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Mode II fracture mechanics properties of solid wood measured by the three-point eccentric end-notched flexure test

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ABSTRACT

A three-point eccentric end-notched flexure test was conducted using specimens of western hemlock to determine the fracture mechanics properties under Mode II conditions while extending the crack length range for stabilising the crack propagation. The location of the loading point was varied during the test, and the effect of the loading point location on the initiation and propagation fracture toughness values was examined. With the proposed method, fracture mechanics properties were appropriately obtained at greater crack propagation lengths than in the conventional three-point end-notched flexure test when the loading point was not extremely close to the supporting point at the crack-free region.

1. Introduction

When a crack propagates in a fibrous material such as solid wood, the fracture toughness often increases as the crack length increases because of the existence of a fracture process zone (FPZ) ahead of the crack tip and fibre bridgings between the crack surfaces. Therefore, the fracture mechanics properties of fibrous materials including solid wood have often been evaluated by a resistance curve (*R*-curve) that is typically determined from the relationship between the fracture toughness and the crack length increment during the crack propagation. A three-point end-notched flexure (3ENF) test is a simple method for determining Mode II fracture mechanics properties such as the initiation fracture toughness and the *R*-curve. In recent conventional 3ENF tests where the load is applied to the mid-span, the fracture mechanics properties have been frequently mathematically defined according to beam theory [1–12]. When measuring the *R*-curve, however, the 3ENF test has a drawback in that the ratio of the initial crack length to the half span should be greater than 0.7 to stabilise the crack propagation. To obtain information on the fracture mechanics properties, it is desirable to obtain the *R*-curve by stabilising the crack propagation length over a wide range. Several methods such as stabilised end-notched flexure (SENF), end-loading shear (ELS), tapered end notched flexure (TENF), over-notched flexure (ONF), and four-point bend end-notched flexure (4ENF) tests have been used to stabilise crack propagation over a range wider than the 3ENF test [13–25]. Nevertheless, there are several disadvantages in these methods, even though they are effective at stabilising crack propagation. A SENF test requires a servo valve-controlled testing machine that is often complicated to control [13]. The testing data in an ELS test can often vary according to the clamping conditions [14,15]. The equation for deriving the fracture toughness in the TENF test is more complicated than that of a 3ENF test [16]. In an ONF test, the effect of the frictional forces between the crack

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Nomenclature

$2H$	depth of the specimen
$2L$	total span length
a	crack length
a_0	initial crack length
a_{eq}	equivalent crack length
a_{eq0}	initial value of equivalent crack length
a_{min}	minimum crack length for stabilising the crack propagation
B	crack/specimen width
c	distance between the loading point and supporting point at the cracked portion
C_L	load–deflection compliance
C_{L0}	initial load–deflection compliance
C_S	load-longitudinal strain compliance
E_x	Young's modulus in the longitudinal direction
E_y	Young's modulus in the tangential direction
F_x^j	nodal force at the crack tip in the x-direction
F_y^j	nodal force at the crack tip in the y-direction
G_{xy}	shear modulus in the longitudinal-tangential plane
G_I	Mode I energy release rate
G_{II}	Mode II energy release rate
G^{VCCT}	total energy release rate obtained from the VCCT
G_I^{VCCT}	Mode I energy release rate obtained from the VCCT
G_{II}^{VCCT}	Mode II energy release rate obtained from the VCCT
G_{IIc}	Mode II initiation fracture toughness
G_{IIR}	Mode II propagation fracture toughness
$\overline{G_{IIR}}$	representative value of the Mode II propagation fracture toughness
l_s	path length where the crack propagates stably
P	applied load
x	length direction of the specimen, which corresponds to the longitudinal direction of wood
y	traverse direction of the specimen, which corresponds to the tangential direction of wood
ν_{xy}	Poisson's ratio in the longitudinal-tangential plane
δ	deflection at the loading point
δ_x^i	relative crack face displacement between the nodes adjacent to the crack tip in the x-direction
δ_y^i	relative crack face displacement between the nodes adjacent to the crack tip in the y-direction
Δ	correction value of crack length calculated from the compliance combination method
$\Delta\alpha$	length in the x- and y-directions of the element at the delamination front
Δa_{eq}	equivalent propagation crack length
ε_x	longitudinal strain at the mid-point on the top surface of the cracked portion in the specimen
σ_{max}	maximum value of the bending stress in the specimen subjected to the 3EENF loading
3ENF	conventional three-point bend end-notched flexure
3EENF	three-point eccentric end-notched flexure
ERR	energy release rate
VCCT	virtual crack closure technique

surfaces is very significant and continuously increases the *R*-curve during crack propagation [17–19]. The 4ENF test may be superior to the aforementioned methods because of its simplicity and stability in crack propagation [14,20–25]. To apply a 4ENF test to solid wood, however, it is often difficult to let the crack propagate while preventing the specimen failure by bending at the loading point in the cracked portion without cutting deep grooves in both side-surfaces [23,24]. In fact, there are few examples of applying a 4ENF test to solid wood. It is more convenient to measure the *R*-curve over a wide range of propagation crack lengths through simple procedures such as equipment and specimen preparation. In a conventional 3ENF test in which the load is applied at the mid-span of the specimen, the range of the crack length enabling stable propagation is theoretically restricted from 0.35 to 0.5 times the span. This range can be easily extended without preparing any special equipment or specimens with a three-point eccentric end-notched flexure (3EENF) test, the details of which are demonstrated below.

This study conducted a 3EENF test on western hemlock specimens to obtain an *R*-curve, defined as the relationship between the propagation fracture toughness and the propagation crack length, was obtained. Based on the *R*-curve, Mode II initiation fracture toughness and represented value of the propagation fracture toughness, defined as the averaged value of the propagation fracture toughness at the plateau portion of the *R*-curve. The location of the loading point was