J Wood Sci (2013) 59:389–395
DOI 10.1007/s10086-013-1346-2

ORIGINAL ARTICLE

Behavior of center-bored round timber beams in center-point bending test

Jinah Lim · Jung-Kwon Oh · Hwanmyeong Yeo · Jun-Jae Lee

Received: 21 December 2012 / Accepted: 22 April 2013 / Published online: 23 May 2013

Abstract Due to the lack of large cross-section wood, the concern regarding the utilization of small-diameter logs from forest thinning has increased as a worldwide issue recently. Round shape is advantageous to efficient use of small-diameter logs, there is a difficulty of drying and preservative treatment. It is necessary to apply a new technique. In this study, center-boring technology was applied to improve the efficiency of manufacturing. The effect of a hole was not expected to make a significant effect on the flexural performance because the hole is located at the centroid of beam under bending moment. Unlike a round timber beam, the failure of center-bored round timber beam starts with a crack and is followed by a longitudinal split. When designing center-bored round timber as guardrail beam, additional strength reduction by flattening should be considered.

Keywords Round timber · Center-bored timber · Ultimate load · MOR · Cross-sectional flattening

Introduction

The concern regarding the utilization of small-diameter logs from forest thinning has increased as an issue of worldwide recently due to the lack of large cross-section wood resource and increased demand of wood and wood products. Korea also does not have enough large cross-section wood resource and approximately 87 % of logs are less than 180 mm in diameter [1]. The small-diameter logs are chipped for the panel and paper industry, used as firewood or not even collected from the forest site. To utilize the small-diameter logs, various wood products have been developed such as massive walls of cabin and other leisure buildings, piles, and poles [2, 3], but more products need to be developed that provide additional opportunities.

A possible application is wooden guardrail beam that utilizes small logs. Although steel W-beam guardrail and steel post are widely used currently, wood can be a great material for the guardrail because of the ability of the carbon sink and beauty. Wooden post and steel W-beam guardrail have been developed and already used [4–6]. Zhang et al. [7] developed another wooden guardrail system which consists of cedar round timber beam and concrete post. Guardrail beam is an important road facility to save a life. The guardrail beams should satisfy the requirements of structural performance. One of the requirements is that the guardrail beam should have enough strength to withstand the force of vehicle impact.

As well as the structural performance, the production efficiency should be carefully considered to develop the wooden guardrail system. Wolfe and Moseley [3] and Wolfe and Murphy [8] suggested that round cross-section timber produces less waste than rectangular cross-section timber and increases production yield. On the basis of section properties, the round shape has a two- to larger bending load capacity than rectangular shape that could be sawn from log [8]. Additionally, round timbers are not susceptible to the strength-reducing effects of grain angle and knots due to the section geometry and the tree physiology [9–13].

J. Lim
Department of Forest Sciences, Seoul National University, Seoul, Korea

J.-K. Oh · H. Yeo · J.-J. Lee (✉)
Department of Forest Sciences, Research Institute for Agriculture and Life Sciences, Seoul National University, Seoul, Korea
e-mail: junjae@snu.ac.kr

Although products with a round shape give benefits of better production yield, they were rarely used structurally because of little information available to provide a basis for the round timber structural element in applications efficiently. Also, round timber does not dry as quickly as sawn lumber and high temperatures used to accelerate drying could cause structural problems as well as physical degrade. The presence of surface checks on round timber may reduce structural performance, such as holding power of fasteners. Also, it can decrease their appearance quality. It is because drying round cross-section timber is difficult to obtain uniform moisture profile and surface quality [14, 15]. Besides, the preservative treatment of round timber is not easy.

To facilitate drying and the preservative treatment of round timber, Evans et al. [14] and Yeo et al. [16] suggested using a center-boring technique which makes hole passing through one end to the other end in the timber. They reported that center-boring can reduce both the moisture gradient and drying stress from core to surface, thus reducing the number and overall size of drying checks, and allowing for quick drying. In addition, the decreased weight by removing the core section may provide benefits in structural design and filed work. Yeo et al. [16] reported that the center-boring did not make significant difference in maximum compression load parallel to the grain because of a uniform quality and removal of weak part such as juvenile wood. He mentioned that the center-boring technique can give a benefit in energy consumption without loss of structural performance. To improve production efficiency, the center-bored round timber was chosen as the guardrail beam in this study.

The ultimate goal of this study was to develop wooden guardrail system using small-diameter logs. The aim of present study was to investigate the performance of the bending members and to determine the effects of the center-bored hole.

Materials and methods

Materials

Thirty-eight pitch pine (*Pinus rigida* Mill.) trees were randomly selected from plantation forest and 103 logs were obtained. The logs were sorted by end-diameter in order to produce maximum yield when it is manufactured. The logs were debarked and then processed into five different sizes of round timber, 100 mm (R100), 120 mm (R120), 140 mm (R140), 160 mm (R160), and 180 mm (R180) in diameter by a rounding machine. The round timbers were stacked at room temperature for 6 months to be air-dried. After a flexural test, the moisture content (MC) was measured by the oven-dry method. The final moisture content was consistently around 18.9 %.

An additional 68 logs were prepared to make center-bored round timber. After debarking, the logs were center-bored to a hole depth of 1.5 m at one end and then another center-boring process was performed at the other end, because the drill could bore only a 2-m deep hole. The inner hole diameters (D_i) were 85 and 105 mm. After center-bored processing, the logs were made into round shapes by the rounding machine with outer diameter (D_o) 140 and 160 mm (Fig. 1). Center-bored specimens were kiln-dried and the final moisture content was below 15 %. There was no surface and end check in all specimens.

Finally, four groups of 17 pieces of center-bored round timer and 97 pieces of round timber without center-boring were prepared (Table 1). All of the specimens were trimmed into 2.4 m in length.

Experimental procedures

To utilize the center-bored round timber as guardrail beam, car crash test must be carried out. Because of its cost and time, AASHTO [17] provide a guideline to

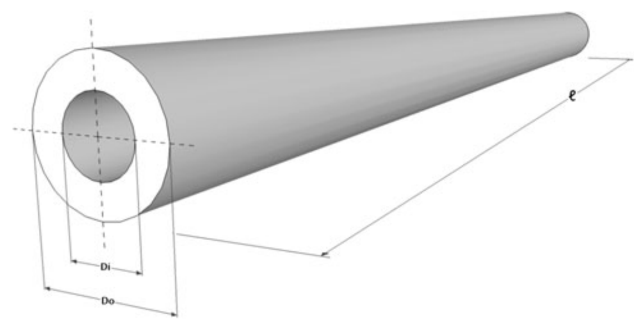

Fig. 1 A center-bored round timber beam (D_o outer diameter (mm), D_i inner diameter (mm), l specimen length)

Table 1 Specimens of round and center-bored round timber beam

Specimen	Specimens size (mm)			Number of specimens
	D_o	D_i	l	
Round timber (R)				
R100	100	–	2,400	18
R120	120	–		45
R140	140	–		23
R160	160	–		9
R180	180	–		8
Center-bored round timber (CB)				
CB140-85	140	85	2,400	17
CB140-105	140	105		17
CB160-85	160	85		17
CB160-105	160	105		17

D_o outer diameter of timber beams, D_i inner diameter of timber beams, l length of specimen describe the requirement of guardrail beam. Forces which must resist under static loading on simple support according to the level of guardrail are tabulated in this guideline. Therefore, center-point loading on simple support was used to evaluate the capacity of center-bored round timber. The test span was 2 m and specimens were tested by a Universal Testing Machine (Zwick, max load 10 ton) at a loading rate of 15 mm/min. Since the timber beams were circular-shaped in the cross section, V-shaped and custom-made steel saddles were placed between the specimen and the end supports to avoid lateral movements.

The modulus of rupture (MOR) for each specimen was calculated according to the following Eq. (1) [18];

$$\mathrm{MOR} = \frac{Mc}{I} \tag{1}$$

where, M is the bending moment (kN m), I is the moment of inertia (m^4), and c is the distance from the neutral axis to the surface (mm).

For the round and center-bored round timber, the moment of inertia in Eqs. (2) and (3) was calculated by the following:

$$I = \frac{\pi\left(D_\mathrm{o}^4\right)}{64} \quad \text{(round timber)} \tag{2}$$

$$I = \frac{\pi\left(D_\mathrm{o}^4 - D_\mathrm{i}^4\right)}{64} \quad \text{(center-bored round timber)} \tag{3}$$

where, D_o is the outer diameter and D_i is the inner diameter.

After the flexural test, specimens for moisture content and specific gravity (SG) were obtained near the failure location of each specimen in both round and center-bored round timber beams. MC and SG were calculated by dimension method [19, 20].

From each round timber, a disk was taken to evaluate the area ratio of juvenile wood in the cross section. The juvenile wood was defined as the 20 annual rings counted outward from the pith [8, 21].

Results and discussion

Flexural performance of round timbers

Five diameter groups of round timber were prepared from 100 to 180 mm with 20 mm interval. The flexural tests were performed for the round timbers. Table 2 shows the mean MOR value for each diameter groups. In case of R180 group, the load carrying capacity was beyond the maximum limit of the testing machine. Therefore, the MOR of R180 is the value calculated by the maximum applicable force of testing machine and the MOR must be higher than the value in Table 2. Because the timber beams were similar in size and number of defects, similar strength properties was expected; however, larger than 160 mm diameter groups (R160 and R180) showed higher MOR than smaller groups and the MOR tends to increase with the increase of its diameter (Fig. 2). Besides, actual MOR of R180 must be higher than the value in Table 2. The R160 showed approximately 20 % greater MOR than the R140 specimen. The Analysis of Variance (ANOVA) test showed that there is significant difference in MOR between R140 and R160 at the 95 % significant level. Based on fundamental theory on timber strength, size effect, the bigger timber is supposed to show lower strength. Larson et al. [22] reported that the apparent size effect may be weakened as the ratio of juvenile wood increases. Green et al. [15], Ranta-Maunus [13], Wolfe and Moseley [3] and Wolfe and Murphy [8] also obtained similar results to Larson's study. The test result of this study may support the explanation of the previous studies that the ratio of juvenile wood weakens the size effect.

Around 87 % of logs from Korean forest have smaller than 180 mm diameter. Most of these logs come from silvicultural thinning process. These logs contain large amount of juvenile wood because the originating trees are young. The round timber from those logs must have large fraction of juvenile wood. After the flexural test, a disk

Table 2 The flexural properties of round timber beams

Specimen	Ultimate loads (kN)	MOR (MPa)		Specific gravity		Juvenile wood[a] (%)
		Mean	COV	Mean	COV	Mean
R100	9.3	47.2	0.20	0.46	0.11	100.0
R120	16.5	48.6	0.22	0.46	0.03	100.0
R140	27.2	49.8	0.27	0.47	0.09	91.3
R160	49.1	61.0	0.13	0.51	0.09	78.1
R180	Exceed[b]	85.5[c]	–	–	–	–

[a] Percentage of juvenile wood area in the cross section. The 20 annual rings outward from the pith were regarded as juvenile wood (Voorhies and Jameson [21]; Wolfe and Moseley [3])

[b] The load-carrying capacity was beyond the maximum limit of the testing machine

[c] The MOR of R180 is the value calculated by the maximum limit of testing machine

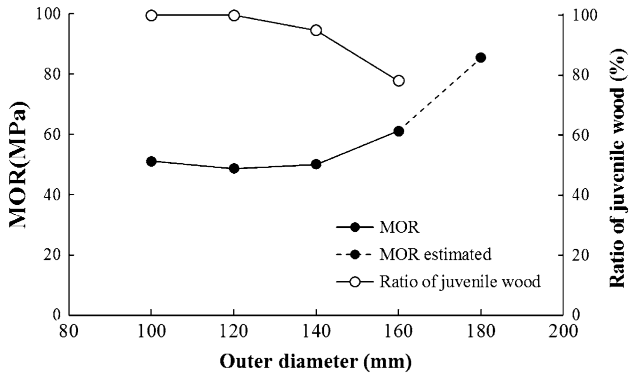

Fig. 2 The mean MORs and juvenile wood ratio of round timber groups according to the outer diameter

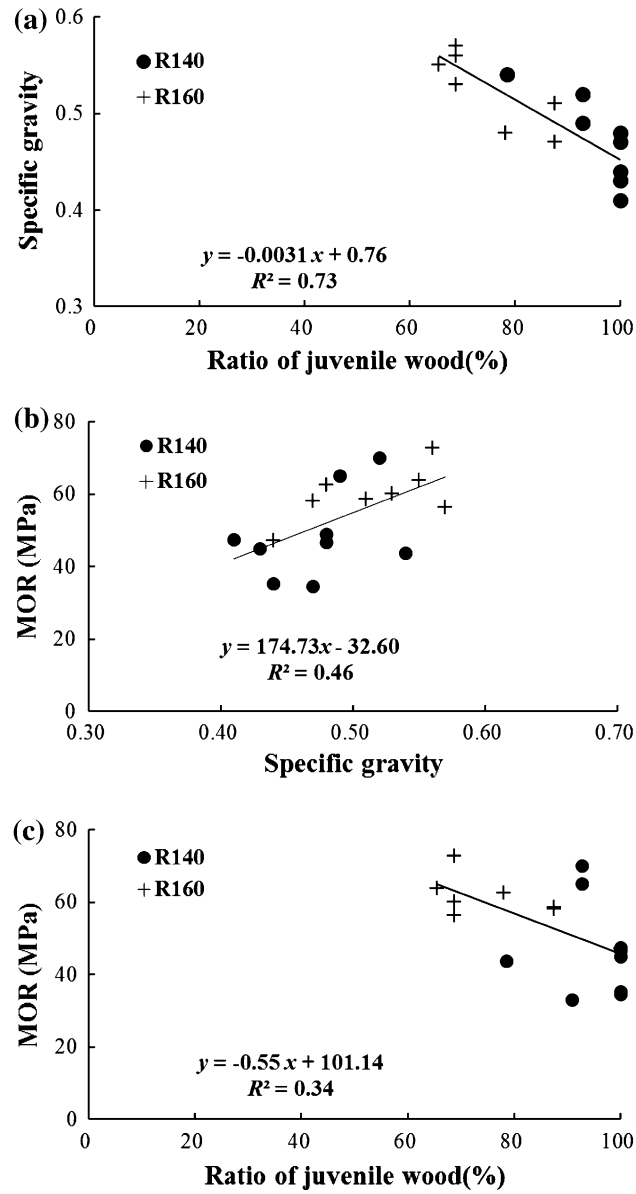

Fig. 3 MOR, specific gravity and ratio of juvenile wood for round timber specimens R140 and R160; **a** specific gravity and ratio of juvenile wood, **b** MOR and specific gravity, **c** MOR and ratio of juvenile wood

was obtained from each specimen near the failure location. The specific gravity and the rate of juvenile wood were measured from the disk. The specific gravity of all groups was similar to each other except R160. The specific gravity of the R160 showed around 8.5 % higher value than other groups (Table 2). Specific gravity (or density) is one of the properties to affect the timber performance. As Fig. 3a shows, this lower specific gravity seems to be caused by its larger ratio of juvenile wood. The ratios of juvenile wood in the round timbers with R160 and R140 were 78.1 and 95.0 %, respectively, and other groups have 100 % ratio of juvenile wood (Table 2). It is well known that the strength and specific gravity decrease with the increase of juvenile wood [11, 15, 21]. As Fig. 3b, c shows, the MOR was related to the specific gravity. Also it showed relationship with ratio of juvenile wood.

Generally, knots and slope of grain are regarded as the most important strength-reducing defects in dimension lumber. However, Green et al. [15] reported that strength of round timber is not sensitive to such strength-reducing defects. In this study, the knots and slope of grain were also measured to investigate the effect of them on strength but its effect was not significant. Instead, the test results of this study indicated that the specific gravity of round timber and the ratio of juvenile wood are important properties to affect round timber strength. In case of small round timber like R100, R120, and R140, the ratio of juvenile wood is almost 100 %. Their flexural performance was much lower than R160 and R180 round timber, because R160 and R180 has mature wood in circumferences. In other viewpoint, this means that the inner part of R160 and R180 round timber has relatively low-strength property. Besides, when considering stress distribution in bending, the center part of beam less contributes to the flexural performance of round timber.

The effect of center-boring on the flexural behavior

The inner part of round timber with 160 and 180 mm diameter contributes less to the flexural performance because of this low-strength property and less stress in bending moment. Therefore, the center-boring technique was not expected to reduce the performance of the beam especially, 160 mm diameter logs.

Yeo et al. [16] and Kim [23] reported that there was no significant difference in maximum compression load of center-bored timber. Besides, Yeo et al. [16] stated that the

Table 3 The flexural properties of center-bored round timber beams

Specimen	Ultimate load (kN)		MOR (MPa)		
	As-measured	Difference[a]	Mean	COV	Difference[a]
CB140-85	18.9	−30.5 % (8.3)	43.8	0.27	−12.0 % (6.0)
CB140-105	10.4	−61.8 % (16.8)	33.3	0.24	−33.1 % (16.5)
CB160-85	33.3	−32.2 % (15.8)	48.8	0.22	−20.0 % (12.2)
CB160-105	24.4	−50.3 % (24.7)	42.3	0.21	−30.7 % (18.7)

[a] Mean difference from the round timber with same outer diameter (D_o)

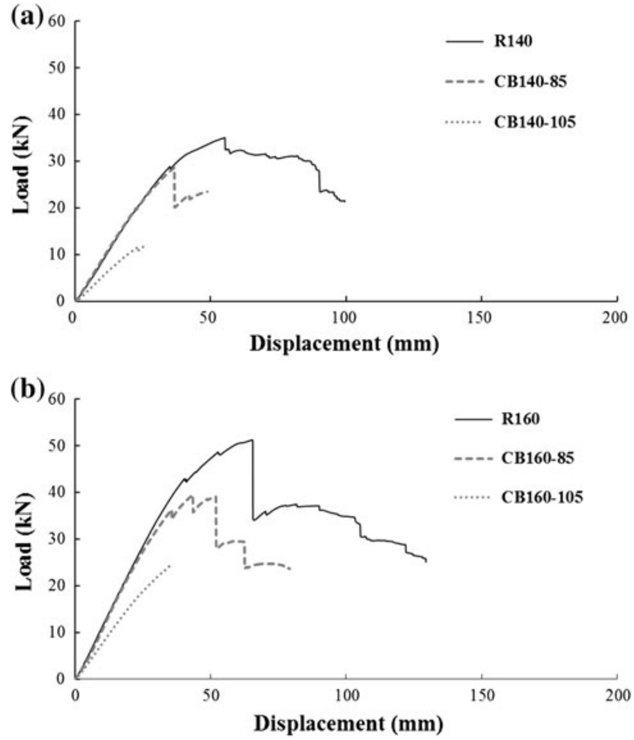

Fig. 4 Load–displacement curve for round and center-bored round timber beams; **a** outer diameter 140 mm, **b** outer diameter 160 mm

center-bored timber showed even higher compressive strength than the solid timber with the same outer diameter because of subsequently a more overall uniform quality and removal of weak part such as juvenile wood. The hole in the center-bored beam is located near the neutral axis and the removed part is mostly weak juvenile wood. Theoretically, the influence of the center hole on flexural performance is minimal like the previous research on compressive performance.

To investigate how many the center-boring makes effects on the bending performance of center-bored beam, 4 types of center-bored round timber beam were tested and the results were compared with the round timber. However, ultimate load of the center-bored round timber beam was much lower than the round timber with the same outer diameter (Table 3). The loss of cross section by center-boring may reduce the flexural performance. Therefore, MOR was calculated with the section modulus of the tube-shape cross section. Because this MOR has already considered the cross section loss, the MOR of center-bored round timber beam was expected to be very close to the round timber. However, the test on center-bored beam showed much lower MOR than the round timber with corresponding outer diameter. The load–displacement curve of the round and center-bored round timber beam is shown in Fig. 4. The existence of inner radius affects the load carrying capacity.

The MORs of center-bored timber specimens, CB140-85 and CB140-105, were 88.0 and 66.9 % of the corresponding R140 round timber, respectively. The MORs of CB160-85 and CB160-105 were 74.1 and 65.6 % of the corresponding R160 specimen. The ANOVA showed the inner hole made a significant effect at the 95 % significance level. Based on this comparison, it was concluded that the inner hole may negatively affect the flexural performance and MOR. This means that the center-bored round timber beam cannot be designed only by changing the moment of inertia from a circular shape into a tube shape.

To find the reason why the inner hole made the timber lose more load capacity than expected, the failure mode was investigated. The beginning of fracture occurred when the discontinuity of the fibers during the rounding process and the circumference of the knots in the tension side. The shear failure was not observed. Wolfe and Moseley [3] and Wolfe and Murphy [8] also reported the similar failure mode in round timber beam. However, center-bored round timber beams failed in different failure mode. A cross-sectional flattening occurred right below the loading block of center-point bending test as Fig. 5 shows. A crack started in the loading direction from inner hole to outer surface. Two inward cracks were also occurred at the outer surface as Fig. 5a, b. With the increase of load, the cracks became wider and deeper until they developed to the end (Fig. 5c). After this flattening, the center-bored round timber beams collapsed. There was no localized buckling of fibers on the compression side.

Wood is anisotropic material and wood has very low tension strength in perpendicular to the grain direction. The flexural load causes bending moment which consists of tension and compression stress. At the same time the local compressive stress below loading block squeezes the

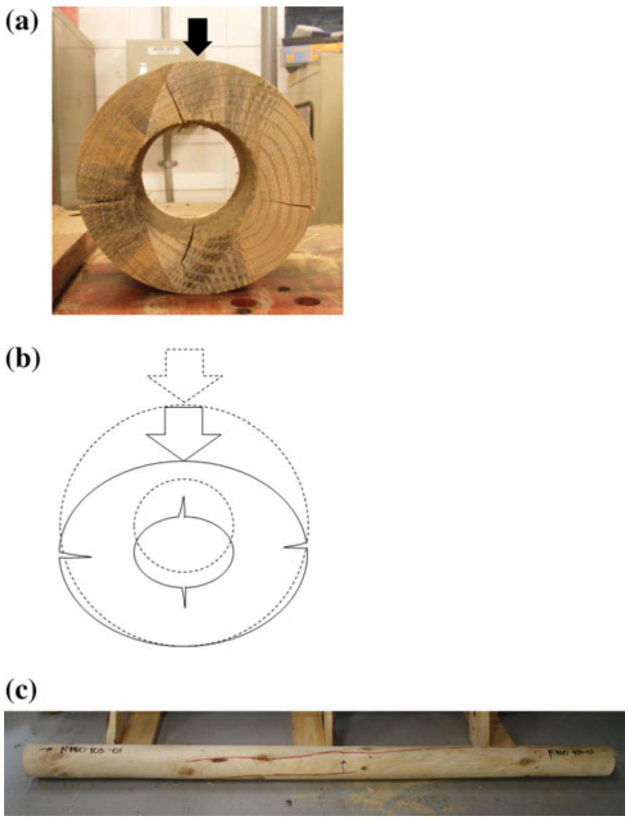

Fig. 5 The failure mode for center-bored round timber beams; **a** cross-sectional flattening, **b** cross-section drawing of flattening failure, **c** longitudinal cracks as the result from cross-sectional flattening

tube-shape center-bored round timber like rubber tube. The squeezing force caused tension stress in perpendicular to the grain at the outer surface and inner surface of the cross section. As a result, the center-bored round timbers were flattened and collapsed. This flattening failure mode is well known in steel pipe design. Under center-point bending stress, a pointing load forms plastic hinges in the steel pipe which are separated by a 90° angle at the circumference. Because of the plastic hinges, the stress pipe can be flattened. In a tree with a hole inside due to decay, a similar failure mode was observed [24–26]. A tree splinters longitudinally at theses points into at least four pieces [25, 27]. The center-bored round timber specimens in this study collapsed similarly as a tress with an inner hole.

Impact load acts with a single blow impact in a quite a few cases i.e. highway guardrail, decking in harbors and railway ties. Therefore, short span (2 m) and a center point loading were chosen as test set-up. This test set-up was not typical test method for flexural performance. Under typical loading condition for building material, four-point loading test is commonly used.

Unlike initial expectation, the center-bored round timber resisted much lower load under the center-point flexural test. This low load carrying capacity could be explained flattening failure mode of center-bored round timber distinguishing the solid round timber failure. This flattening failure is not caused by bending moment; therefore, the results of this study do not indicate that the flexural performance of center-bored round timber is much lower than solid timber. Actually, this failure was caused by compressive stress perpendicular to the grain, not by bending moment. The center-bored round timber needs to be designed with consideration of the flattening failure mode and the inner hole size needs to be optimized to use this center-bored round timber as a structural beam. As a guardrail member, the center-bored round timber beam will be loaded by a single-point force which will be induced by vehicle impact. Therefore, the flattening failure would be more important factor in guardrail beam design.

Conclusions

The ultimate goal of this study was to develop wooden guardrail using small-diameter logs. As a first step to achieve this ultimate goal, this study aimed at finding factors that affect load carrying capacity of center-bored guardrail beam under center-point load.

To investigate the effect of outer diameter on flexural performance, center-point bending tests were performed on the round timbers without center-hole. The flexural performance tends to increase with the increase of diameter. This could be explained by the ratio of juvenile wood. In case of smaller round timber (R100, R120 and R140), juvenile wood occupies most of all cross section. However, larger round timber (R160 and R180) has some mature wood in circumference. This tendency indicates that the inner part around the pith has lower strength than the part in circumstance. When considering the stress distribution under bending moment, the inner part of round timber seems to less contribute the flexural performance.

Round timbers with 140 and 160 mm diameter were bored at the center of the cross section from one end to the other. The flexural performance of center-bored round timber was expected not to show large differences from the round timber with corresponding outer diameter. However, it showed much lower load-carrying capacity than round timber. The center-bored round timber failed by flattening mode. Because this failure was caused by compressive stress perpendicular to the timber length, it was concluded that the design of center-bored round timber guardrail beam requires additional design calculation on the flattening failure.

Acknowledgments This study was supported by a Forest Science and Technology grant (Project No. S120810L70120) funded by the Korea Forest Service.

References

1. KFS (2011) Comprehensive plan for wood industry. Korea Forest Service, Seoul
2. Wolfe R (2000) Research challenges for structural use of small-diameter round timbers. For Prod J 50(2):21–29
3. Wolfe R, Moseley C (2000) Small-diameter log evaluation for value-added structural applications. For Prod J 50(10):48–58
4. Bligh RP, Alberson D, Butler BG (1995) Applications of recycled materials in roadside safety devices. Texas Transportation Institute, Texas A&M University System, Austin
5. Leijten AJM (2001) Impact crash and simulation of timber beams. Wessex Institute of Technology, Southampton
6. Bligh R, Bullard D (1995) Crash testing and evaluation of round, wood post, W-beam guardrail system. Research Report 405391-1F, Texas Transportation Institute, Texas A&M University, College Station, Texas
7. Zhang R, Kanemaru K, Nakazawa T, Iimura Y, Nakamura M (2004) Timber guardrail combined of round log rails and concrete posts. In: Ranta-Maunus A, Toratti T (eds) 8th World Conference on Timber Engineering. Finnish Association of Civil Engineering, VTT Technical Research Centre of Finland, Wood Focus, Lahti, pp 271–276
8. Wolfe R, Murphy J (2005) Strength of small-diameter round and tapered bending members. For Prod J 55(3):50–55
9. Cerda G, Wolfe RW (2003) Bending strength of Chilean radiata pine poles. For Prod J 53(4):61–65
10. Green DW, Gorman TM, Evans JW, Murphy JF (2006) Mechanical grading of round timber beams. J Mater Civ Eng 18(1):1–10
11. Evans JW, Senft JF, Green DW (2000) Juvenile wood effect in red alder: analysis of physical and mechanical data to delineate juvenile and mature wood zones. For Prod J 50(7/8):75–87
12. Larson D, Mirth R, Wolfe R (2004) Evaluation of small-diameter ponderosa pine logs in bending. For Prod J 54(12):52–58
13. Ranta-Maunus A (1999) Round small-diameter timber for construction. Final report of project FAIR CT95-0091
14. Evans PD, Wingate-Hill R, Barry SC (2000) The effects of different kerfing and center-boring treatments on the checking of ACQ treated pine posts exposed to the weather. For Prod J 50(2):59–64
15. Green DW, Gorman TM, Evans JW, Murphy JF, Hatfield CA (2008) Grading and properties of small-diameter Douglas-fir and ponderosa pine tapered logs. For Prod J 58(11):33–41
16. Yeo HM, Eom CD, Smith WB, Shim KB, Han Y, Park JH, Lee DS, Le HW, Park MJ, Park JS, Lee NH (2007) Effects of center boring and kerf treatment on kiln-drying of larch square and round timbers. For Prod J 57(11):85–92
17. AASHTO (2005) Bridge design specifications. American Association of State Highway and Transportation Officials, Washington, DC
18. ASTM (2005) D198 standard test methods of static tests of lumber in structural sizes. American Society for Testing and Materials, West Conshohocken
19. ASTM (1992) D4442 standard test methods for direct moisture content measurement of wood and wood-base materials. American Society for Testing and Materials, West Conshohocken
20. ASTM (2007) D2395 standard test methods for specific gravity of wood and wood-based materials. American Society for Testing and Materials, West Conshohocken
21. Voorhies G, Jameson D (1969) Fiber length in southwestern young-growth ponderosa pine. For Prod J 19(5):52–55
22. Larson D, Mirth R, Wolfe R (2004) Evaluation of small-diameter ponderosa pine logs in bending. For Prod 54(12):52–58
23. Kim GC (2010) A study on the compressive strength of the improved skin-timber. Mokchae Konghak 38(4):282–291
24. Mattheck C, Breloer H (1994) The body language of trees: a handbook for failure analysis. HMSO Publications Centre, London
25. Mattheck C, Bethge K, Tesari I (2006) Shear effects on failure of hollow trees. Trees-Struct Funct 20(3):329–333
26. Piao C, Shupe TF, Hse CY (2004) Mechanical properties of small-scale wood laminated composite poles. Wood Fiber Sci 36(4):536–546
27. Prinja N, Chitkara N (1984) Post-collapse cross-sectional flattening of thick pipes in plastic bending. Nucl Eng Des 83(1): 113–121