

Fracture energy along the grain of teakwood under mode I loading after selected drying schedules

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ABSTRACT

Fracture energy characterization and measurements along the grain particularly in the crack propagation systems RL (radial/longitudinal) and TL (tangential/longitudinal) under mode I loading of plantation teakwood (*Tectona grandis* L.) from Costa Rica were investigated in this study. Furthermore two different drying schedules, a constant and an alternating climate and their effects on the mechanical behaviour of solid teakwood have been studied. The load-displacement curves of double cantilever beam (DCB) were obtained from the fracture energy tests in order to compare the corresponding values of each drying schedule. The results of the present research work show that a severe seasoning technique has a statistically significant influence on the mechanical properties of teakwood, especially the fracture energy (G_f) and the maximum breaking load (F_{max}) in both crack propagations.

INTRODUCTION

Machining and treatment of solid wood affects mechanical properties due to its complex natural material performance. The anisotropic, inhomogeneous and hygroscopic behaviours of solid wood modify the characteristics recorded for several mechanical tests. According to Griffith (1920) the linear elastic fracture mechanics (LEFM) enables to determine the material parameter of fracture energy which is

defined as the energy required to separate a substance in order to generate two new surfaces. An application of this method applied on kiln dried solid wood would reveal information on the structural deterioration during the stress relief due to seasoning stresses in wood. Fracture energy characterization is a simple and fast evaluation method of machined and treated solid wood. In order to study the influence of the convection drying process on area-related variation of fracture energy, information about the drying and crack behaviour of solid wood is needed.

The kiln drying process represents one of the primary wood processing steps, after felling, logging, transporting, manipulating, debarking and sawmilling of wood. During the drying process, the occurrence of surface and internal cracks at the macroscopic as well as at the microscopic levels leads to a loss in mechanical properties. Seasoning checks appear if the drying stresses exceed the transverse tensile stresses of the wooden structure as a result of shrinkage anisotropy and plastic deformation (Vanek 1991). The drying rate at which the timber dries is controlled by the drying parameters: relative humidity of the air, the air temperature and the air flow across the timber surfaces. The permeability of the timber is the most important determinant of the drying rate – a permeable wood like pine (*Pinus spp.* L.) can sustain a more severe drying schedule than teakwood (*Tectona grandis* L.) which requires

a slower drying schedule. The moisture gradients developed within the timber during the drying process result in differential shrinkage levels. Drying defects such as collapse, case hardening, honeycombing and checking could be minimized by slow drying but that would be uneconomic. Checks develop at weak points within wood, e.g. knots, and along rays, which dry faster than the surrounding tissue but are restrained from shrinkage (Walker 1993). Conservative drying schedules (e.g. low temperature drying schedules and low drying rates) would affect the mechanical properties to a lesser extent than compared to severe drying schedules. Furthermore, mechanics in wood, in particular fracture mechanics, depends on several parameters such as: density, moisture content (MC) and temperature (Bodig and Jayne 1993), but may also be influenced by drying regimes as discussed by Oltean et al. (2007). Bhat (1998) stated that fast growing teakwood species do not necessarily have low density values, when compared to slow growing species. In the study of Kokuse et al. (2004), a strong correlation between density and tree-age and density and breast-height diameter was shown. According to Bhat et al. (2004) mechanical properties of plantation and primeval teak do not differ significantly, nor does timber from various distribution areas. Slow but good drying with low affection of checking or warping is by the ability to stay a major processing feature of teakwood (Wagenführ 1996).

In the early study by Schwankl (1938) Indian Rangoon teakwood in the RL (radial/longitudinal) crack propagation system in form of cleavage tests were performed. A medium density of 0.66 g/cm³ and MC of 10.5 % leads to a medium splitting resistance of 0.27 MPa. In the following decades research methods and specimen geometry have changed (Porter 1964, Schniewind et al. 1982, Stanzl-Tschegg et al. 1994). Applied characteristic measuring parameters in fracture mechanic currently are stress intensity factor (K_I) and fracture energy (G_f) based on strain release rate (G_I). The stress intensity approach is the development of an analytical technique for describing the stress and displacement field in the vicinity of the crack tip. The coefficient K_I is the stress intensity factor and it depends on the load applied, the shape of the body, and the

crack length. Close to the crack tip interactions with the stress field are characterized by the K_I . K_I can be evaluated analytically, numerically or experimentally. The concepts of fracture mechanics require an existing material or structure imperfection. According to the classical Griffith energy balance concept (Griffith 1920) the pre-existing cracks can propagate only if the elastic energy released at fracture is equal to or higher than the energy needed for formation of new surfaces. The change of potential energy during crack propagation quantifies the G_I and is related to stiffness and compliance of a body in case of linear elasticity. Consequently K_I as well as G_I could describe crack behaviour in linear elastic fracture mechanic (LEFM). While K_I parameter characterizes tension, elongation and displacement on the crack tip as a local parameter, G_I parameter quantifies the change in the potential energy during crack propagation as a global parameter (Vasic 2000, Eckmann 2007).

The knowledge of convection drying of solid plantation teakwood and fracture mechanics should enable the characterization of seasoning defects invisible to the naked eye (microcracks) with the instrument of fracture energy analysis. The aim of the present research work was to investigate the influence of two different drying schedules on G_f . The null hypothesis is that G_f is not influenced by the constant and alternating drying schedules applied.

MATERIAL AND METHODS

Plantation teakwood (*Tectona grandis* L.), from Costa Rica was used in this study. Two eighteen year old trees were harvested, measured, containerized in green conditions, shipped to Europe and finally carried to an Upper Austrian sawmill. Stems with an average diameter of 27 cm and a log length of 5.7 m were chosen and cut to a thickness of 30 mm. To conserve the average initial moisture content of 109 % the logged boards were bucked to 1.5 m, wrapped separately in flexible PVC films and stored at a temperature of -15 °C. The average density value for teakwood heartwood was 0.62 g/cm³, which was comparable to the density values of teakwood from different provenances (Bhat 1998).

The preparations before seasoning included a gentle defrosting of the selected boards, adhesive end coating in order to prevent drying from the cross sectional ends and a documentation of the initial state of the wooden surface. For the experiments a convectional laboratory kiln drier made by Mühlböck with a computer-aided process control according to the industrial specifications was used (Fig.1). Values of temperature, humidity and air velocity could be regulated over a wide range.



Figure 1: Laboratory kiln drier to be used for the experiments

Teakwood boards were dried from green to a final moisture content (MC) of 8.5 %, according to two different drying schedules presented in table 1. Constant as well as alternating drying schedules were used. In the alternating drying schedule, a dual drying system was used that changed from severe to a gentle drying schedule at an interval of six hours. After the drying process, all boards were checked and selected in order to get clear boards. The boards were conditioned in a climate chamber at 20 °C and 65 % relative humidity (RH) until constant conditions were reached.

Table 1: Drying schedules applied for investigated teakwood

Drying schedule	constant climate	alternating climate
Drying time [d,h,min]	13d 15h 19min	22d 8h 43min
Temperature [°C]	78.3 - 54.7	76.3 - 28.4
Equilibrium Moisture Content [%]	12.7 - 2.9	17.3 - 2.0
Drying gradient	2.9 - 2.3	6.4 - 1.7
Air velocity during drying [m/s]	> 2	> 2

After reaching the uniform MC across the whole board thickness, clear wood specimens with a rectangular shape with dimensions of 20 x 20 x 200 mm (in RT and TR directions) were prepared and planed for the fracture energy tests. Crack initiation was machined with a 3 mm band saw blade to a depth of 28.5 mm, and the final notch to the depth of 30 mm by razor blade. To fix double cantilever beam (DCB) specimens to the testing machine, holes with a diameter of 4.5 mm were drilled at 10 mm of the cross sectional area and at 3 mm next to crack initiation area. The specimens were marked and stored again until constant climate was reached. Two crack propagation systems to the orthotropic nature of wood were investigated. Tangential direction in the RL plane (radial/longitudinal) and radial direction in the TL plane (tangential/longitudinal) were tested for crack propagation (Fig. 2). The first letter indicates the direction perpendicular to the crack propagation and the second determines the direction along the crack propagation. Application of load was carried out in crack opening mode I, which is defined as pure tensile stress.

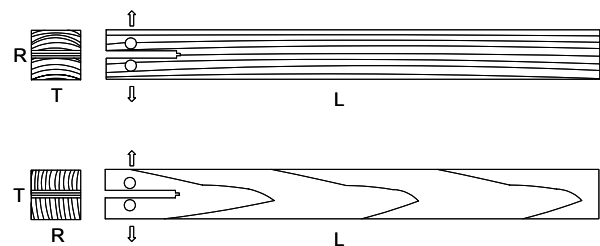


Figure 2: Schematic plot of dual cantilever beam (DCB) specimens (RL, TL) and points of force transmission.

The specimens were tested on a Universal Testing Machine (Zwick/Roell 100 kN) equipped with a 2.5 kN load cell. Test specification was configured with 1 mm/min ground test speed and an acceleration factor of 0.028 that speeded up to 100 mm/min at the end of testing. First, a pre-load of 20 N is applied as a reference position, before maximum testing force is reached. Procedure was interrupted when a maximum elongation of 50 mm was reached. For every load-cycle a force displacement curve was recorded. Fracture energy (G_f) was determined by integrating the area under the curves, where load is plotted vs. displacement. G_f values were calculated according to the formula

presented in figure 3. G_f quantifies the total energy that is required for crack propagation. Maximum breaking force (F_{max}) during fracture energy tests marks the highest point in the load-displacement diagram and represents a foundation to finite element calculation of the stress intensity factor (K_I). According to Reiterer et al. (2002) the initial slopes characterize the stiffness of the sample and are proportional to an effective modulus of elasticity (Fig. 3).

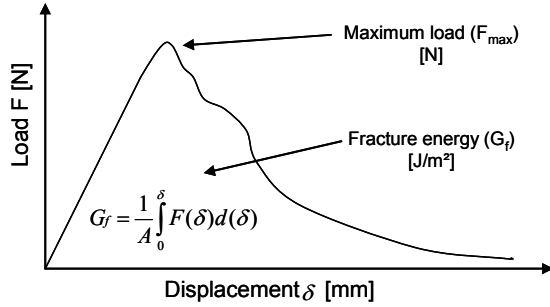


Figure 3: Schematic plot of a typical load-displacement curve. Determination of G_f from the area below the load-displacement diagram and F_{max} (according to Stanzl-Tschegg et al. 2009).

RESULTS AND DISCUSSION

Statistical analyses were performed (one-way ANOVA) at a 5 % significance level. For each drying schedule, mean values and standard deviation values are presented in table 2. In the case of the constant drying schedule, the fracture energy (G_f) distribution of values ranged in RL (radial/longitudinal) direction between 283.3 and 525.2 J/m², and in TL (tangential/longitudinal) direction between 303.2 and 554.6 J/m², respectively. In the case of the alternating drying schedule, G_f values ranged in RL direction from 237.4 to 524.8 J/m², and in TL direction from 231.3 to 323.3 J/m², respectively. The fracture energy data characterize the whole fracture process from the crack initiation and propagation to the complete separation of the specimen into two halves.

Results for the maximum breaking force (F_{max}) for the constant drying schedule ranged in the RL direction from 201.0 to 312.5 N, and in the TL direction from 225.7 to 309.3 N, respectively. Values in the alternating drying schedule varied in the RL direction under mode I loading from 213.1 to 364.9 N, and from 202.7 to 229.1 N in TL direction,

respectively. F_{max} indicates the maximum stress and characterizes the peak in the load displacement curve.

Table 2: Mean values (\bar{x}) and standard deviation (σ) values for G_f and F_{max} after different drying schedules.

	constant climate				alternating climate			
	RL		TL		RL		TL	
	\bar{x}	σ	\bar{x}	σ	\bar{x}	σ	\bar{x}	σ
G_f [J/m ²]	365.0	66.85	403.5	67.29	293.5	89.51	269.5	30.48
F_{max} [N]	274.5	30.75	265.5	24.25	265.7	48.06	217.5	10.70

The aim of this study was to investigate the influence of different drying schedules on G_f and F_{max} , determined under mode I loading perpendicular to the grain, in RL and TL directions applied for teakwood. In the case of the teakwood, the fracture mechanical parameters investigated G_f and F_{max} show a strong relation to the two different drying schedules investigated. This relationship is shown in the box plots from figures 4 and 5. G_f shows highly significant dependences when compared to the drying schedules applied. Clear decreasing tendencies with the drying schedules applied in the RL direction as well as in the TL direction are plotted in figure 4. The decrease in G_f in both crack propagation directions is highly significant when comparing the two drying schedules, while by anatomical comparison the RL and the TL directions are unaffected. In disagreement to our studies, the investigation on oak wood (*Quercus robur* L.), a wood species comparable to teak due to its anatomical features, Reiterer et al. (2002) found a significant difference between the RL and TL directions during the fracture energy tests. These differences were explained by the reinforcement of the radially oriented rays of hardwoods. Beside the differences in the experimental design, testing procedures and conditions, the fast-growing teakwood species and the enormous increment diameter per year as well as the predominant part of juvenile wood in the first two decades of growing, might provide an explanation. Rays, fibre length, distribution, form and diameter of the vessels and microfibrillar angle require a further analysis of anatomy of wood in interrelation with fracture mechanics.

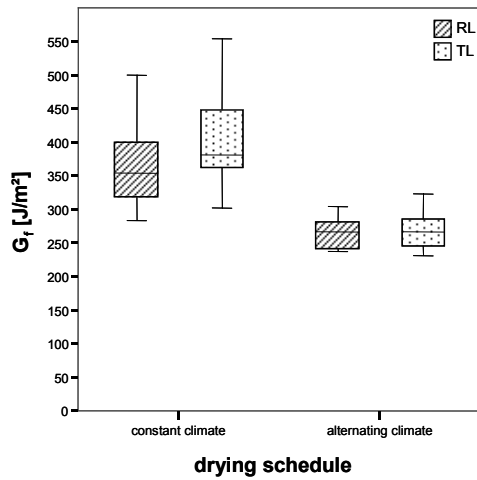


Figure 4: Influence of drying schedules on G_f in the RL and the TL orientation.

F_{max} behaviour shows a similar tendency as G_f (Fig.5). No statistical differences for both crack propagation systems were found when the two drying schedules were compared. While the fracture energy values show no significant differences in their anatomical crack propagation systems, F_{max} shows partially differences. According to the conducted one-way ANOVA there are significant differences within the group of alternating drying schedules between the RL and TL direction systems. With regard to the elastic properties structural features have to be distinguished in order to explain this anisotropy between the radial and tangential direction.

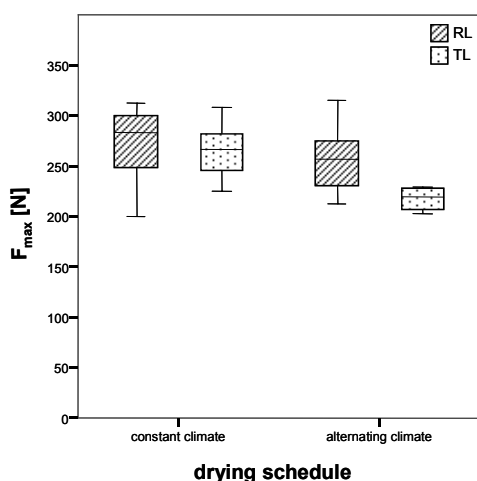


Figure 5: F_{max} versus drying schedule in the RL and the TL crack extension.

CONCLUSION

In conclusion, one can say that the null hypothesis of this research paper, that the fracture energy (G_f) is not influenced by different drying schedules applied, has to be declined. In both cases of crack propagation systems, RL (radial/longitudinal) and TL (tangential/longitudinal), a statistically significant decrease (one-way ANOVA at 5 % significance level) in G_f of solid teakwood (*Tectona grandis* L.) under mode I loading was observed. Comparing constant climate to alternating climate, G_f showed a decrease in the RL in the range of 19.6 % and in the TL in the range of 33.2 %. Therefore, G_f represents a useful mechanical parameter in order to characterize the kiln drying process. A similar decrease in G_f behaviour was observed for the maximum breaking load (F_{max}) behaviour. But from the two directional systems investigated, only the TL system shows a highly significant decrease in F_{max} in the range of 18.1 %. According to the two anatomical fibre orientations, the RL and the TL, no significant differences were found for both mechanical characteristics investigated, except for F_{max} for the alternating climate drying in the range of 18.1 %. The two drying schedules used in this study are also applied in practice and did not reveal any visible quality differences. However, the energy based concept studied in the present paper shows reliable results in order to appropriately characterize teakwood species dried with different drying schedules. Further research of the influence of the drying schedules applied with a variation in the drying parameters, especially temperature and humidity, particularly considering the characteristics of the wood anatomy and orientations will be performed.

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