Hiroshi Yoshihara, Hikaru Mizuno[1]

Mode I Critical Stress Intensity Factor of Medium-Density Fiberboard Obtained by Single-Edge-Notched Bending Test

Faktor kritičnog intenziteta naprezanja (I. mod) MDF ploča dobiven testom savijanja

ABSTRACT • *The Mode I critical stress intensity factor (K_{Ic}) obtained by single-edge-notched bending (SENB) tests of medium-density fiberboard (MDF) was experimentally analyzed. In the SENB test, the critical load for crack propagation (P_c) was determined from the relationship between load/loading-line displacement and load/crack opening displacement (COD). A double cantilever beam (DCB) test was also conducted and the results were compared with those of SENB tests. The value of Mode I critical stress intensity factor was obtained by introducing an additional crack length, when the crack length ranged from 0.5 to 0.7 times the depth of the specimen. This range coincided well with that used to derive the appropriate K_{Ic} value in the single-edge-notched tension (SENT) test, which was conducted using the specimens with a similar configuration cut from the MDF panel used in this study.*

Key words: additional crack length, Mode I critical stress intensity factor, medium-density fiberboard (MDF), western hemlock, single-edge-notched bending (SENB) test

SAŽETAK • *U radu se eksperimentalno analizira faktor kritičnog intenziteta naprezanja (I. mod) (K_{Ic}) dobiven testom savijanja s jednim rubnim urezom (SENB) za ploče vlaknatice srednje gustoće (MDF ploče). U SENB testu kritično opterećenje za širenje pukotine (P_c) određeno je iz odnosa opterećenja i linije pomaka te iz odnosa opterećenja i širenja pukotine (COD). Proveden je i dvostruki konzolni test (DCB), a rezultati su uspoređeni s rezultatima SENB testova. Vrijednost faktora kritičnog intenziteta naprezanja (I. mod) dobiven je uvođenjem dodatne duljine pukotine kada je duljina pukotine u rasponu od 0,5 do 0,7 debljine uzorka. Taj se raspon podudario s rasponom koji se koristi za dobivanje odgovarajuće K_{IC} vrijednosti u tenzijskom testu s jednim rubnim urezom (SENT), a proveden je na uzorcima slične konfiguracije izrađenima od MDF ploče koja je upotrijebljena i u ovom istraživanju.*

Ključne riječi: dodatna duljina pukotine, faktor kritičnog intenziteta naprezanja (I. mod), ploče vlaknatice srednje gustoće (MDF), test savijanja s jednim rubnim urezom (SENB test)

[1] Authors are professors at Faculty of Science and Engineering, Shimane University, Matsue, Shimane, Japan.
[1] Autori su profesori Fakulteta prirodoslovlja i inženjerstva, Shimane sveučilište, Matsue, Shimane, Japan.

1 INTRODUCTION
1. UVOD

In analyzing the fracture behavior of material based on fracture mechanics theory, the value of critical stress intensity factor K_c is often measured because it can be regarded as a material constant. Of the three independent fracture modes, the crack opening mode (Mode I) is regarded as more important than the in-plane shear mode (Mode II) and out-of-plane shear mode (Mode III) because the Mode I critical stress intensity factor (K_{Ic}) is usually smaller than those of Mode II and Mode III, K_{IIc} and K_{IIIc}, respectively. To determine the K_{Ic} value, single-edge-notched bending (SENB), single-edge-notched tension (SENT), compact tension (CT), and double cantilever beam (DCB) tests, the diagrams of which are shown in Figures 1(a)-(d), respectively, are most frequently performed because the crack propagation under the opening mode can be easily induced by these tests.

In previous works, the K_{Ic} value of medium-density fiberboard (MDF) was examined by SENT and CT tests (Yoshihara, 2010b; Yoshihara and Usuki, 2011). In these tests, we found that the K_{Ic} value of MDF can be effectively measured when considering the additional crack length ahead of the crack tip and restricting the range of initial crack length with respect to the

specimen geometry. Nevertheless, these tests require attachments to apply the tensile load, so the use of the attachments often restricts the specimen geometry. The SENB test is attractive because it can be conducted using specimens with various geometries more easily than the SENT and CT tests (Yoshihara, 2010a).

In this study, we examined the K_{Ic} value of MDF by the SENB test using two types of specimens with different dimensions. The results were compared with those obtained from the DCB tests, which can be determined based on energy consideration and are mathematically well defined (Adams *et al.*, 2003).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

An MDF panel, which was used in previous works (Yoshihara, 2010b; Yoshihara and Usuki, 2011), was investigated. The density of the MDF at 12 % moisture content (*MC*) was 580 ± 10 kg/m³. The panel was stored in a room at a constant 20 °C and 65 % relative humidity (*RH*) before the test, and the specimens were confirmed to be in an air-dried state. These conditions were maintained throughout the tests. Five specimens were tested for each test condition.
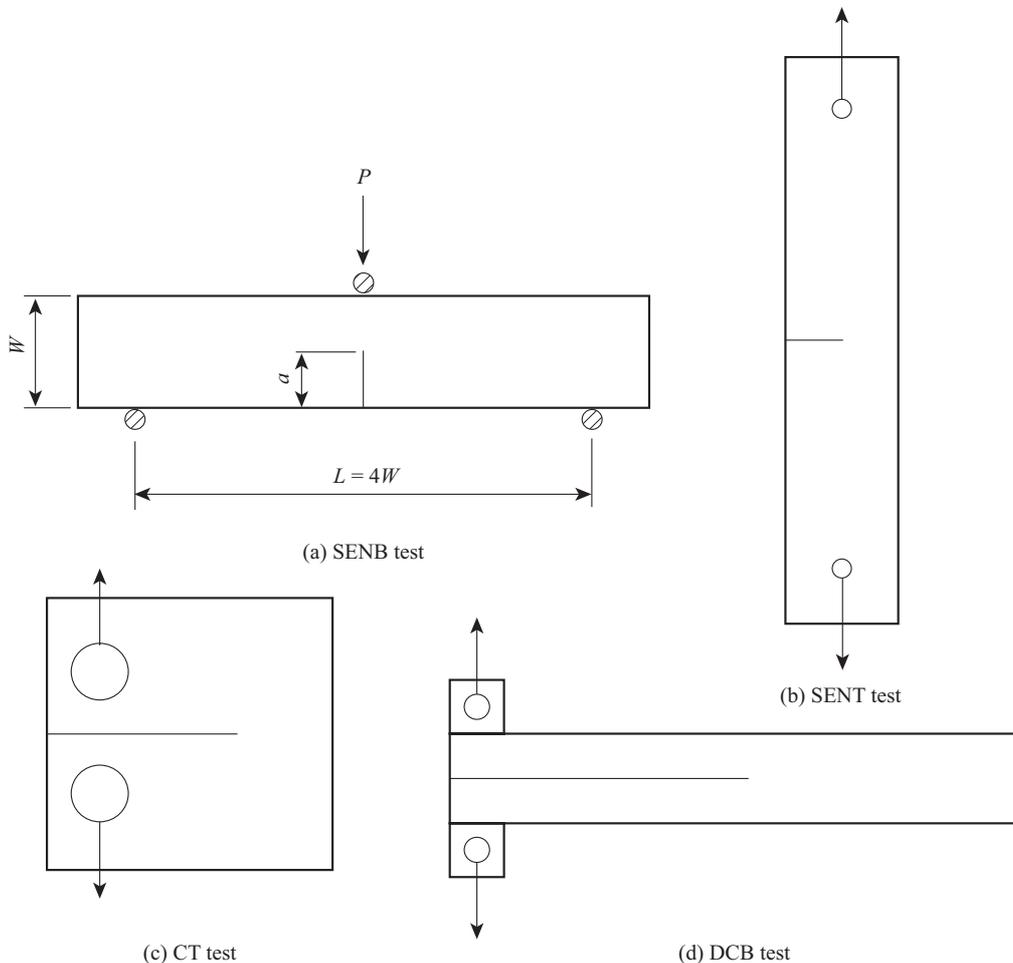

(a) SENB test

(b) SENT test

(c) CT test

(d) DCB test

Figure 1 Typical Mode I fracture tests
Slika 1. Tipični testovi loma drva I. moda

2.2 SENB tests
2.2. SENB testovi

Figure 1(a) shows the diagram of the SENB test. Two kinds of specimens were tested. Specimen A had dimensions of 20 × 90 × 15 mm³, while these dimensions were 40 × 180 × 15 mm³ in specimen B. The specimen depth *W* was 20 and 40 mm in specimens A and B, respectively. The crack was first cut with a band saw (thickness = 1 mm) and then extended 1 mm ahead of the crack tip with a razor blade. The crack length *a* varied from 1 to 18 mm at intervals of 1 mm in specimen A, and from 2 to 36 mm at intervals of 2 mm in specimen B. Thus, the value of *a/W* varied from 0.1 to 0.9 at intervals of 0.1. The specimen configurations were similar with those of SENB tests for western hemlock (Yoshihara, 2010a).

In the SENB test of western hemlock, the nonlinearity in the relationship between the load (*P*) and loading-line deflection (δ) was not significant until the initiation of crack propagation, so the critical load for crack propagation was determined as the maximum load (Yoshihara, 2010a). From the results of the SENT and CT tests of MDF in which the crack opening displacement (*COD*) was measured, the nonlinearity was marked in the *P-COD* relationship (Yoshihara, 2010b; Yoshihara and Usuki, 2011). Although the loading-line displacement in the SENB test is significantly larger than that in the SENT and CT tests, we thought that the measurement of the *COD* was effective to detect the nonlinearity and δ. To measure the *COD*, a clip gauge

extensometer (capacity = 5 mm; UB-5, Tokyo Sokki, Co., Tokyo, Japan) was used. The specimen was symmetrically supported and loaded at the mid-span. The span lengths (*L*) were 80 and 160 mm in specimens A and B, respectively, giving an *L/W* value of 4. A steel platen was placed between the specimen and the support to reduce indentation at the supporting point. The load *P* was applied at a crosshead speed of 0.5 mm/min[1] until the load markedly decreased. The total testing time was approximately 5 min.

Figure 2 shows typical *P-δ* and *P-COD* relationships obtained by the SENB tests. In the results for western hemlock, the crack often propagates unstably when the initial crack length is less than 0.3 times the depth of the specimen, whereas it propagates stably when the initial crack is longer than 0.4 times the depth (Yoshihara, 2010a). In the results of MDF, however, the crack always propagates stably all over the range of the initial crack length. In addition, the *P-δ* and *P-COD* relationships were significantly nonlinear before the load reached its maximum. Therefore, the critical load for crack propagation P_c was provisionally determined to be the load at the onset of nonlinearity. This was determined in the same manner as that used for the SENT and CT tests (Yoshihara, 2010b; Yoshihara and Usuki, 2011) and for the DCB tests described below.

Similar to the previous investigation (Yoshihara 2010a), the K_{Ic} value was initially evaluated using the following two equations, which were originally proposed by Gross and Srawley (1965) and Srawley (1976):

$$K_{Ic} = \frac{3 \cdot P_c \cdot L}{2 \cdot B \cdot W^2} \cdot \sqrt{\pi \cdot a} \cdot \left[1.09 - 1.735 \cdot \left(\frac{a}{W} \right) + 8.20 \cdot \left(\frac{a}{W} \right)^2 - 14.18 \cdot \left(\frac{a}{W} \right)^3 + 14.57 \cdot \left(\frac{a}{W} \right)^4 \right] \quad (1)$$

$$K_{Ic} = \frac{3 \cdot P_c \cdot L}{2 \cdot B \cdot W^2} \cdot \sqrt{\pi \cdot a} \cdot \left[\frac{1.99 - \left(\frac{a}{W} \right) \cdot \left(1 - \frac{a}{W} \right) \cdot \left[2.15 - 3.93 \cdot \left(\frac{a}{W} \right) + 2.7 \cdot \left(\frac{a}{W} \right)^2 \right]}{\sqrt{\pi} \cdot \left[1 + 2 \cdot \left(\frac{a}{W} \right) \right] \cdot \left[1 - \frac{a}{W} \right]^{\frac{3}{2}}} \right] \quad (2)$$
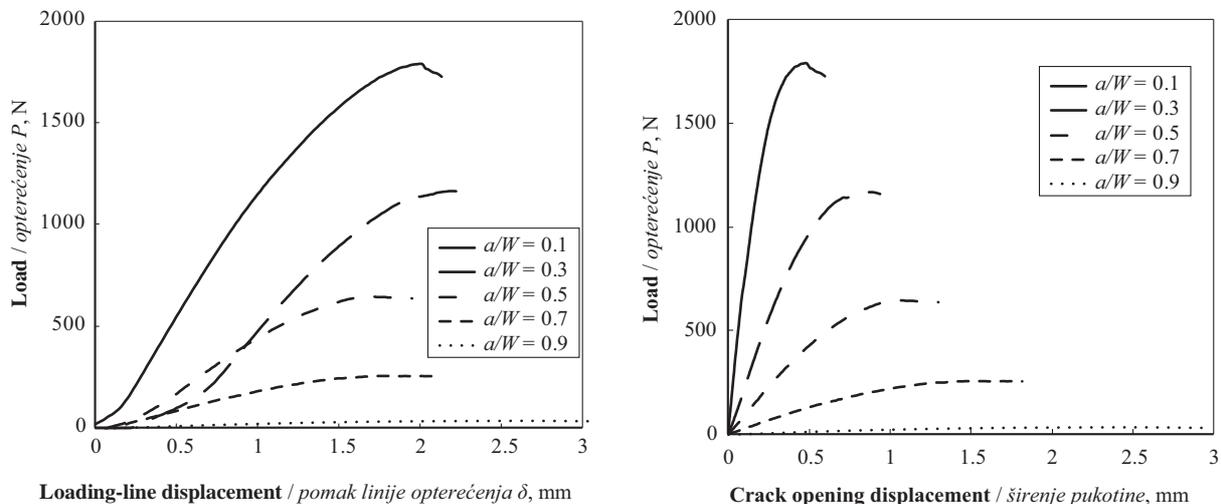
where *B* is the beam width.

Figure 2 Typical example of the relationship between load *P* and loading-line displacement δ and that between *P* and the crack opening displacement *COD* for various crack lengths *a* in SENB test. Depth of the specimen *W* = 40 mm
Slika 2. Tipičan primjer odnosa između opterećenja *P* i pomaka linije opterećenja δ te između opterećenja *P* i širenja pukotine *COD* za različite duljine pukotine *a* u SENB testu; debljina uzorka *W* = 40 mm

2.3 DCB tests
2.3. DCB test

The K_{Ic} value was measured by the DCB test using a side-grooved specimen independent of the SENB test, and it was compared with those obtained from the SENB test. The details of the DCB test were similar to those previously conducted (Yoshihara, 2010a, b).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Figure 3 shows the K_{Ic}-a/W relationships obtained from the SENB tests using Eqs. (1) and (2) and a comparison of these relationships with the results obtained by the DCB tests. A convex trend was identified in these relationships. This trend is different from that obtained by the SENB tests of western hemlock. That trend was almost constant in the a/W range of 0.1-0.7 and 0.1-0.9 when using Eqs. (1) and (2), respectively (Yoshihara, 2010a). The K_{Ic} value obtained from specimen A is larger than that from specimen B when comparing the same a/W value, except for a/W = 0.1, so the K_{Ic} values obtained from Eqs. (1) and (2) are regarded to be dependent on the specimen geometry. The point at the onset of nonlinearity, the load at which it was provisionally defined as the critical load for crack propagation P_c, could be found earlier in the *P-COD* relationship than in the *P-δ* relationship. Therefore, the K_{Ic} value obtained from the *P-COD* relationship is smaller than that obtained from the *P-δ* relationship.

Figure 3 suggests that the K_{Ic} values obtained using Eq. (1) and (2) are definitively smaller than that obtained by the DCB test because the development of a softened region ahead of the crack tip, such as fracture process zone (FPZ), is not taken into account in these equations. Due to the softened region, the cracked specimen often behaves as if the crack were longer than the actual length. Similar to the approach adopted in previous investigations (Yoshihara, 2010a, b; Yoshihara and Usuki, 2011), the relationship between K_{Ic} and a is modified by introducing an additional crack length Δ into Eqs. (1) and (2) as follows:
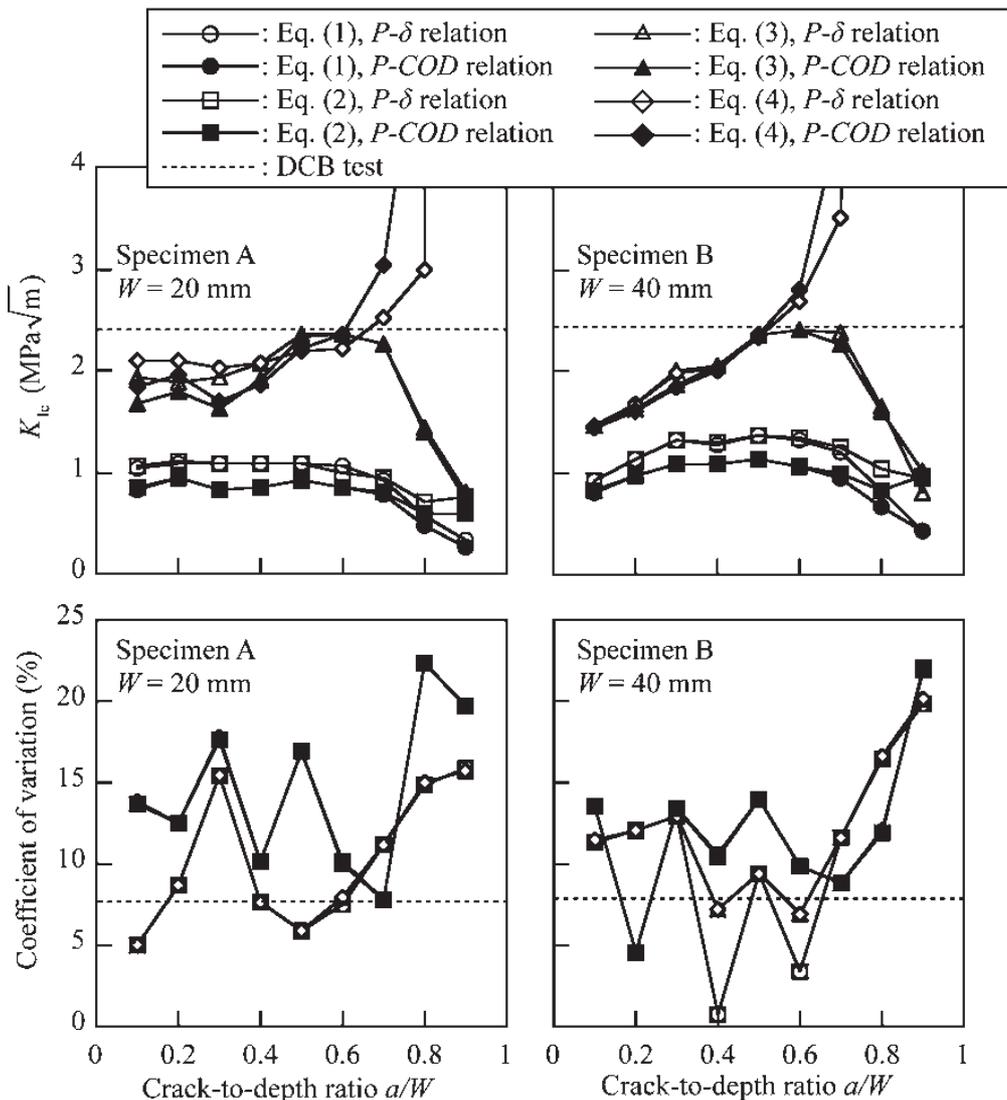

Figure 3 Comparison of the relationships between K_{Ic} and a/W obtained by SENB test and that obtained by DCB test
Slika 3. Usporedba odnosa između K_{Ic} i a/W dobivenoga SENB testom i DCB testom

$$K_{Ic} = \frac{3 \cdot P_c \cdot L}{2 \cdot B \cdot W^2} \cdot \sqrt{\pi \cdot (a+\Delta)} \cdot \left[1.09 - 1.735 \cdot \left(\frac{a+\Delta}{W}\right) + 8.20 \cdot \left(\frac{a+\Delta}{W}\right)^2 - 14.18 \cdot \left(\frac{a+\Delta}{W}\right)^3 + 14.57 \cdot \left(\frac{a+\Delta}{W}\right)^4\right] \quad (3)$$

and

$$K_{Ic} = \frac{3 \cdot P_c \cdot L}{2 \cdot B \cdot W^2} \cdot \sqrt{\pi \cdot (a+\Delta)} \left[\frac{1.99 - \left(\frac{a+\Delta}{W}\right) \cdot \left(1 - \frac{a+\Delta}{W}\right) \cdot \left[2.15 - 3.93 \cdot \left(\frac{a+\Delta}{W}\right) + 2.7 \cdot \left(\frac{a+\Delta}{W}\right)^2\right]}{\sqrt{\pi} \cdot \left[1 + 2 \cdot \left(\frac{a+\Delta}{W}\right)\right] \cdot \left[1 - \frac{a+\Delta}{W}\right]^{\frac{3}{2}}}\right] \quad (4)$$

The appropriate value of additional crack length Δ was determined from the following procedure, which was similar to those conducted in previous studies (Yoshihara, 2010a, b; Yoshihara and Usuki, 2011). By altering the value of Δ, the probability value (*p*-value) for the averages of *K*Ic obtained by the SENB test corresponding to each *a/W* and DCB test is calculated by Student's *t*-test. Then the *p*-values corresponding to each Δ are summed up. When the amount of the *p*-values is large, the average values of *K*Ic obtained by the SENB and DCB tests can be regarded as being close to each other. The Δ value was obtained by binary search algorithm as shown in Table 1. The Δ values listed in Table 1 are longer than those of western hemlock, which were 2 and 4 mm for specimen A and B, respectively (Yoshihara, 2010a).

Table 1 Additional crack length Δ derived by statistically comparing K_{Ic} values obtained from SENB and DCB tests (unit = mm)
Tablica 1. Dodatna duljina pukotine Δ dobivena statističkom usporedbom vrijednosti K_{Ic} ustanovljene SENB testom i DCB testom (jedinica mm)

W	Equation *Jednadžba*	Relationship / *Odnos*	
		P-δ	*P-COD*
20	(3)	4.1	4.8
20	(4)	4.2	5.7
40	(3)	6.1	7.9
40	(4)	5.9	7.6

The Δ value obtained from the *P-COD* relationship is larger than that obtained from the *P*-δ relationship. Figure 3 also shows the results calculated by Eqs. (3) and (4). The values of K_{Ic} obtained from Eq. (3) are close to those obtained by the DCB tests when *a/W* falls in the approximate range of 0.5 to 0.7. A statistical analysis of the difference between the K_{Ic} values obtained using the SENB and DCB tests shows that the difference is not significant in this *a/W* range, regardless of whether the P_c value is determined from the *P*-δ or *P-COD* relationship. This range coincides well with the range used to derive the appropriate K_{Ic} value in the SENT test (Yoshihara 2010b). When using Eq. (4), however, the applicable range of *a/W* is narrower than that obtained using Eq. (3). When the *a/W* value is smaller than 0.4, material nonlinearity precedes the crack propagation, so the load at the onset of nonlinearity in the *P*-δ and *P-COD* relationships P_c cannot be regarded as the critical load for crack propagation

(Yoshihara 2010b). Therefore, the K_{Ic} values for *a/W* values smaller than 0.4 were measured to be smaller than those in the *a/W* range from 0.5 to 0.7. In contrast, the value of K_{Ic} calculated from Eq. (3) decreases in the *a/W* range larger than 0.8, whereas that calculated from Eq. (4) diverges when *a/W* exceeds 0.8 because the value of $1 - (a+\Delta)/W$ contained in the equation is close to zero. Therefore, the K_{Ic}-*a/W* relationships obtained from Eqs. (3) and (4) are extremely different from each other when the value of *a/W* exceeds 0.8. Additionally, when the crack tip is close to the loading point, the compressive stresses due to the indentation of the loading nose hinder self-similar crack propagation (de Moura *et al*., 2010). From these reasons, the appropriate range for introducing the additional crack is restricted. From the results obtained here, the K_{Ic} value should be measured using Eq. (3) in the *a/W* range from 0.5 to 0.7.

In this research, the additional crack length Δ is determined by statistically comparing the K_{Ic} values obtained from the *P*-δ and *P-COD* relationships and that obtained by the DCB test. Therefore, the Δ value is dependent on the relationship used in the analysis, as shown in Table 1. Based on the concept of the FPZ, however, the value of Δ can be physically obtained (Vasic and Smith, 2002; Vasic *et al*., 2003; Morel *et al*., 2003; 2005; de Moura *et al*., 2008, 2010; Dourado *et al*., 2008, 2010). As shown in Figure 2, the K_{Ic} values obtained from both *P*-δ and *P-COD* relationships are similar to each other when correcting the crack length. Therefore, it is difficult to determine which relationship is more valid for determining the K_{Ic} value. Microscopic observation (Vasic and Smith, 2002; Vasic *et al*., 2003) and digital image correlation observation (Murata *et al*., 2011) around the crack tip during loading may be effective to reveal the validity of the relationships.

According to the research on the Mode II critical stress intensity factor K_{IIc} of wood and MDF as determined by an asymmetric four-point bending test, the K_{IIc} value can be obtained by introducing the additional crack length when *a/W* exceeds 0.8, when an appropriate equation is derived for the crack geometry factor (Yoshihara submitted). In the SENB tests of solid wood (Yoshihara, 2010a) and MDF, two previously proposed equations (Eqs. (1) and (2)) were used and modified by considering the additional crack length. Further research should be conducted to find a new equation that can derive the K_{Ic} value properly for the specimen with an *a/W* value larger than 0.8. In addition, the compressive stresses due to the indentation of the loading nose

can be reduced when conducting the four-point SENB (4SENB) test in which the loading-line deviates from the crack pass, and the range of *a/W* can be extended. Therefore, further research should also be conducted on the 4SENB test of MDF and solid wood.

4 CONCLUSIONS
4. ZAKLJUČAK

A single-edge-notched bending (SENB) test of MDF was conducted to obtain the Mode I critical stress intensity factor K_{Ic}. The test results were compared with those of the double cantilever beam (DCB) tests, an approach that is thought to be valid because the K_{Ic} value can be determined based on energy considerations.

The above results are interpreted to indicate that the critical stress intensity factor K_{Ic} in Mode I can be obtained effectively by introducing the additional crack length Δ as in Eq. (3) under the range of the crack length/specimen depth ratio *a/W* from 0.5 to 0.7. This range coincided well with that obtained in the single-edge-notched tension (SENT) tests of MDF Yoshihara, 2010b). To determine the value of K_{Ic} under a wide range of *a/W*, further research should be undertaken on issues such as additional crack lengths, other equations for determining the K_{Ic} value, and other test methods including the four-point SENB (4SENB) test.

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Corresponding address:

Professor HIROSHI YOSHIHARA, Ph.D.

Shimane University
Faculty of Science and Engineering
Nishikawazu-cho 1060
Matsue, Shimane 690-8504, JAPAN
e-mail: yosihara@riko.shimane-u.ac.jp