Original

Bending Quality of Main Korean Wood Species*[1]

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(Received May 31, 2002)

Abstract——The aim of this study was to evaluate the bending quality for ten kinds of main Korean wood species and to investigate the effect of the metal strap thickness on the bending quality of Korean red pine.

Bitter wood (*Picrasma quassioides*), horn beam (*Carpinus laxiflora*), birch (*Betula schmidtii*), painted maple (*Acer mono*) and cork oak (*Quercus variabilis*) showed excellent quality. Sargent cherry (*Prunus sargentii*), Korean red pine (*Pinus densiflora*) and pitch pine (*Pinus rigida*) showed intermediate quality. Basswood (*Tilia amurensis*) and royal paulownia (*Paulownia tomentosa*) showed worse quality. The density of wood species was the main factor to determine the bending quality.

As for the relationships between annual ring orientation and metal strap thickness, the bending quality of specimens with intermediate annual ring orientations was better than that of flat-grained specimens in the strap thickness of 1.0 mm and 0.8 mm, while the reverse result was obtained in the strap thickness of 0.6 mm and 0.4 mm. These findings suggested that it was important to determine the appropriate strap thickness in relation to wood species, thickness of specimens, form radii and annual ring orientations in specimens.

Keywords : bending quality, Korean wood species, radius of curvature, strap, annual ring orientation

1. Introduction

In the middle of the 19th century, an effective technique for wood bending based on steam pretreatment was established. This technique was introduced to many countries all over the world and it is still widely used to obtain various curved parts of furniture, musical instruments, barrels, interior decorations and so on.

When a wood piece is bent, the convex side of the bend is stretched while the concave side of the bend is compressed[1)]. The wood piece softened by steaming can be compressed considerably, but it can be stretched very little[2)]. By fixing the wood piece on a metal strap in such a way that the strap supports the tensile stress, it can be bent to a great extent. This technique is called the Thonet-method.

The bending quality (BQ) of wood, however, varies widely not only among the different species but also within the same species[3,4)]. Considerable kinds of temperate hardwoods have good BQ, while most of coniferous woods and tropical hardwoods are generally unsuitable for wood bending. Although the BQ depends greatly on wood species, it relates somewhat to the extent of softening of the cell walls and loading modes. Wood is strong and brittle in dry condition, but the moistening and heating of wood decrease its stiffness and increase its breaking strain, which results in an increase of the BQ. In transverse direction, the compression occurs easily by the transverse crushing of the honeycomb-like cell structure, while in longitudinal direction, the majority of the cell walls are stressed along their length and the mechanism of their deformation may depend greatly on the extent of softening.

In this paper, the BQ of main Korean wood species is evaluated and the effect of the strap thickness on the BQ of Korean red pine is investigated.

2. Materials and Methods

2.1 Bending quality of main Korean wood species

The bending quality of ten kinds of main Korean wood species were estimated. They were sargent cherry (*Prunus sargentii*), bitter wood (*Picrasma quassioides*), horn beam (*Carpinus laxiflora*), cork oak (*Quercus variabilis*), birch (*Betula schmidtii*), painted maple (*Acer mono*), basswood (*Tilia amurensis*), red pine (*Pinus densiflora*), pitch pine (*Pinus rigida*) and royal paulownia (*Paulownia tomentosa*). Table 1 shows diameters at the breath height, tree ages and moisture contents in air dry condition for logs from which specimens for the wood bending were prepared. The dimension of specimens was 10 mm (R) by 20 mm (T) by 300, 350 or 450 mm (L). Jigs made of a strap (carbon steel, thickness (t) : 0.6 mm and 0.8 mm) with wood handles at both ends as well as wooden forms were used in the bending operation. Radii of forms (ρ) were 40, 60 mm and 100 mm. The number of specimens subjected to the bending operation per each species, each form radius and each strap thickness were eight. After water-saturated specimens were heated with microwaves for 90 seconds up to about 100°C, they were subjected to the bending operation. After the operation, specimens were

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Table 1. Diameters at the breath height (DBH), tree ages (TA), moisture contents in air dry condition (MC) and the array of pores (PA, DP: diffuse-porous wood, RP: ring-porous wood) for logs of ten kinds of Korean species from which specimens for the wood bending were prepared.

Species	sargent cherry	bitter wood	horn beam	birch	painted maple	cork oak	basswood	red pine	pitch pine	royal paulownia
DHB (mm)	250	180	200	180	170	230	240	200	350	180
Age (year)	40	40	20	45	50	35	35	40	25	10
MC (%)	15	18	20	17	18	20	17	16	13	11
PA	DPW	RPW	DPW	DPW	DPW	RPW	DPW	—	—	DPW

clamped and dried for two hours at 80°C. The BQ of bent specimens was grouped into three grades according to the extent of damage occurred on the concave side; that is, A grade: without any damage, B grade: with slight damage removable by sanding, C grade: with severe damage unsuitable for wood bending. Most curved parts and members of wood products can be produced using specimens of A or B grade. The BQ of specimens was evaluated for results of each species, each form radius and each strap thickness.

2.2 Effect of strap thickness and annual ring orientation

To investigate the effect of strap thickness and annual ring orientation on the BQ, specimens of Korean red pine with the dimension of 330 mm (L) by 10 mm (R) by 20 mm (T) were used. Before the bending operation, modulus of elasticity (MOE) values of specimens were determined by the static bending test (cross-head speed=2 mm/min) using a universal testing machine. After MOE measurements, all specimens were saturated with water under vacuum (180% moisture contents (MC)) and then subjected to the bending operation. Strap thicknesses were 0.4, 0.6, 0.8 mm and 1.0 mm, and form radii were 70 mm and 90 mm. The number of specimens per each strap thickness and each annual ring orientation was eight. Bent specimens were dried under restraint in an oven at 90°C for five hours to fix the deformation and then conditioned at 20°C and 65% RH for about two weeks.

2.3 Measurement of radius of curvature

Fig. 1 shows a schematic diagram of the bent specimen[4]. The radius of curvature (ρ) and the compressive strain (ε) on the concave surface of the bent specimen are calculated by following equations.

$$\rho=\frac{a^2+b^2}{2b},\quad \varepsilon=\frac{L-L_0}{L_0}\times 100,\quad L=2\rho\cdot\sin^{-1}\left(\frac{a}{\rho}\right),$$

where L_0 is the segmental length of the specimen before bending and L is that on the concave surface of the specimen after bending.

3. Results and Discussion

3.1 Bending quality of main Korean wood species

Results of the bending operation are shown in Table 2. Results showed distinctly that the BQ of specimens depended remarkably on wood species as had been reported. Horn beam, birch, painted maple and cork oak, which are temperate hardwoods with a high density, had especially good BQ. Percentages of the number of specimens grouped into A or B grade for sargent cherry, cork oak, basswood, royal paulownia, which are temperate hardwoods, were 58, 83, 29% and 8%, respectively. All specimens of basswood and royal paulownia could not be bent to ρ=40 mm. On the other hand, percentages of specimens of red pine and pitch pine, which are coniferous woods, were 44% and 56%, respectively. Results of the BQ evaluation in regard to each radius of curvature and

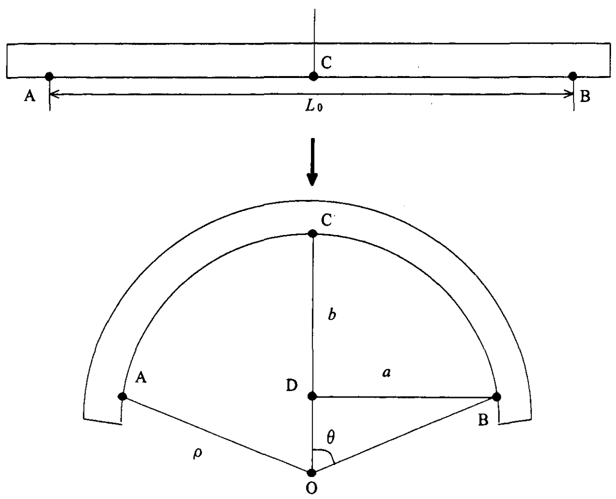

Fig. 1. A shematic diagram of the bent specimen. L_0; Distance of line AB before bending, L; Distance of line AB after bending, a; Distance of line BD, b; Distance of line CD, ρ; Radius of curvature, line AO or BO, line CO.

Table 2. The evaluation of the bening quality (A : no damage, B : slight damage, C : severe damage) at the indicated strap thickness (t) and form radius (ρ) and percentage of the number of specimens (A+B) to the total number of specimens (A+B+C) for ten kinds of main Korean wood species.

Species	t (mm)	Grade A ρ (mm)			B ρ (mm)			C ρ (mm)			100 (A+B)/(A+B+C) (%)	
		40	60	100	40	60	100	40	60	100	Each	Average
sargent cherry	0.6	1	0	2	4	2	4	3	6	2	54.1	58.3
	0.8	1	4	5	3	1	1	4	3	2	52.5	
bitter wood	0.6	5	4	6	3	4	2	—	—	—	100	100
	0.8	7	7	7	1	1	1	—	—	—	100	
horn beam	0.6	8	8	8	—	—	—	—	—	—	100	100
	0.8	8	8	8	—	—	—	—	—	—	100	
birch	0.6	8	8	8	—	—	—	—	—	—	100	100
	0.8	8	8	8	—	—	—	—	—	—	100	
painted maple	0.6	8	8	8	—	—	—	—	—	—	100	100
	0.8	8	8	8	—	—	—	—	—	—	100	
cork oak	0.6	4	5	7	0	2	1	4	1	0	79.2	83.3
	0.8	3	5	8	3	2	0	2	1	0	87.5	
basswood	0.6	0	1	1	0	1	6	8	6	1	37.5	29.2
	0.8	0	0	2	0	0	3	8	8	3	20.8	
red pine	0.6	0	1	7	1	3	0	7	4	1	50.0	43.8
	0.8	0	0	4	2	3	0	6	5	4	37.5	
pitch pine	0.6	2	3	6	1	2	0	5	3	2	58.3	56.3
	0.8	2	5	3	3	0	0	3	3	5	54.2	
royal paulownia	0.6	0	0	0	0	1	0	8	7	8	4.2	8.4
	0.8	0	0	0	0	1	2	8	7	6	12.4	

Table 3. The evaluation of the bending quality (○ : excellent, no damage, △ : good, slight damage, × : worse, severe damage) at the indicated radius (ρ) and strap thickness (t) for the kinds Korean wood species.

ρ (mm)	t (mm) 0.6					0.8					
40	○	△	×	×	×	○	△	△	×	×	×
60	○	△	△	×	×	○	○	△	△	×	×
100	○	○	○	○	×	○	○	△	△	△	×
Species	A, B, C, D, E, F	I	H	G	J	B, C, D, E, F	A	I	H	G	J

A : sargent cherry, B : bitter wood, C : horn beam, D : cork oak, E : birch, F : painted maple, G : basswood, H : red pine, I : pitch pine, J : royal paulownia.

each strap thickness for main Korean species examined are shown in Table 3. Open circles (○) and open triangles (△) represent that the indicated wood species could be bent to the prescribed radii of curvature without any damage and with slight damage, respectively, while crosses (×) represent that the indicated species could not be bent to the prescribed radii of curvature. The effect of strap thickness on the BQ was not so significant. However, it is considered that the strap thickness may be related to the drying speed after the bending operation, the thinner the strap thickness is, the faster the drying speed becomes. Table 4 shows the relationship between the BQ and

Table 4. The relationship between the evaluation of the bending quality (○ : excellent, no damage, △ : good, slight damage, × : worse, severe damage) and densities at the indicated form radius (ρ) and strap thickness (t).

t (mm)	ρ (mm)	Density (kg/m^3) 240	380	470	530	630		700	730	880	930
0.6	40	×	×	×	△	○	○	○	○	○	○
	60	×	×	△	△	○	○	○	○	○	○
	100	×	○	○	○	○	○	○	○	○	○
0.8	40	×	×	×	△	△	○	○	○	○	○
	60	×	×	△	△	○	○	○	○	○	○
	100	×	△	△	△	○	○	○	○	○	○
Species		J	G	H	I	A	B	F	C	D	E

A : sargent cherry, B : bitter wood, C : horn beam, D : cork oak, E : birch, F : painted maple, G : basswood, H : red pine, I : pitch pine, J : royal paulownia.

Table 5. The number of specimens (A or B (A+B+C)) at the indicated strap thickness (t) and form radius (ρ) for flat-grained specimens and specimens with intermediate annual ring orientation of Korean red pine.

Grain t (mm)	Flat-grain ρ (mm)		Intermediate annual ring orientation ρ (mm)	
	70	90	70	90
0.4	2	2	0	4
0.6	2	2	0	2
0.8	0	2	4	2
1.0	0	2	2	4

A: excellent, no damage, B: good, slight damage, C: fail, severe damage.

Table 6. Compressive strain of bent specimens grouped into excellent (A) and good (B) grades and moduli of elasticity in air dry condition (MOE) at the indicated strap thickness (t) and form radius (ρ) for flat-grained specimens and specimens with intermediate annual ring orientations of Korean red pine.

Grain t (mm)	Flat-grain ρ (mm)		Intermediate annual ring orientation ρ (mm)	
	70	90	70	90
0.4	14.0	10.7	—	9.4
0.6	12.5	9.6	—	9.4
0.8	—	10.4	12.3	10.4
1.0	—	9.3	12.2	10.0
MOE (MPa)	5.6	5.0	3.3	4.4

densities of wood species in air-dried condition. Results indicated that the BQ of Korean wood species depended significantly on the density. Densities of bitter wood, painted maple, horn beam, cork oak and birch which were grouped into A grade were larger than 600 kg/m^3.

3.2 Effect of strap thickness and annual ring orientation

The relationship between the BQ and the strap thickness for Korean red pine is shown in Table 5. In radii of $\rho=70$ and 90 mm, the significant difference in the BQ was not recognized except in the case of $t=0.4$ mm. So and Chai[5] investigated the wood bending of black locust using microwave heating to produce curved parts of furniture and classified the BQ into four grades, 1) without failure, 2) minor compressive failure on the concave side, 3) remarkable failure, 4) broken. In this study, however, the BQ was grouped into three grades, because such damage as breakage did not occur in the concave side of all bent specimens. Table 5 shows the bending quality of Korean red pine as a function of strap thickness. It is considered that specimens of Korean red pine belonging to A or B grade can be used for materials of the wood bending. Under the same experimental conditions, the BQ was better in the strap of $t=1.0$ mm than in $t=0.4$ mm. It seems that there are no significant differences in results of the BQ for flat-grained specimens and specimens with intermediate annual ring orientations. However, a careful examination showed that the BQ of specimens with intermediate annual ring orientations was slightly better than that of flat-grained specimens in straps of $t=1.0$ mm and 0.4 mm. Both flat-grained specimens and specimens with intermediate annual ring orientations could be bent without any damage in the strap of $t=0.6$ mm. Interlocked-grain was observed on the concave surface of some specimens with bad BQ. These results suggested that the annual ring orientation in specimens is one of important factors to improve the yield rate of wood bending. Table 6 shows compressive strains of bent specimens grouped into A and B grades. Since the BQ of flat grained specimens bent using straps of $t=0.8$ mm and 1.0 mm and that of specimens with intermediate annual ring orientations bent using straps of $t=0.4$ mm and 0.6mm were grouped into C grade in the case of the form radius of $\rho=70$ mm, results of compressive strains were eliminated from Table 6. These results suggested that the appropriate selection of the strap thickness according to the annual ring orientation in specimens was very important to improve the yield rate of wood bending.

4. Conclusions

In this paper, the bending quality for ten kinds of main Korean wood species was evaluated and the effect of the metal strap thickness on the bending quality for Korean red pine was investigated. The following results were obtained.

1) Bitter wood, horn beam, birch, painted maple and cork oak showed excellent quality. Sergent cherry, red pine and pitch pine showed intermediate quality. Basswood and royal paulownia showed worse quality.

2) The density of wood species was the main factor to determine the bending quality and wood species with a density larger than 600 kg/m^3 showed excellent quality.

3) The bending quality of red pine specimens with intermediate annual ring orientations was better than that of flat-grained specimens in the case of metal straps of 1.0 mm and 0.8 mm, while the reverse results were obtained in the case of metal straps of 0.6 mm and 0.4 mm.

4) The appropriate thickness of straps in relation to wood species, thickness of specimens, radii of curvature of forms and annual ring orientations in specimens was

important to improve the yield rate of wood bending.

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