Tension tests were simulated based on lattice principles and prescribing displacement conditions at the position of external loading. Equilibrium was determined by solving the global stiffness equations for the system for each displacement increment. The force in each network element was then checked against its assigned strength. If the force in the element exceeded the strength the element was considered broken and removed from the lattice. Removing broken elements introduced the damage and cracking in a physically realistic sequence and manner. Fig. 3 shows that lattice network modelling can accurately predict both stiffness and maximum load of CT specimens.

An important finding from the cracking pattern of the CT specimen is that the damage does not occur only in the notched plane (although it is predominant there), but also can be anywhere in the specimen if the strength of the microstructural features is exceeded. Damage patterns do not resemble the formation of a fracture process zone ahead of the main crack. It can be concluded that the fracture energy is dissipated in weak planes throughout the specimen. The question of how to estimate actual fracture plane area to be used in fracture calculations arises naturally. It should be noted that all numerical Load-Crack Mouth Opening Displacement (P-CMOD) curves were obtained with equal statistical material properties of the network elements (means and standard deviations) and a unit cell size that corresponds to a bundle of longitudinal cells. The final percentage of the failed elements was of similar order of magnitude for specimens of all thickness. Load-CMOD curves of CT specimens of different thickness were modelled with good accuracy.

Based on the obtained acceptable agreement between experimental responses and numerical lattice simulations of P-CMOD curves of CT specimens of different thickness, it is concluded that a lattice 3-D network modelling strategy is a powerful tool for representing damage progression and fracture softening in wood. Furthermore, physical reconstruction of the cracking patterns throughout the failure process provides better understanding of the fracture phenomena in wood and the thickness effect, allowing for the improvements in the numerical procedures. In the case of the thickness effect, the model exhibits the capability of explicitly capturing both statistical and structural size effects. However, application of lattice network models to wood is in its infancy and more work undoubtedly needs to be done before the technique can be generally applied. Based on the results reported here it is speculated that neither the commonly used fictitious crack nor weakest-link modelling concepts are correct for wood.

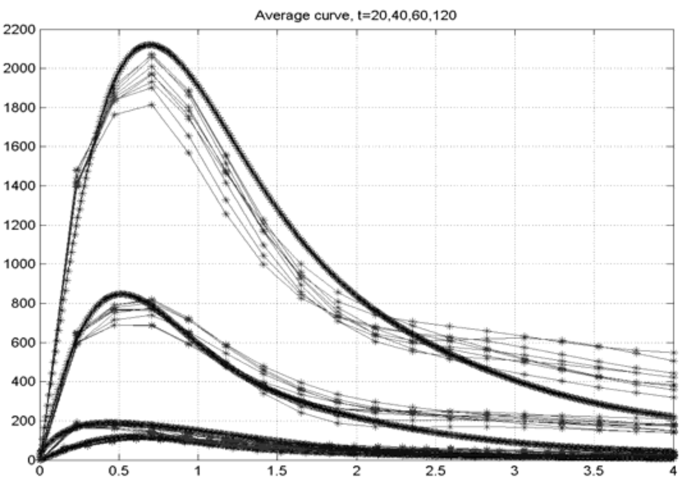


Fig. 3 Load-CMOD experimental and numerical curves

(thick lines = experimental curve)

(thin lines = lattice simulations)

4 CONCLUSIONS

Despite reports in the literature, the authors found no evidence of any clear effect of specimen dimensions on toughness or total energy release rate for Compact Tension (CT) specimens of green or dry spruce. Three-dimensional lattice network modelling strategies were found to be a powerful tool for mimicking experimental load-deformation responses of CT specimens.

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