Turkish Journal of Forestry | Türkiye Ormancılık Dergisi
2022, 23 (2): 135-140 | Research article (Araştırma makalesi)

Influence of density on Mode I fracture behavior of southern yellow pine (*Pinus taeda* L.) wood

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Abstract: This study aimed to investigate the influence of density on the fracture behavior of southern yellow pine (*Pinus taeda* L.) wood in radial-longitudinal crack propagation direction under mode I loading. The density of the crack-tip location for each fracture test block was determined by using an X-ray density profile analyzer. Three fracture parameters were obtained from the load-deformation curve of each fracture test block, namely fracture toughness, initial slope, and specific fracture energy. In general, the results showed that the fracture parameters were strongly influenced by the density. Crack-tip locations with higher density were found to be more resistant to crack initiation. The initial slope of the load-deformation curve increased as the crack density in the wood increased. As a result of the regression analysis, it was observed that there were positive and strong correlations between density and each fracture parameter.
Keywords: Fracture, Fracture toughness, Southern yellow pine, Specific fracture energy, Initial slope

Yoğunluğun güney sarıçam (*Pinus taeda* L.) ağacının Mod I kırılma davranışı üzerine etkisi

Özet: Bu çalışma, güney sarıçam (*Pinus taeda* L.) odununun mod I yüklemesi altında radyal-boyuna çatlak ilerleme yönünde kırılma davranışına yoğunluğun etkisini araştırmayı amaçlamıştır. Her bir kırılma testi bloğu için çatlak ucu konumunun yoğunluğu, X-ışını yoğunluk profili analizörü kullanılarak belirlenmiştir. Her bir kırılma test bloğunun yük-deformasyon eğrisinden başlangıç eğimi, kırılma tokluğu ve özgül kırılma enerjisi olmak üzere üç kırılma parametresi elde edilmiştir. Genel olarak, sonuçlar kırılma parametrelerinin yoğunluktan güçlü bir şekilde etkilendiğini göstermiştir. Yüksek yoğunluğa sahip çatlak ucu konumları, çatlak başlangıcına karşı daha dirençli görülmüştür. Yük-deformasyon eğrisinin ilk eğimi, ahşaptaki çatlak yoğunluğu arttıkça artmıştır. Regresyon analizi sonucunda yoğunluk ile her bir kırılma parametresi arasında pozitif ve güçlü korelasyonların olduğu gözlemlenmiştir.
Anahtar kelimeler: Kırılma, Kırılma tokluğu, Güney sarıçam, Özgül kırılma enerjisi, Başlangıç eğimi

1. Introduction

Fracture is a process that affects the structure of the material, resulting in broken bonds and the formation of new surfaces (Vasic, 2000). Wood has remarkable mechanical properties despite its low weight (Fruhmann et al., 2002). However, natural characteristics (knots, grain deviation, etc.), as well as environmental conditions (moisture content, temperature, etc.), can all have an impact on the mechanical properties of wood (Smith et al., 2003). The fracture behavior of wood also depends on how the material is loaded relative to the grain orientation axis. For wood, there are six principal crack propagation systems (LR, LT, RL, RT, TR, and TL) as shown in Figure 1. Each of the six systems is represented by two letters, the first of which describes the grain orientation perpendicular to the crack plane and the second of which determines the direction of crack propagation (Reiterer et al., 2002), for instance, RL indicates the system has its crack growing in the longitudinal direction on the radial direction perpendicular to the crack plane. The material's fracture behavior can be characterized using three different loading conditions (Smith et al., 2003): mode I (tensile mode), mode II (in-plane shear mode), and mode III (out-of-plane shear mode).

The ability of a material containing a crack to resist crack initiation is described by its fracture toughness (Ohuchi et al., 2011). According to previous studies, the fracture toughness of wood is strongly influenced by its natural features such as density (Ashby et al., 1985; Conrad et al., 2003; Patton-Mallory and Cramer, 1987; Petterson and Bodig, 1983; Schniewind et al., 1982). Petterson and Bodig (1983) investigated the mode I fracture toughness of ten different wood species (douglas-fir, hemlock, larch, loblolly pine, lodgepole pine, ponderosa pine, redcedar, redwood, shortleaf pine, spruce) in TL crack propagation systems. Ashby et al. (1985) also measured the fracture toughness of different wood species (ash, balsa, beech, mahogany, oak, pine, and teak) with densities ranging from 70 to 800 kg/m^3. According to the results, a positive correlation was found between each fracture toughness value of the wood species and their densities. Reiterer et al. (2002) investigated the fracture behavior of four wood species (spruce, alder, oak, and ash)

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✓ **Received** (Geliş tarihi): 07.01.2022, **Accepted** (Kabul tarihi): 06.04.2022

Citation (Atıf)**:** Konukçu, A.Ç., 2022. Influence of density on Mode I fracture behavior of southern yellow pine (*Pinus taeda* L.) wood. Turkish Journal of Forestry, 23(2): 135-140.
DOI: 10.18182/tjf.1054428

under mode I loading in the RL and TL crack propagation systems. The results show that the fracture parameters were higher in dense species in both crack propagation systems, however, the fracture parameters in the RL crack system were greater than in the TL crack system. The initial slope, which indicates the stiffness of the species, was greater in the RL crack propagation system and had a strong influence on density in both systems.

The main objective of this study was to examine the effects of density on fracture behavior of southern yellow pine wood in the RL crack propagation system under pure mode I loading. Fracture parameters such as initial slope, fracture toughness, and specific fracture energy were determined from the obtained load-deformation curves. Regression analysis was done to observe if there was a statistically significant relation between crack-tip density and fracture parameters.

2. Materials and methods

2.1. Material

Lumber was purchased from a local lumber company in Starkville, Mississippi, USA. The lumber was selected based on straight grain and defects-free. The average density of the air-dried lumber was 421±59 kg/m^3. It was calculated by using ASTM (D2395-14) standard (2014).

2.2. Methods

First, the density profile of southern yellow pine blocks was investigated. The density profile testing blocks from the lumber were cut, and 30 samples were randomly selected. The density profile testing blocks had dimensions of 51×51×30 mm, and the density profile was measured on a thickness of 30 mm. Figure 2 shows a typical density profile testing block configuration and an illustration of how fracture test samples were obtained from the block. The density profile testing blocks were placed in a conditioning room at 20ºC and 42% relative humidity to reach an equilibrium moisture content of approximately 8% before density profile measurement. An X-ray density profile analyzer (QMS Model QDP-01X) was used to examine the density profiles throughout the thickness.

Based on the standard established by ASTM (E399-09) standard (2009), the fracture test blocks were prepared. Figure 3 shows a typical fracture test block configuration for the CT test method. First, an initial crack was cut into the specimens with a thickness of 1 mm with a band saw and then extended approximately 1 mm ahead of the crack-tip with a razor blade to create a sharp crack. Then, the prepared test blocks were placed in a conditioning room at 20ºC and 42% relative humidity to reach an equilibrium moisture content of approximately 8% before fracture toughness testing. A total of 30 test blocks were prepared in the RL system.

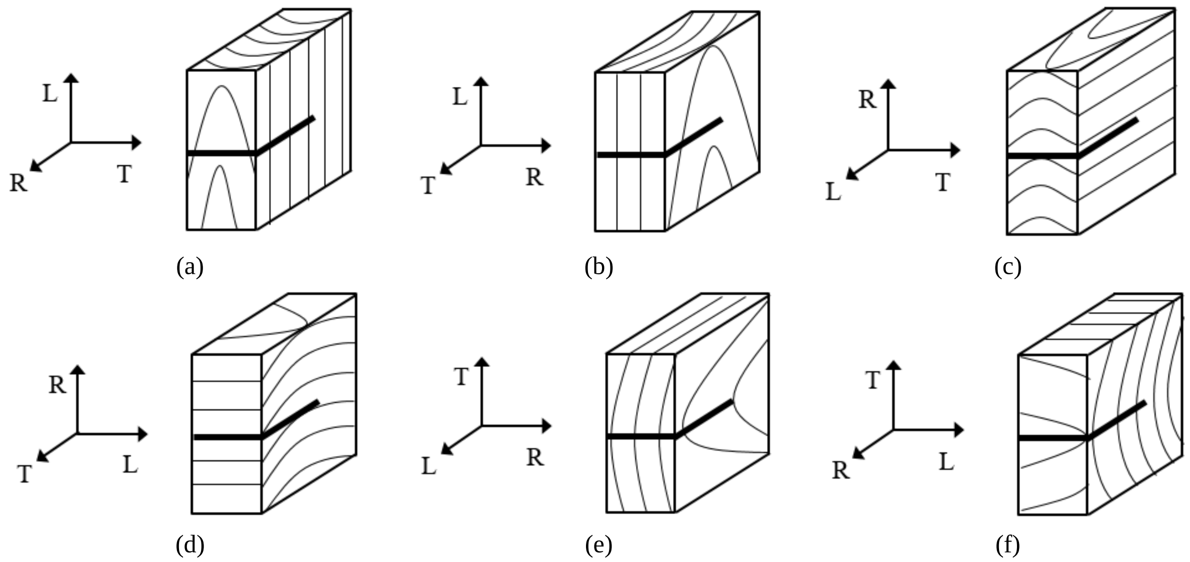
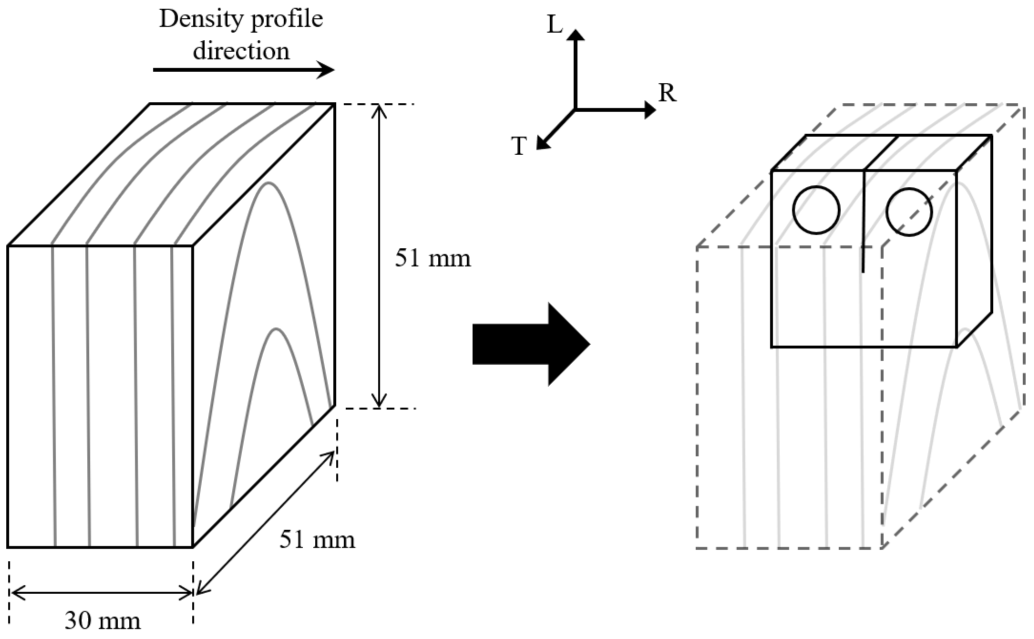


Figure 1. Crack propagation systems of wood: (a) LR, (b) LT, (c) RL, (d) RT, (e) TL, and (f) TR.



(a) (b)

Figure 2. A typical density profile testing block configuration (a) and illustration of how a fracture test block was obtained from a measured block (b)

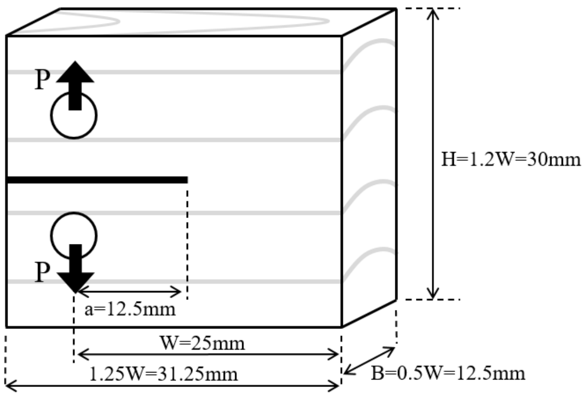


Figure 3. A typical fracture test block configuration for the CT test method

The fracture test blocks were tested on a universal testing machine (Instron Corporation, 5566 series, Norwood, MA, USA). The rate of loading was 2 mm/min during the tests. The load-deformation curves of all loaded fracture test blocks were recorded until complete surface separation. Three fracture parameters were obtained from the curve, namely initial slope (k_{init}), fracture toughness (K_{IC}), and specific fracture energy (G_f).

The initial slope, k_{init} (N/mm), in the elastic region of the load-deformation curve characterizes the stiffness of the material at a specific density level. It can be determined by dividing the difference between the upper and lower limit of load within the linear elastic region (ΔP) by the deflection difference corresponding to ΔP (Δδ) (Reiterer et al., 2002; Reiterer and Tschegg, 2002; Tukiainen and Hughes, 2016).

The following equation was used to calculate the fracture toughness (ASTM E399-09, 2009):

$$K_{IC} = \frac{P_Q}{B\sqrt{W}} f\left(\frac{a}{W}\right) \quad (1)$$

where P_Q is the load initiating crack propagation, a is the initial crack, B is the thickness, and W is the distance between the center of the hole and the end of the specimen, respectively. $f\left(\frac{a}{W}\right)$ is the polynomial function of the specimens as shown in the following formula (Konukcu et al., 2021; Ohuchi et al., 2011; Wu et al., 2012):

$$f\left(\frac{a}{W}\right) = 29.6\left(\frac{a}{W}\right)^{1/2} - 185.5\left(\frac{a}{W}\right)^{3/2} + 655.7\left(\frac{a}{W}\right)^{5/2} - 1017.0\left(\frac{a}{W}\right)^{7/2} + 638.9\left(\frac{a}{W}\right)^{9/2} \quad (2)$$

where the polynomial function, $f\left(\frac{a}{W}\right)$, is applicable for the orthotropic materials in the range of $0.3 \leq \frac{a}{W} \leq 0.7$ (Valentin and Adjanohoun, 1992; Yoshihara and Usuki, 2011).

The specific fracture energy, G_f (J/m^2), represents the work required to separate the fracture surfaces. It was obtained by dividing the integrated area under the load-deformation curve by the fracture surface area using the following formula (Majano et al., 2010; Reiterer and Tschegg, 2002; Tukiainen and Hughes, 2016):

$$G_f = \frac{1}{A}\int_0^{\delta_{max}} P(\delta)\, d\delta \quad (3)$$

where P is the load, δ is the deflection at the loading point, and A is the area of the fracture surface.

Regression analysis was used to investigate any statistically significant relationship between the density and fracture parameters in the RL crack system. The fracture toughness, initial slope, and specific fracture energy were modeled using the linear regression model. Density as an independent variable was considered for statistical analysis. For data analysis, SAS 9.4 statistical software was used.

3. Results and Discussion

Figure 4 shows a typical density profile of a density profile testing block measured in this study using the density profile machine. In the figure, peaks represent latewood regions whereas distinct valleys represent earlywood regions. The density of the crack-tip location for each fracture test block was determined based on their density profiles of blocks. The density of the crack-tip location for the samples was in the range between 126.87 kg/m^3 and 703.69 kg/m^3.

The values of the initial slope, the fracture toughness, and the specific fracture energy for the wood evaluated in this study were calculated. Table 1 summarizes the results of the statistical parameters such as mean value, standard deviation, coefficient of variation, maximum and minimum values.

As can be seen in Figure 5, in general, the fracture parameters of the wood are influenced by its density. The fracture toughness as a function of density is shown in Figure 5b. The values range from 0.22 to 0.44 MPa√m in the RL system. The general trend is that the fracture toughness increases with increasing density. Similar results have been reported in some previous studies (Ashby et al., 1985; Konukcu et al., 2021; Petterson and Bodig, 1983; Schniewind et al., 1982). Ashby et al. (1985) investigated the fracture toughness of different types of wood species (ash, balsa, beech, pine, and teak) in the RL and LR crack propagation systems and correlated it with their density. They found that high-density wood had higher fracture toughness values than low-density wood. Kretschmann et al. (1991) also found that the mode I fracture toughness values of wood were positively correlated to its density. It means that wood species with higher density have a higher resistance against crack initiation.

The initial slope and the specific fracture energy as a function of density are shown in Figures 5a and 5c, respectively. The values range from 83.90 to 148.85 N/mm for the initial slope and from 134.87 to 305.46 J/m^2 for the specific fracture energy. In general, the initial slope and the specific fracture energy in the RL crack propagation system are influenced by the density of the crack-tip location. Reiterer et al. (2002) investigated fracture behavior of different wood species (spruce, alder, oak, and ash) in the RL and TL systems under mode I loading. They found similar findings that the fracture parameters are positively affected by increasing the density. The differences with the increasing density of the wood were higher, resulting in a higher slope of the regression line. It means that the wood has higher stiffness with higher density.

The specific fracture energy is based on the work required for the complete separation of surfaces and it requires the whole load-deformation curve including crack initiation and crack propagation phases. The specific fracture energy increases as the density of the crack-tip location increases because the crack initiation is not only getting stiffer but also the crack propagation phase consumes more energy. Previous studies have shown that the specific fracture energy increases as the dissipated energy increases during crack initiation and propagation, increasing the ductility of the wood (Majano et al., 2010; Reiterer and Tschegg, 2002). Fruhmann et al. (2002) also pointed out that the specific fracture energy can be affected by other characteristics such as density since it does not depend on the loading mode or the crack propagation system.

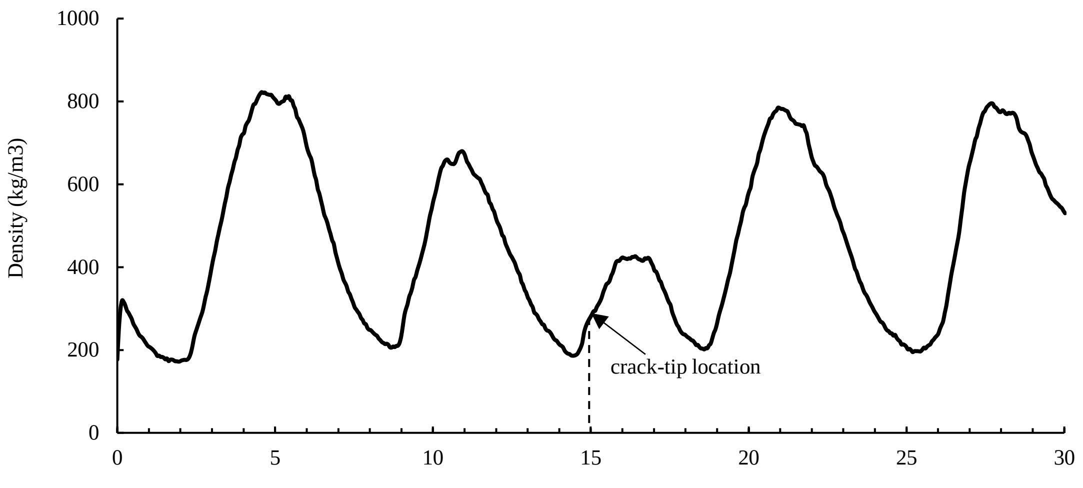
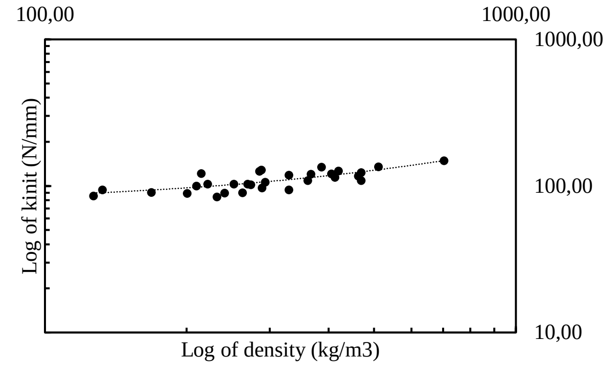


Figure 4. Typical density profile of a density profile testing block measured in this study

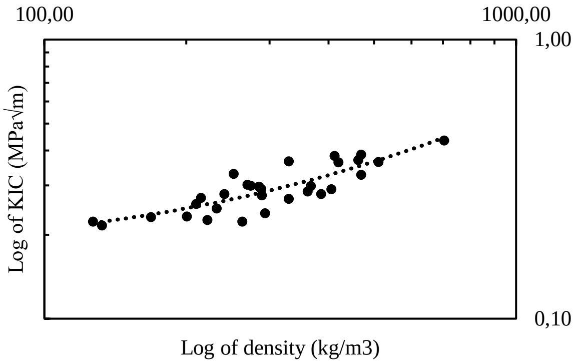
Table 1. Summary of the results of the statistical parameters of fracture test

Statistics	Density (kg/m^3)	Failure load (N)	Initial slope (N/mm)	Fracture toughness (MPa√m)	Specific fracture energy (J/m^2)
Mean	319.63	60.78	109.35	0.30	201.54
SD	125.43	11.89	16.83	0.06	50.41
CV (%)	39.24	19.57	15.39	19.57	25.01
Maximum	703.69	89.54	148.85	0.44	305.46
Minimum	126.87	44.44	83.90	0.22	134.87

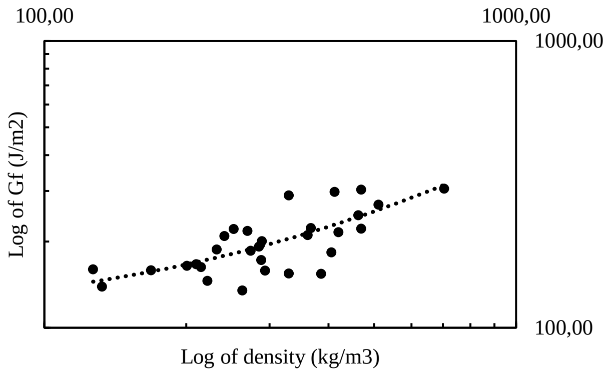
SD: Standard deviation, CV: Coefficient of variation.



(a)



(b)



(c)

Figure 5. Log-log plots showing the relationship between (a) initial slope (k_{init}), (b) fracture toughness (K_{IC}), and (c) specific fracture energy (G_f) versus density

The regression scatter plots of the initial slope, the fracture toughness, and the specific fracture energy values versus their corresponding density values are given in Figure 5. It can be seen that there are positive correlations between variables. Based on the correlations between density and each fracture parameter, linear regression models were created. The linear regression analysis pertains to one dependent variable (y) and one independent variable (x) as follows:

$$y = \beta_0 + \beta_1 x \tag{4}$$

where β_0 and β_1 are regression constants.

Table 2 summarizes the regression analysis findings. The Pearson's coefficient of correlation between the density and the fracture parameters of southern yellow pine were significant in the RL crack propagation system. The Pearson coefficient indicated strong positive associations between density with initial slope (r = 0.77), fracture toughness (r = 0.85), and specific fracture energy (r = 0.73). In general, the fracture toughness and density were found to have the best correlation and regression. The coefficients of determination, r^2, were 0.59, 0.72, and 0.54 for the initial slope, the fracture toughness, and the specific fracture energy, respectively. The significant linear model for each fracture parameter was validated by a p-value of less than 0.0001.

4. Conclusion

In this study, the effect of crack-tip density on mode I fracture behavior of southern yellow pine has been investigated. The fracture toughness, initial slope, and specific fracture energy values of each test sample were determined using the whole load-deformation curve. According to the results, in general, all fracture parameters increased with increasing the crack-tip density. The whole fracture process is mainly divided into two phases: crack initiation and crack propagation. Crack-tip locations with higher density had higher resistance against crack initiation. The initial slope of the load-deformation curve increased as the crack-tip density of the wood increased, and the crack initiation became stiffer. Furthermore, the crack propagation phase used more energy, resulting in higher specific fracture energy. The regression analysis also shows that there were positive and strong correlations between density and each fracture parameter. It can be concluded that this relationship could be used to predict the fracture parameters of wood.

Table 2. Pearson correlations and linear regression results of fracture parameters as a function of density for southern yellow pine.

Parameter	Replicate	β_0	β_1	*Pearson's r*	r^2	*p*-value
k_{init}	30	76.399	0.103	0.77	0.59	<.0001
K_{IC}	30	0.17049	0.00039	0.85	0.72	<.0001
G_f	30	107.441	0.294	0.73	0.54	<.0001

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