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Fracture Behavior of Wood Under Mode I Loading in Tangential Direction

Ponašanje loma drva pri vlačnom opterećenju (model I.) u tangentnom smjeru

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ABSTRACT • *The aim of this study was to determine the fracture behavior of southern yellow pine (Pinus taeda L.) and red oak (Quercus falcata) wood under mode I loading in the tangential-radial and tangential-longitudinal crack propagation systems by a compact tension test method. The results of the study indicated that, in general, red oak had a significantly different fracture behavior than southern yellow pine for each of the two crack propagation systems. The fracture toughness was higher in the tangential-radial crack propagation system than that in the tangential-longitudinal crack system, but there was no significant difference between the two crack propagation systems for southern yellow pine. The specific fracture energy of the tangential-longitudinal crack propagation system for both wood species was significantly lower than that of the tangential-radial crack propagation system. It means that more energy per unit area for the tangential-radial crack propagation system was needed to separate a wood sample into two halves. The difference in the fracture behavior of wood by the crack propagation system can be explained by the structural features of the tested samples since the crack propagation of the tangential-radial system crosses the annual ring and wood fibers can bridge the crack surface.*

KEYWORDS: *fracture; fracture toughness; southern yellow pine; red oak; specific fracture energy*

SAŽETAK • *Cilj ovog istraživanja bio je utvrditi ponašanje loma drva južnoga žutog bora (Pinus taeda L.) i crvenog hrasta (Quercus falcata) u tangentno-radijalnome i tangentno-longitudinalnom smjeru širenja pukotine primjenom kompaktne vlačne metode ispitivanja (model I.). Rezultati istraživanja pokazali su bitno drugačije ponašanje loma drva crvenog hrasta od drva južnoga žutog bora za svaki od dva načina širenja pukotine. Lomna žilavost drva crvenog hrasta bila je veća u tangentno-radijalnom smjeru širenja pukotine nego u tangentno-longitudinalnom smjeru, dok na drvu južnoga žutog bora nije uočena značajna razlika između dva načina širenja pukotine. Specifična energija loma u tangentno-longitudinalnom smjeru širenja pukotine za obje vrste drva bila je mnogo niža od one u tangentno-radijalnom smjeru. To znači da je bilo potrebno više energije po jedinici površine da se uzorak drva odvoji na dvije polovice u tangentno-radijalnom smjeru širenja pukotine. Razlika u ponašanju loma drva, odnosno u širenju pukotine može se objasniti strukturnim obilježjima ispitivanih uzoraka jer širenje pukotine u tangentno-radijalnom smjeru prelazi granicu goda i drvna vlakanca mogu premostiti površinu pukotine.*

KLJUČNE RIJEČI: *lom; lomna žilavost; južni žuti bor; crveni hrast; specifična energija loma*

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1 INTRODUCTION
1. UVOD

It is well-known that wood is an orthotropic material having independent mechanical properties in three different grain orientations of longitudinal (L), radial (R), and tangential (T) direction (Figure 1). Orthotropic materials have six principal systems of crack propagation as shown in Figure 2 (Schniewind and Centeno, 1973), and each of the six systems is indicated by two letters, i.e., the first letter specifies the grain orientation perpendicular to the crack plane, whereas the second letter specifies the direction of crack propagation. For instance, TR indicates that the system has its crack growing in the radial direction on the tangential direction perpendicular to the crack plane.

Fracture is usually defined as a process that changes the structure of the material results in broken bonds and new surfaces are formed when a sufficient load is applied (Vasic, 2000; Smith *et al*., 2003). Atack *et al*. (1961) first applied the concepts of fracture mechanics to wood. Walsh (1972) mentioned that linear elastic fracture mechanics (LEFM) are ideally applicable to wood because a wood member under tensile or shear loads behaves like brittle materials (Smith *et al*., 2003; Stanzl-Tschegg, 2009). Therefore, LEFM can be an efficient tool to investigate wood fracture-related problems (Qiu *et al*., 2012). Zink *et al*. (1995) also mentioned that fracture mechanics is useful in predicting the strength of wood subjected to tensile loads at high angles in grain orientation.

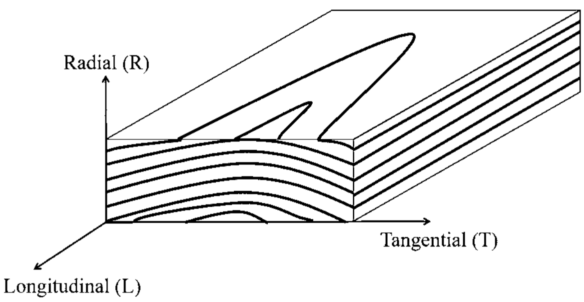


Figure 1 Three principal axes of wood in reference to wood grain orientations
Slika 1. Tri glavne osi drva u odnosu prema orijentaciji drvnih vlakanaca

Fracture toughness is a geometry-independent material property of wood (Mall *et al*., 1983), which is defined as the material's resistance to crack growth (Smith *et al*., 2003). Fracture toughness test can be performed based on three different loading conditions (Conrad *et al*., 2003) as shown in Figure 3: Mode I (tensile mode), Mode II (in-plane shear mode), and Mode III (out-of-plane shear mode). Mode I is typically the dominant failure mode for most engineering materials (Smith *et al*., 2003). Mode I and Mode II are the most common failure modes observed in wooden structures, whereas Mode III fracture occurs in wooden beams with side checks (Patton-Mallory and Cramer, 1987). There is no standardized test method for measuring fracture toughness of wooden materials. Previous studies have been referencing ASTM (E399-09) standard (2009) for metallic materials. The fracture toughness of a wood specimen can be evaluated using a variety of specimen configurations subjected to tensile, shear, or bending loads, i.e., single-edge-notched bending (SENB), single-edge-notched tension (SENT), and compact tension (CT). The CT test method is suitable for testing wood materials when different wood grain orientations are considered (Fonselius and Riipola, 1992). A combination of Mode I and Mode II often occurs together in wooden components in the form of cracking along the grain direction (Qiu *et al*., 2012).

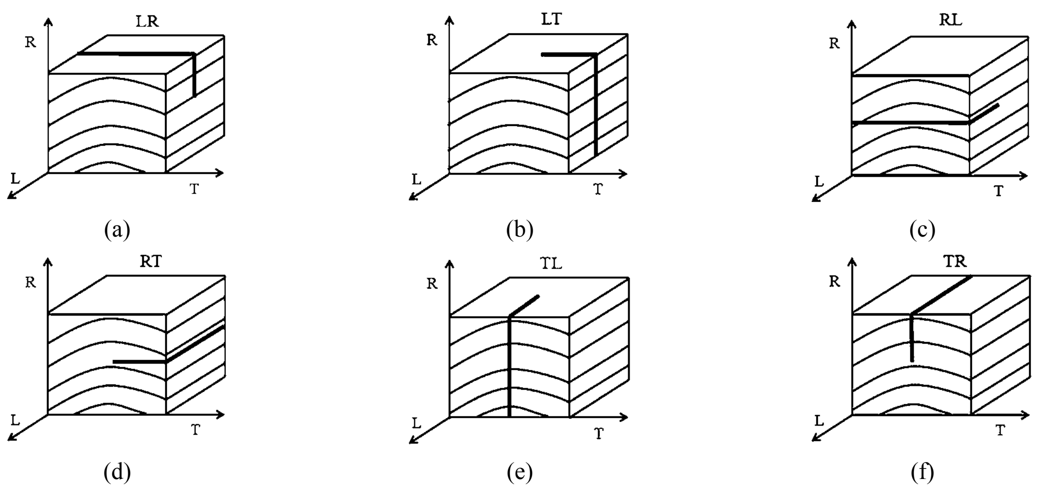
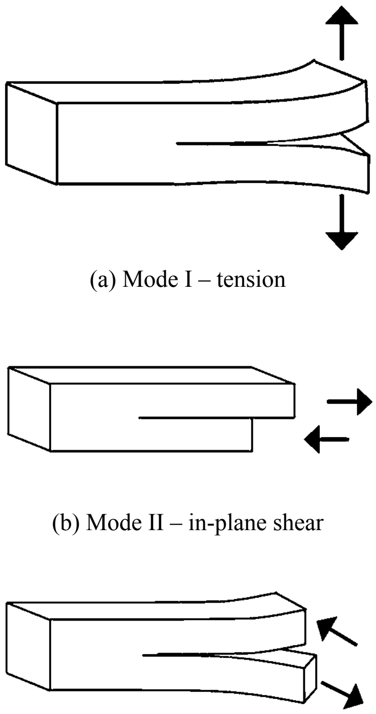


Figure 2 Six crack growth orientations, LR (a), LT (b), RL (c), RT (d), TL (e), and TR (f) in reference to wood grain orientation axis of radial (R), tangential (T), and longitudinal (L) directions, respectively
Slika 2. Šest orijentacija širenja pukotine: LR (a), LT (b), RL (c), RT (d), TL (e) i TR (f) u odnosu prema radijalnoj (R), tangentnoj (T) i longitudinalnoj (L) osi orijentacije žice drva



(a) Mode I – tension

(b) Mode II – in-plane shear

(c) Mode III – out-of-plane shear

Figure 3 Basic fracture modes of specimens subjected to a tensile load (a), an in-plane shear load (b), and an out-of-plane shear load (c)
Slika 3. Osnovni modeli loma uzoraka izloženih vlačnom opterećenju (a), smičnom opterećenju u ravnini (b) i smičnom opterećenju izvan ravnine (c)

Tan *et al*. (1995) studied fracture toughness of wood failing in Mode I and Mode II and concluded that fracture toughness values of Model II were 4-5 times those of Mode I.

Fracture toughness is a function of applied load, specimen geometry, and crack length. However, fracture toughness of wood is strongly influenced by its natural characteristics such as specific gravity (SG) and environmental conditions such as relative humidity (RH) and temperature (Porter, 1964; Johnson, 1973; Mall *et al*., 1983; Patton-Mallory and Cramer, 1987; Smith *et al*., 2003; Dourado and de Moura, 2019).

All six principal systems (Figure 2) can be divided into two groups according to the location of the crack plane and the direction of crack propagation. The LT and LR systems have been defined as one group, and the RL, RT, TL, and TR as another. Schniewind and Centeno (1973) studied the fracture toughness of air-dry Douglas fir in all six principal systems and concluded that the fracture toughness of two principal systems (LT and LR) were significantly higher than the ones in the rest of the systems. The fracture toughness of air-dry Douglas fir measured in LT and LR systems ranged from 2.42 to 2.69 MPa√m, whereas the fracture toughness in RL, RT, TL, and TR systems ranged from 0.31 to 0.41 MPa√m. The RL and TL systems have been mostly studied because of the low strength and stiffness values of wood perpendicular to the grain (Kretschmann *et al*., 1991; Smith *et al*., 2003) even though these four of six systems (RL, RT, TL, and TR) are of practical importance (Barrett, 1976). Moreover, Qiu *et al*. (2012) mentioned that the RL and RT crack propagation systems were the common cracks observed in wood composites because of their low strength in tension perpendicular to grain.

The fracture toughness of wood increases with increasing its SG (Ashby *et al*., 1985; Conrad *et al*., 2003; Petterson and Bodig, 1983; Schniewind *et al*., 1982). Kretschmann *et al*. (1991) found that the fracture toughness values of wood failed in both Mode I and Mode II and were positively correlated to its SG. Schniewind *et al*. (1982) studied the effects of SG on the fracture toughness of wood using five softwood species (douglas-fir, incense-cedar, pondersa pine I, pondersa pine II, redwood, white fir) and nine hardwood species (apitong, balsa, beech, birch, black oak, lauan, madrone, hard maple, tanoak I, tanoak II) in TL and LT systems. The results indicated that the fracture toughness values can be predicted by highly correlated linear equations with knowing their average SG values (r^2= 0.73 for the TL system and r^2= 0.74 for the LT system).

The fracture toughness of wooden materials can be affected and reduced by increasing their moisture content (MC) (Majano-Majano *et al*., 2012; Reiterer and Tschegg, 2002; Tukiainen and Hughes, 2016a; Tukiainen and Hughes, 2016b; Vasic and Stanzl-Tschegg, 2007). Atack *et al*. (1961) also indicated that the fracture toughness of wooden materials with a higher MC could become questionable because their plasticity could increase during crack propagation. Kretschmann *et al*. (1991) studied the effects of MC on fracture toughness values of Mode I and Mode II for southern pine in the TL system, respectively. The results showed that the fracture toughness values of wood increased with decreasing MC. However, the fracture toughness reached the maximum values with MC ranging from 7.5 and 10 %. Ewing and Williams (1979) studied the effects of specimen thickness and MC on the fracture toughness of scots pine and concluded that the fracture toughness reached the maximum values at the MC of 10 % for all thickness levels investigated.

In this study, we investigated the fracture behavior of wood under pure Mode I loading in the TR and TL crack propagation systems using the CT test method. Results of two wood species, one softwood, southern yellow pine (*Pinus taeda* L.), and one hardwood, red oak (*Quercus falcata*), are presented. Differences between the softwood and hardwood are shown and discussed. Moreover, differences between the two crack propagation systems are discussed.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Southern yellow pine (*Pinus taeda* L.) (SYP) and red oak (*Quercus falcata*) (RO) lumber were purchased from a local lumber company in Starkville, Mississippi. The selected lumber was straight-grain and free from defects. The CT test specimens were prepared according to the standard established by ASTM (E399-09) standard (2009). Figure 4 shows the general configuration of a fracture toughness testing specimen for a CT test method. Twenty samples were investigated for each crack propagation system and wood species. An initial crack in the test specimens, 1 mm thick, was first cut using a band saw and then extended about 1 mm ahead of the crack tip with a razor blade to make a sharp crack. Prior to the fracture test, all specimens were kept in the conditioning room with the temperature and relative humidity controlled at 20 °C and 42 %, respectively. The average measured density of SYP and RO was 487±24 kg/m^3 and 609±7 kg/m^3, respectively.

The test was performed on an INSTRON 5566 universal test machine with a loading speed of 2 mm/min. Load-deformation curves of all tested specimens loaded until the complete separation of surfaces occurred were recorded. Three fracture parameters were obtained from the curves, i.e., fracture toughness (K_{IC}), initial slope (k_{init}), and specific fracture energy (G_f). The fracture toughness, K_{IC} (MPa√m), was calculated using the following equation (ASTM 2009):

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

Where:

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

Where: P_Q is the failure load initiating crack propagation (N), W is the distance between the loading point and the end of a CT test block (m), B is the thickness of a CT test specimen (m), a is the initial crack length (m) (Figure 4), and $f(a/W)$ is the polynomial function for wood as an orthotropic material (Fonselius and Riipola, 1992; Smith *et al.*, 2003; Ohuchi *et al.*, 2011; Wu *et al.*, 2012).

The load-deformation curve of a wooden material characterizes its fracture process. In order to characterize the elastic behavior of the material, the initial slope, k_{init}, of the load-deformation curve in the elastic region can be determined by dividing ΔP (the difference between the upper and lower limit of load within the linear elastic region) by $\Delta\delta$ (the deflection difference corresponding to ΔP) (Reiterer et al., 2002; Reiterer and Tschegg, 2002) (Figure 5). The specific fracture energy representing the work required to separate the fracture surfaces was calculated from the integrated area under the whole load-deformation curve (Figure 5) divided by the area of the fracture surface using Eq. 3 (Majano-Majano *et al.*, 2010; Reiterer and Tschegg, 2002):

$$G_f = \frac{1}{(W-a)\cdot B} \int_0^{\delta_{\max}} P(\delta)\, d\delta \tag{3}$$

Where P is the applied load (N), δ is the deflection at the loading point, W is the width of the test specimen (m), a is the initial crack length (m), B is the thickness of the test specimen (m).

All statistical analyses were carried out using the SAS 9.4 statistical software. A two-factor analysis of variance (ANOVA) general linear model (GLM) procedure was first performed for each property evaluated to analyze the main effects and their interactions, followed by performing mean comparisons if the significant interaction was identified using the protected least significant difference (LSD) multiple comparisons procedure. Otherwise, the main effects were concluded. All statistical analyses in this study were performed at the 5 % significance level.

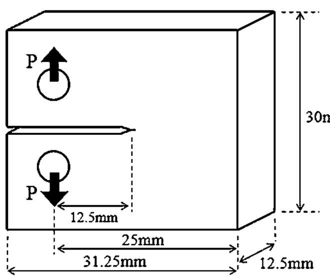


Figure 4 General configuration of a fracture toughness testing specimen
Slika 4. Opća konfiguracija uzorka za ispitivanje lomne žilavosti

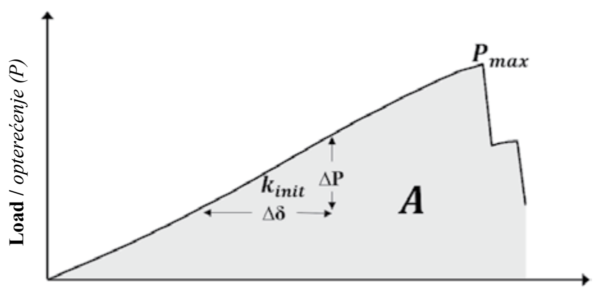


Figure 5 Graphical illustration of how to define initial slope and integrated area based on load-deformation curve
Slika 5. Grafički prikaz definiranja početnog nagiba i integrirano područje na temelju krivulje opterećenje – deformacija

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Typical load-deformation curves obtained by the CT tests in the TR and TL crack propagation systems of both SYP and RO are shown in Figure 6. The curves can clearly illustrate the effect of wood species and crack propagation systems on fracture behavior. The maximum loads in the load-deformation curve for all specimens in both crack systems were defined as the failure loads because the load was found earlier than the intersection drawn with a 5 % reduction in initial slope (Konukcu *et al*., 2021). In general, the RO had a greater failure load than the SYP. It was also observed that the failure load in the TR crack system for both wood species was higher than in the TL crack system.

Table 1 summarizes mean values of failure load, fracture toughness, initial slope, specific fracture energy, and brittleness of SYP and RO in the TR and TL crack propagation systems. ANOVA results (Table 2) indicated that the two-factor interaction was significant for fracture toughness. This suggested that further analyses should be focused on the significant interaction. Table 1 also summarizes mean comparisons of fracture toughness for crack propagation system and wood species. The results were based on a one-way classification with four treatment combinations with respect to the two-factor interaction and mean comparisons among these combinations using a single LSD value of 0.05 MPa√m.

In general, RO had a significantly higher fracture toughness than SYP for each of the two crack propagation systems evaluated. Mean comparison results (Table 1) indicated that, in general, the RO had a significantly higher fracture toughness value of 0.78 MPa√m in the TR crack system than in the TL crack system (0.61 MPa√m). The results show that the fracture toughness of RO in the TR crack system was about 28 % higher than that in the TL crack system, while in the case of SYP the difference was about 3 %. The SYP had a greater fracture toughness value of 0.39 MPa√m in the TR crack system than in the TL crack system (0.38 MPa√m), but there was no significant difference between the two crack propagation systems. Previous studies have reported similar results that the TR crack system has a higher fracture toughness value than the TL crack system (Schniewind and Centeno, 1973; Schniewind and Pozniak, 1971; Thuvander and Berglund, 2000).

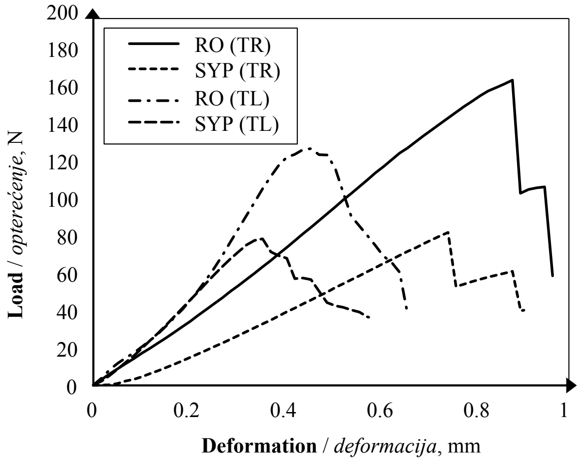


Figure 6 Typical load – deformation curves obtained by CT test in TR and TL crack propagation systems
Slika 6. Tipične krivulje opterećenje – deformacija dobivene CT testom pri TR i TL načinu širenja pukotine

The specific fracture energy is more suitable for characterizing the fracture behavior of wood (Stanzl-Tschegg *et al*., 1995) because the fracture is determined not only by the crack initiation process but also by the propagation energy of an existing crack (Majano-Majano *et al*., 2012). The specific fracture energy, including crack initiation and propagation energies, characterizes

Table 1 Mean values of failure load, fracture toughness, initial slope, specific fracture energy, and brittleness within each combination of crack propagation system and wood species and mean comparisons of fracture toughness and specific fracture energy for crack propagation system and wood species*
Tablica 1. Srednje vrijednosti sile loma, lomne žilavosti, početnog nagiba, specifične energije loma i krtosti unutar svake kombinacije načina širenja pukotine i vrste drva te usporedbe srednjih vrijednosti lomne žilavosti i specifične energije loma za načine širenja pukotine i vrste drva*

Species *Vrsta drva*	**Failure load** *Sila loma,* N		**Fracture toughness** *Lomna žilavost,* MPa/m		**Initial slope** *Početni nagib,* N/mm		**Specific fracture energy** *Specifična energija loma,* J/m²		**Brittleness** *Krtost,* mm	
	TR	TL	TR	TL	TR	TL	TR	TL	TR	TL
SYP	81.16 (9)	77.85 (13)	0.39 (18) (A) (b)	0.38 (18) (A) (b)	128.05 (14)	266.75 (24)	298.26 (21) (A) (b)	181.03 (13) (B) (b)	14.80 (30)	10.29 (11)
RO	159.98 (10)	126.17 (17)	0.78 (12) (A) (a)	0.61 (11) (B) (a)	223.92 (8)	334.10 (20)	444.97 (8) (A) (a)	296.90 (16) (B) (a)	20.83 (18)	12.70 (19)

*Values in parentheses are coefficients of variation in percentage; means not followed by the same uppercase letter in the same row are significantly different one from another at the 5 % significance level considering crack propagation system effect; means not followed by the same lowercase letter in the same column are significantly different one from another at the 5 % significance level considering wood species effect.
**Vrijednosti u zagradama koeficijenti su varijacije u postotcima; srednje vrijednosti iza kojih ne slijedi isto veliko slovo u istom retku međusobno se značajno razlikuju na razini značajnosti od 5 % uzimajući u obzir učinak načina širenja pukotine; srednje vrijednosti iza kojih ne slijedi isto malo slovo u istom stupcu međusobno se značajno razlikuju na razini značajnosti od 5 % uzimajući u obzir učinak vrste drva.*

Table 2 Summary of analysis of variance (ANOVA) results obtained from a general linear model (GLM) procedure performed on two factors for each property evaluated
Tablica 2. Sažetak rezultata analize varijance (ANOVA) dobivenih iz postupka općega linearnog modela (GLM) provedenoga na dva faktora za svako od procijenjenih svojstava

Source / *Izvor*	**Property** / *Svojstvo*			
	Fracture toughness *Lomna žilavost*		**Specific fracture energy** *Specifična energija loma*	
	***F* value** *F-vrijednost*	***p* value** *p-vrijednost*	***F* value** *F-vrijednost*	***p* value** *p-vrijednost*
Wood species / *vrsta drva*	364.18	< 0.0001	170.28	< 0.0001
Crack system / *način loma*	31.03	< 0.0001	173.83	< 0.0001
Wood species × crack system / *vrsta drva × način loma*	20.95	< 0.0001	2.35	0.1296

the whole fracture process until the CT specimen is separated into two halves. Crack initiation energy is the energy that causes the formation of micro-cracks and irreversible deformations around the crack tip, whereas crack propagation energy is the energy that is dissipated through the formation of microcracks that ultimately turn into the main crack (Majano-Majano *et al*., 2010; Reiterer and Tschegg, 2002; Smith *et al*., 2003).

For the specific fracture energy values, ANOVA results (Table 2) indicated that the two-factor interaction was not statistically significant, while the two main effects were both considered statistically significant at the 5 % level. The crack system and wood species effect on the specific fracture energy was determined based on mean comparisons of the main effect directly. Mean comparison results of the specific fracture energy for wood species are summarized in Table 2. The wood species on the specific fracture energy was analyzed by considering the non-significant two-way interaction because the nature of conclusion from interpretation of the main effects also depends on the relative magnitudes of the interaction and individual main effects (Freund and Wilson, 1997). The results were based on a one-way classification with four treatment combinations with respect to the two-factor interaction and mean comparisons among these combinations using a single LSD value of 28.34 J/m^2 for specific fracture energy.

Mean comparison results (Table 1) indicated that in general, the RO had a significantly higher specific fracture energy value of 444.97 J/m^2 in the TR crack system than in the TL crack system (296.90 J/m^2), whereas the SYP had a greater specific fracture energy value of 298.26 J/m^2 in the TR crack system than in the TL crack system (181.03 J/m^2). The results show that the specific fracture energy of SYP in the TR crack system was about 65 % higher than that in the TL crack system, while in the case of RO the difference was about 50 %. A similar result was also reported by Watanabe *et al*. (2011). They researched fracture behavior of sugi (Cryptomeria japonica) in the TR, TL, and intermediate crack systems. They stated that the fracture energy, which means the area under the load-deformation curve in the TR crack system, was more than twice that in the TL and intermediate systems. It means that the crack growing in the radial direction needed more energy per unit area to separate a wood sample into two halves than in the longitudinal direction.

The initial slope is characteristic for the elastic properties and proportional to an effective modulus of elasticity (Harmuth *et al*., 1996; Reiterer *et al*., 2002). The initial slope of the TL specimen was higher than that of the TR specimen. The RO shows higher initial slopes than SYP in both systems. The initial slope results for both wood species indicate that the modulus of elasticity would be expected to be higher under Mode I loading in the TL crack system than in the TR. Ductility increased with increasing both the dissipated energy during the crack initiation and the crack propagation (Reiterer and Tschegg, 2002). As all CT test specimens in this study had the same dimensions, a brittleness parameter was used to characterize whether the material behavior was more ductile or brittle. The parameter was determined from the load-deformation curves using the failure load, initial slope, and specific fracture energy (Reiterer *et al*. 2002; Tschegg *et al*. 2001). It was calculated using Eq. 4:

$$B = \frac{P_{max}^2}{L \cdot k_{init} \cdot G_f} \tag{4}$$

Where P_{max} is the maximum force (N), L is the ligament length, k_{init} is the initial slope of a tested specimen (N/mm), G_f is the specific fracture energy (J/m^2). According to the parameter, a lower value indicates that the material behavior is more ductile, whereas a higher value refers to the material behavior as more brittle. The obtained values clearly show that RO in both crack systems was more brittle than SYP. In general, the TR crack system showed a more brittle behavior than the TL crack system.

Differences in the fracture behavior depending on grain orientation and wood species could be explained by structural features of the tested wood species. Konukcu *et al*. (2021) mentioned that Mode I fracture behavior of a tested specimen can be affected by not only its density but also by its microstructure. The fracture toughness (or failure load) and the specific fracture energy of the TR were larger than those of the TL. This is because the TR specimens were loaded in a tangential direction, while the crack propagated in a radial direction. Therefore, the crack progress in the TR specimen crossed the annual ring and wood fibers could bridge the crack surface. On the other hand, the crack process of TL was small because all the cracks were growing along the longitudinal direction of the CT test specimen. Schniewind and Pozniak (1971) explained that the crack in the TL system can run along the cell axis where the only cell ends and ray cells crossings provide for temporary arrest of crack growth, whereas the crack in the TR system can grow perpendicular to the cells. Kretschmann (2010) also mentioned that the TL is one of the predominant crack systems because of the low strength and stiffness of wood perpendicular to the grain. The difference between SYP and RO could be explained by the fact that RO is denser than SYP because previous studies show that the fracture toughness values of wood were increased with the increase of its density (Conrad *et al*., 2003; Kretschmann *et al*., 1991; Petterson and Bodig, 1983; Schniewind *et al*., 1982).

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, the fracture behavior of SYP and RO was investigated in the TR and TL crack propagation systems using the CT test method in Mode I. The results show that, in general, the RO had a significantly different fracture behavior than SYP for each of the two crack propagation systems. The fracture toughness indicating the resistance against crack initiation was higher in the TR crack propagation system than that in the TL crack system, but there was no significant difference between the two crack propagation systems for SYP. The initial slope indicating the stiffness was higher in the TL than in the TR. However, the specific fracture energy of the TL was significantly lower than that of the TR. It means that more energy per unit area was needed for the TR to separate a wood sample into two halves. It was also found that the behavior of wood in the TR crack system became more brittle than in the TL. Differences in the fracture behavior of wood depending on the crack propagation systems could be explained by structural features of the tested samples because the crack propagation in the TR system crosses the annual ring and wood fibers can bridge the crack surface; however, the crack in the TL system would run along the longitudinal direction of the wood.

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