TECHNICAL NOTE: DUCTILITY AND BRITTLENESS IN SMALL CLEAR NOTCHED S-P-F BEAMS

R. Shmulsky†

Head and Warren S. Thompson Professor of Wood Science & Technology
E-mail: rs26@msstate.edu

*L. M. Spinelli Correa**

Graduate Research Assistant
Department of Sustainable Bioproducts
Mississippi State University
Mississippi State, MS 39762-9820
E-mail: ls2090@msstate.edu

R. J. Ross

Project Leader and Research Professor
Forest Service
E-mail: robert.j.ross@usda.gov

B. Farber

Research Associate II
Forest Products Laboratory and Mississippi State University
Madison, WI 53726-2398
E-mail: bf720@msstate.edu

(Received August 2019)

Abstract. Because wood has both brittle and ductile behaviors, the impact of stress concentration around notches is difficult to quantify. This research used the bending stiffness to strength ratio as a means of evaluating stress concentrations in the tension and compression faces of small clear spruce-pine-fir beams. The bending strength and stiffness behavior of wood and wood composites is of particular interest in ladder rails, laminated beams, and structural cross laminated timber, and other heavy timber construction. It was found that rectangular notches up to half of the beam depth located on the tension face reduced the bending strength by 10.5%. The drop in ductility, as measured by MOE/MOR, was significantly higher, up to 52%. Beams loaded with the notch on the compression face had no statistically significant change in the MOR; however, ductility dropped by as much as 30%.

Keywords: Notches, wood, beam, ductility, brittleness.

INTRODUCTION

The terms ductile and brittle are generally used to describe structural materials which yield before failing and fail before yielding, respectively. Malleable metals such as copper and steel are often described as ductile. Mild steel eg can be cold-drawn to about 25% elongation before failure. Ceramics, concrete, and mineral-based structural materials are typically described as brittle and they generally fail at relatively low strain levels (Horath 1995). Wood exhibits both ductile and brittle behaviors, and thereby varying theories exist regarding the significance of stress concentrations on the bending strength of wood. Stress concentrations are localized areas of increased stress which occur in structural materials wherever imperfections in the said material occur. Some examples of stress concentrations include portholes in ships, rivet holes in airplane construction, and adhesive junctions of dissimilar

* Corresponding author
† SWST member

Wood and Fiber Science, 52(2), 2020, pp. 230-236
https://doi.org/10.22382/wfs-2020-020

materials. These concentrations are caused by a physical disruption or discontinuity in the structural material and subsequent redistribution of stresses there about.

Traditional fracture mechanics theory (based on relatively brittle materials) indicates that large stress concentrations exist in wood beams at knots, notches, splits, corners, etc. (FPL 2010). To a large degree, structural composites develop relatively high design properties not by being stronger than solid wood but by randomly distributing the natural characteristics in wood about which stress concentrations may develop and thereby improving uniformity (Sasaki 1989). Another theory implies that because wood is basically a composite of elongated and oriented cells embedded in a lignin-rich matrix, it is highly resistant to stress concentrations (Gordon 1988), and thus, notches in beams are of little consequence. This theory goes back half a century and says that when a notch is at or near the center of the beam, the net minimum depth should be used for calculating the strength (Hanson 1948). Only minor differences are suggested for tensile- vs compression-face stress. Roughly 50 yr after that, one of the most telling descriptions for notched beams comes from Breyer et al: "The effect of a notch on the bending strength of a beam is not fully understood and convenient methods of analyzing the bending stress at a notch are not currently available…The problem is best handled by avoiding notches (Breyer et al 2015)." All of those are classic references, based on fundamental points which are constant through time.

Most recently, the 2018 International Residential Code for one- and two-family dwellings (International Code Council 2017) prescribed the requirements for cutting, drilling, and notching floor and wall systems. Considering floor systems using saw lumber, the instruction is that "notches shall not exceed one-sixth of the depth of the member, shall not be longer than one-third of the depth of the member, and shall not be located in the middle one-third of the span." In addition, "notches at the end of the member shall not exceed one-fourth the depth of the member." Regarding engineered wood products, notches are prohibited, unless the member capacity has been proved by product manufacturer or design professional. When it comes to wall studs, any stud in an exterior wall/bearing partition and nonbearing partition may be notched, as long as the notch depth does not meet more than 25% and 40% of stud width, respectively. Although these sources provide designers with some guidance toward using notched beams, they do little to fundamentally explain how wood beams respond to notches.

Another factor that may contribute to the behavior of notched structural members is that deflection or strain is focused at the notch. Because the notch has a necessarily smaller section depth as compared with the remainder of the beam, the strain is much more localized at the notch. When visualized, if one loads an ordinary meter stick like a long column, it bends or bows more or less uniformly along its length. If one takes a larger wood member and notches it such that the effective section modulus at midspan equals that of a meter stick and then loads it like a long column, it appears more like two relatively stiff pieces of wood with a hinge at the midspan.

To understand notched wood behavior and provide designers with guidance, many studies have been conducted in the last decades. For instance, de Moura et al (2006, 2018), Silva et al (2006), Arrese et al (2010), and Dourado et al (2015) have focused on mode I, II, and III failures. Valentin and Adjanohoun (1992), Smith and Vasic (2003), Coureau et al (2006), Sedighi-Gilani and Navi (2007), de Moura et al (2010), and Wang et al (2012) have concentrated their efforts in fracture and crack propagation. Henrici (1976), Jockwer et al (2014), and Dewey et al (2018) have studied notch design, shape, and position. Jockwer et al (2016) and Dewey et al (2019) have approached notched wood strength and stiffness; whereas Toussaint et al (2016) and Tran et al (2018) have made use of advanced computer modeling to investigate notched wood behavior.

However, a more practical method from the user's point of view would be to quantitatively compare the nature of deformation and strength of notched wood in tension vs compression, to compare the stiffness to strength ratios of each property. Regarding such ratios, lower numeric values correspond to more ductile materials, ie relatively high strength compared with stiffness. For example, Kevlar is a relatively tough fiber and has a stiffness to strength ratio of approximately 20. Cast iron, known to be brittle, has a ratio of approximately 550.

Using data from Kretschmann and Green (1996), the parallel-to-grain stiffness to strength (MOE: MOR) ratios in tension and compression for clear southern pine are 106 and 317, respectively. This 3-fold difference is primarily due to differences in MOR ie wood's stress–strain relationship is similar for both compression and tension parallel-to-grain. Wood is significantly stronger, however, in tension parallel-to-grain, which suggests that wood has better ductility characteristics in tension than in compression.

By comparison, in bending, the same two species of southern pine (loblolly and shortleaf) have an average stiffness to strength ratio of about 136 (FPL 2010), near that of wood stressed in tension parallel-to-grain. This comparison illustrates that the ultimate breaking strength of wood in bending is governed primarily by the stiffness to strength properties in tension which provide the highest strength and the highest ductility, although normal wood in bending virtually always fails initially in compression parallel-to-grain.

Qualitative failure modes for tension and compression seem, however, to be reversed. Typically, compression parallel-to-grain failure is viewed as ductile, manifesting itself as a crushing and folding of the lignocellulosic wood matrix. This failure precedes the seemingly more brittle catastrophic tension failure that is noted as the cellulose fibers fail under stress and release their stored energy. Thus, it is difficult to classify wood in only one or the other category (ductile vs brittle) because the quantitative and qualitative properties do not seem to agree. Parallel-vs perpendicular-to-grain strength differences in compression, shear, and tension further complicate classification.

For structural applications, beams that exhibit relatively ductile failure are generally safer because the strain deflection caused by overloading becomes apparent well before catastrophic failure. Fundamental information in this regard is necessary for safe and efficient design with both solid and new wood-based composite products and for the development of new wood-based composite architectures. Cross-laminated timber is one such example wherein the structural behavior around notches in panels may be important.

This research focused on using notched beams to investigate ductile and brittle performance in wood beams. Secondarily, it investigated the effect of notches on the performance of wood beams in a cursory manner.

MATERIALS AND METHODS

To better understand the brittle and ductile performance of wood, a comparison of beams with and without notches was carried out. Matched, clear, straight-grained beams were manufactured from a parent population of kiln-dried 38 × 140-mm (2 × 6 in.) spruce-pine-fir lumber. The candidate stock for the small clear beams was randomly matched. All beams, both notched and non-notched controls, had a maximum depth at point of loading of 19 mm and a constant width of 38.1 mm. Test beams were notched at midspan to induce stress concentration points near the location of maximum bending moment. Thirty beams of each type were manufactured and tested for a total of 150 beams. Both notched and control beams were destructively tested to failure. Notched beams were tested in both orientations ie with the notch upward on the compression face and downward on the tension face (Fig 1). Notches were 25 mm wide and of rectangular shape. This rectangular shape created an abrupt transition in the beam surfaces, and thus enhanced stress concentrations. At midspan, horizontal shear stress was the same for all beam types and thus was not considered a treatment factor.

All beams were center-point loaded at a rate of 2.5 mm per minute. To maintain a span to depth ratio of 14, all beams were tested across a 266-mm

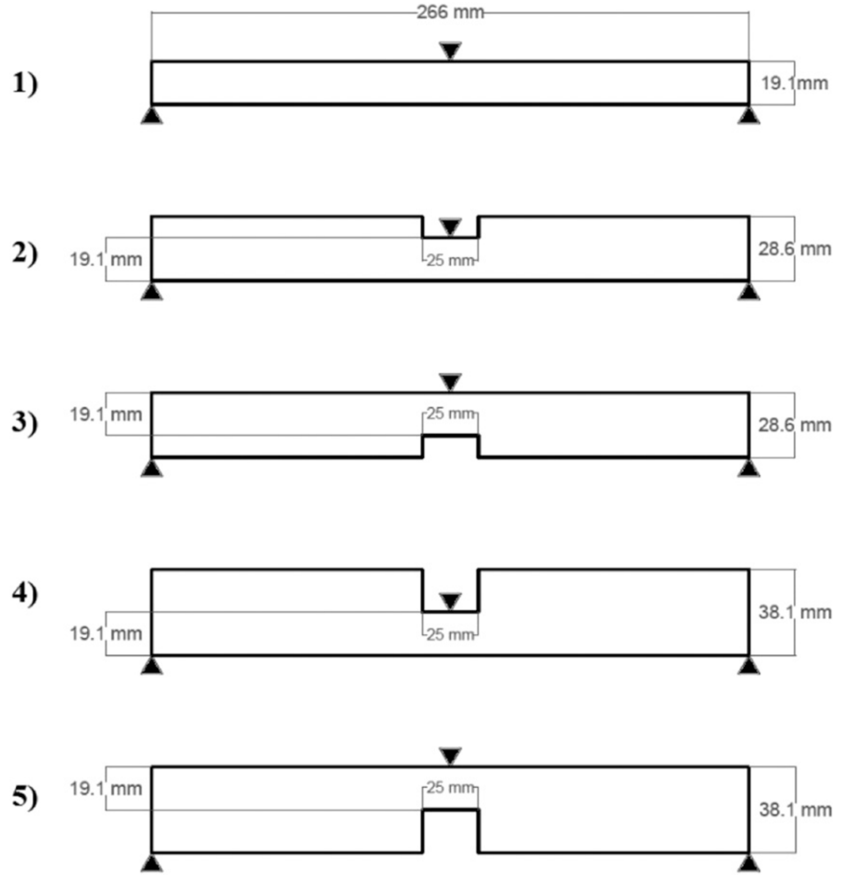

Figure 1. Depiction of the loading schemes on the five beam types. 1 is straight, 2 & 3 are notch to one-third beam depth, and 4 & 5 are notch to one-half beam depth. All beams had a constant width of 38.1 mm.

span. This span to depth ratio was determined as per ASTM (2017) D143. Table 1 shows the beam dimensions and loading schemes. MOR values for the beams were calculated by using MOR equation (flexure formula) and compared for notched and control beams.

MOR Equation (flexure formula):

$$\text{MOR (psi)} = M/Z.$$

Here,

M = maximum moment (pound inches) = $P \cdot l/4$
P = maximum load (pounds)
l = span (inches)
Z = section modulus (inch^3) = $b \cdot h^2/6$ (for a rectangular section where):
b = width of the beam (inches)
h = depth of the beam (inches) at midspan

Strength results were analyzed to address two objectives. First, to evaluate strength differences in notched vs straight control beams of equal minimum cross section. This subdivision of the analysis provided insight into wood's ability to dissipate stress concentrations and thus provide a qualitative indicator of ductility. Second, with regard to notched beams, the comparison of strength values for compression- vs tension-face beams provided data for contrasting wood's ductility/brittleness for tension to that for compression. The strength and stiffness were evaluated as completely randomized designs. The $\alpha = 0.05$

Table 1. Beam loading parameters.

Class	n	Maximum depth (mm)	Minimum depth (mm)	Depth ratio minimum:maximum	Beam type
1	30	19.1	19.1	1.00	Control
2	30	28.6	19.1	0.67	Comp. //@ notch
3	30	28.6	19.1	0.67	Tens. //@ notch
4	30	38.1	19.1	0.50	Comp. //@ notch
5	30	38.1	19.1	0.50	Tens. //@ notch

was used for statistical tests of significance. Significance was determined by one-way analysis of variance and mean separations were calculated by least significant difference analyses.

RESULTS AND DISCUSSION

No statistically significant interaction was found between loading scheme (controls, tension-notched, or compression-notched) and notch depth. As main effects, however, the loading scheme was statistically significant ($p = 0.0065$) and notch depth was not. Therefore, further analysis was conducted regarding the effect of loading scheme. With respect to MOR, there were statistically significant differences for the different loading schemes ($p = 0.0351$). In general, the straight control beams and those loaded with the notch in compression were not statistically different. Considering beams with notches on the tension side, Class 3 beams (those with 0.67 depth ratio) were significantly weaker than the control and the beams notched on the compression side. However, no statistical difference was seen between the two groups (Class 3 and 5) with notches under tension (Table 2).

Maximum deflection at time of failure was also evaluated. With regard to loading scheme, it was highly significant ($p < 0.0001$). Maximum center-point deflections are shown (Table 3). In general, the straight control beams deflected the most, whereas the beams loaded with the notches in tension deflected the least, again suggesting the lowest ductility.

To better discern the stiffness to strength relationships, an additional analysis was run which compared the ratio of MOE with MOR for each beam type and loading scheme, similar to the comparisons made in the *Introduction* section. Recall that lower stiffness to strength index values indicate greater deflection at the time of failure and better ductility. Differences in values were highly significant ($p < 0.0001$). Mean separation for this ratio is shown in Table 4. The control beams performed the best ie they exhibited the highest deflection at the time of failure. This result was expected because of the straight control beams' ability to strain more evenly along their length and the tendency of notched beams to concentrate bending strain at the notch.

With the deeper sections along most of their lengths, the notched beams had higher bending strain levels localized at the notches despite their lower total deflections. Generally, the beams with the notch loaded in tension parallel-to-grain deflected the least before full failure as noted by their relatively high stiffness to strength values

Table 2. Separation of average beam MOR values (MPa) by class.

Class	Average MOR
2	83.2 a
1	82.5 a
4	81.6 a
5	77.5 ab
3	73.7 b

Least significant difference is 6.90 MPa. Letters "a and b" indicate the statistical grouping. Averages with the same letter are not significantly different.

Table 3. Separation of average maximum deflection values (mm) by class.

Class	Average deflection
1	8.97 a
2	7.80 b
4	7.11 bc
5	6.78 cd
3	6.25 d

Least significant difference is 0.752 mm. Letters "a, b, c, and d" indicate the statistical grouping. Averages with the same letter are not significantly different.

Table 4. Separation of average MOE/MOR values by class.

Class	Average ratio
3	140.9 a
5	127.6 ab
4	121.0 cb
2	107.4 cd
1	92.7 d

Least significant difference is 15.5. Letters "a, b, c, and d" indicate the statistical grouping. Averages with the same letter are not significantly different.

(Table 4). Among these beams, tension perpendicular-to-grain failure (cleavage type splitting) was frequently noted at the notch's corners before full failure. This failure likely served to relieve localized strain at the point of maximum bending moment and, theoretically, should not have appreciably weakened the straight-grained beams.

CONCLUSIONS

Evidently, the wood was better able to dissipate stress concentrations for notches in compression parallel-to-grain better than for notched in tension parallel-to-grain, suggesting better ductility for wood in compression. This finding supports the old school of thought that notched beams may be analyzed as straight beams using their minimum cross section, provided that the notches are loaded in compression only. A reasonable explanation for this is found at the molecular level. The three-dimensional lignin matrix has the ability, to some extent, to deform under compression and shear stress (as found in the notches).

Regarding strength performance, all beams exhibited characteristics of both ductile and brittle materials. The notches had less of an effect on strength than would be predicted based on stress concentrations alone. This is evidenced by the lack of statistically significant differences between beams with notches of differing depths when the loading scheme was constant (either tension or compression). Whereas notches in these wood beams had some effect on strength, as noted by reductions of as much as 10.5%, the effect on ductility is perhaps equally important. Compared with un-notched straight controls, beams loaded with notches in tension had stiffness to strength ratios up to 52% higher (140.9 vs 92.7), indicating less deflection before failure, ie lower ductility.

To improve the safe and efficient design of composite wood products and structural design with all wood products, it is prudent to increase the incidence of ductile type failure. In that case, high levels of deflection can alert individuals that structures are overloaded before full failure occurs. This is largely the case with solid wood beams that are overloaded. In wood-based composites, internal voids can act as areas of stress concentration along with post-manufacture boring, routing, or other machining operations that remove significant amounts of wood. In addition to strength performance, it is prudent to consider ductility in the design, manufacture, and application of such products.

ACKNOWLEDGMENTS

This publication is a contribution of the Forest and Wildlife Research Center, Mississippi State University. This material is based on a work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, McIntire-Stennis project under accession number 1009735. This paper was approved as journal article SB971 of the Forest & Wildlife Research Center, Mississippi State University.

REFERENCES

Arrese A, Carbajal N, Vargas G, Mujika F (2010) A new method for determining mode II R-curve by the end-notched flexure test. Eng Fract Mech 77:51-70.

ASTM (2017) D143-14 standard test methods for small clear specimens of timber. American Society of Testing and Materials, Conshohocken, PA. 31 pp.

Breyer DE, Cobeen KE, Fridley KJ, Pollock DG (2015) Design of wood structures, ASD/LRFD, 7th edition. McGraw Hill, New York, NY. 976 pp.

Coureau JL, Gustafsson PJ, Persson K (2006) Elastic layer model for application to crack propagation problems in timber engineering. Wood Sci Technol 40:275-290.

de Moura MFSF, Dourado N, Morais J (2010) Crack equivalent based method applied to wood fracture characterization using the single edge notched-three point bending test. Eng Fract Mech 77:510-520.

de Moura MFSF, Silva MAL, de Morais AB, Morais JJL (2006) Equivalent crack based mode II fracture characterization of wood. Eng Fract Mech 73:978-993.

de Moura MFSF, Silva MAL, Morais JJL, Dourado N (2018) Mode II fracture characterization of wood using the four-point end-notched flexure (4ENF) test. Theor Appl Fract Mech 98:23-29.

Dewey J, Tuladhar R, Sivakugan N (2018) Review of design methods for round notched timber sections subjected to flexure and shear. J Build Eng 18:130-141.

Dewey J, Tuladhar R, Sivakugan N (2019) Experimental study on the performance of notched round timber sections. J Build Eng 25:100840.

Dourado N, de Moura MFSF, Morel S, Morais J (2015) Wood fracture characterization under mode I loading using the three-point-bending test. Experimental investigation of *Picea abies* L. Int J Fract 194:1-9.

FPL (2010) Wood handbook - Wood as an engineering material. Gen Tech Rep FPL-GTR-190. USDA For Serv Forest Products Laboratory, Madison, WI. 508 pp.

Gordon JE (1988) The new science of strong materials. Princeton University Press, Princeton, NJ. 287 pp.

Hanson HJ (1948) Timber engineers' handbook. J. Wiley & Sons, Ltd., New York, NY. 882 pp.

Henrici D (1976) Spannungsoptische untersuchung rechtwinkelig ausgeklinkter sowie lochbelasteter biegeträger. Holz als Roh Werkst 34:91-100.

Horath L (1995) Fundamentals of materials science for technologists. Prentice Hall, Englewood Cliffs, NJ. 550 pp.

International Code Council (2017) IRC: International residential code for one- and two-family dwellings. ICC. Country Club Hills, IL. 962 pp.

Jockwer R, Steiger R, Frangi A (2014) State-of-the-art review of approaches for the design of timber beams with notches. J Struct Eng 140(3):04013068.

Jockwer R, Steiger R, Frangi A, Serrano E (2016) Load-carrying capacity and failure modes of glulam beams with reinforced notches. Eur J Wood Wood Prod 74:481-482.

Kretschmann DE, Green DW (1996) Modeling moisture content-mechanical property relationships for clear southern pine. Wood Fiber Sci 28(3):320-337.

Sasaki H (1989) Laminated veneer lumber. Pages 163-165 *in* AP Schniewind, ed. Concise encyclopedia of wood & wood based materials. MIT Press, Cambridge, MA.

Sedighi-Gilani M, Navi P (2007) Micromechanical approach to wood fracture by three-dimensional mixed lattice-continuum model at fiber level. Wood Sci Technol 41: 619-634.

Silva MAL, de Moura MFSF, Morais JJL (2006) Numerical analysis of the ENF test for mode II wood fracture. Compos Part A Appl Sci Manuf 37:1334-1344.

Smith I, Vasic S (2003) Fracture behaviour of softwood. Mech Mater 35:803-815.

Toussaint E, Fournely E, Moutou Pitti R, Grédiac M (2016) Studying the mechanical behavior of notched wood beams using full-field measurements. Eng Struct 113:277-286.

Tran TB, Bastidas-Arteaga E, Aoues Y, Pambou Nziengui CF, Hamdi SE, Moutou Pitti R, Fournely E, Schoefs F, Chateauneuf A (2018) Reliability assessment and updating of notched timber components subjected to environmental and mechanical loading. Eng Struct 166:107-116.

Valentin G, Adjanohoun G (1992) Applicability of classical isotropic fracture mechanics specimens to wood crack propagation studies. Mater Struct 25:3-13.

Wang VZ, Ginger JD, Narayan K (2012) Intralaminar and interlaminar fracture characterization in glued-laminated timber members using image analysis. Eng Fract Mech 82: 73-84.