Is the branch of Viburnum odoratissimum var. awabuki reaction wood? Unusual eccentric growth and various distributions of growth strain

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Unusual eccentric growth and various distributions of growth strain

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Abstract

For *Viburnum odoratissimum* var. *awabuki*, a pronounced growth promotion was observed on the lower side of the branches, which is a special case in angiosperms. To study the biomechanics of *V. odoratissimum* branch, we measured the growth strain (GS) in the standing tree based on a cumulative method and a direct method. GSs showed various distribution patterns: for some branches, the values on both sides corresponded to a tensile growth stress typical of normal wood, sometimes a high tensile GS was found in the upper side similar to tension wood, and for other branches, the values on the lower side corresponded to a compressive growth stress. At most measuring positions, a relatively larger growth stress was observed on the upper side of the branches opposite to eccentric growth, which is unusual in angiosperms. To investigate the effect of eccentric growth on the mechanical properties of the branch wood, we measured basic density (BD), microfibril angle (MFA), elastic modulus (E_L) and the creep deformation of the samples cut from the upper and lower sides of the branch. BD of the lower-side wood was relatively larger, but the influence of BD on the creep deformation was weak. Although MFA was different between the trees, E_L of the lower-side wood was larger that that of the upper-side wood, meaning that MFA does not play an important role in the mechanical properties of the branch wood. Moreover, the creep compliance curves showed that the upper-side wood had a low elasticity and a high fluidity whereas the lower-side wood had a large elasticity and a low fluidity. These results mean that the stable growth of the branches in *V. odoratissimum* should has a unique mechanism different from that in reaction wood.

Keywords: Growth stress, microfibril angle, creep compliance, reaction wood

Introduction

In trees, the pith may be located eccentrically in the trunk or the branch because the stem deviates from the vertical position or because of an uneven distribution of loading on a branch. Generally, most woody angiosperms show a pronounced growth promotion on the upper side of the leaning stems and branches, whereas growth eccentricity occurs on the lower side in gymnosperms. This phenomenon of eccentric growth is usually associated with the formation of reaction wood (Tsoumis 1991). However, growth eccentricity on the lower side in angiosperms has occasionally been reported. For example, Onaka (1949) and Yoshizawa (1993) observed that *Buxus microphylla* exhibits a pronounced growth promotion on the lower side of the inclined stem and that its xylem has some anatomical features similar to those of compression wood. Kucera and Philipson(1977, 1978) have reported that growth eccentricity of *Pseudowintera colorata* occurs on the lower side of the inclined branch and that the lower-side tracheids have a large microfibril angle, but *P. colorata* develops neither tension wood nor compression wood.

We recently found that the inclined branches of *Viburnum odoratissimum* var. *awabuki* have a pronounced growth promotion on the lower side. Compared with other special cases (*B. microphylla* and *P. colorata*), *V. odoratissimum* has no anatomical feature similar to that in reaction wood, and the anatomical features of the xylem do not differ obviously between the upper and lower sides of the branches (Wang et al. 2009). However, the information about the growth stress and the mechanical property of the inclined branch for *V. odoratissimum*, is few. Therefore, in this study, to understand the effects of unusual eccentric growth on branch biomechanics, we measured the growth eccentricity and the released surfaces growth strain (GS) in the trunk and the inclined branches of three *V. odoratissimum* trees, and examined some mechanical properties of the branch wood.

Materials and methods

Plant material

Three 12-year-old trees (I, II and III) of *V. odoratissimum* grown in Uji campus (130^{o}82' E, 34^{o}81' N~130^{o}80' E, 34^{o}81' N), Kyoto University, Japan were studied. The trees were about 6m high with several branches in various orientations.

Growth strain measurement

Measurements were made twice in September 2007 and December 2008. There were two measuring positions (no.1 and 2) in the trunk and each branch. Position no.1 was about 30 cm from the base of the branch to avoid the influence of growth stress around the joint. The distance between no.1 and no.2 was at least 5 times greater than the diameter of the branch. After removing the bark at the measuring position, electrical resistance strain gauges (FLA-5-11-5LT, Tokyo Sokki Kenkyujo Co., Ltd, Japan) were glued with cyanoacrylate adhesive to the xylem in the longitudinal direction on the trunk and the upper and lower sides of the branches. Measurements were made with a portable digital strain meter (TDS500, Tokyo Sokki Kenkyujo Co., Ltd, Japan) with an 80-channel scanner.

At the first time, we used a cumulative method to measure GSs in the trunk and all branches of tree I (Wang et al. 2009). After calibrating the strain gauges to zero, first, the twigs at the branch tips that induced bending of the branch were cut down, and the spring-back strains resulting from the removal of twigs ($\varepsilon_s=\delta\varepsilon_s$) were measured in the standing tree; then, GSs (ε_r) on the upper and lower sides of the branches were measured after they were released by cutting grooves 3-5 mm deep with a handsaw on both sides of the strain gauges (Yoshida et al. 2002). The value of ε_r ($\varepsilon_r=\delta\varepsilon_s+\delta\varepsilon_r$) is equal to the sum of the strain increment at the steps of load removal and stress release.

At the second time, GSs in several branches of two trees (II and III) were measured with a direct method. That is, no twigs and branches were cut down from the trees; GSs (ε_r) in the branches were directly measured by cutting groove in the stranding trees. The value of ε_r ($\varepsilon_r=\delta\varepsilon_r$) including the influences of self-loading is equal to the strain increment at stress release. Theoretically, values of ε_r obtained from both methods approach the real growth stress of standing tree (Yamamoto et al. 1989).

Creep experiment

After growth strain measurement, the branches of tree II and III were cut down, and samples (25X2X1mm^3, L, T, R) between the measuring positions were cut from the upper and lower sides of the branches. These samples were kept in water as green wood. The creep deformation of each green wood was test on the cantilever condition for 5.7 h. The load was 0.45 N well within proportional limits and the span was 20 mm. After the test, the sample was heated at 80 ^{o}C to release internal stress, and slowly cooled. After 24 h, the creep deformation of heated sample was tested. The microfibril angles (MFAs) of the air-dried samples were measured using X-ray diffraction (XRD) method. Finally, the basic density of the sample was expressed on the base of the oven-dried weight and the swollen volume.

Results and discussions

Growth eccentricity and growth strain of the trunk and branches

Table 1 summarized growth eccentricity, MFA, spring-back strain and GS of tree I. Except for branch no. I-A, which exhibited no growth eccentricity, the other branches showed pronounced growth promotion on the lower side and the pattern of growth eccentricity did not change along their length. The MFAs of the base position for the branches were about 11-14 ^{o} based on polarizing light. There was little difference in the MFAs of the upper and lower sides of the branches for tree I.

Table 1. MFAs, spring-back strains, and growth strains in the trunk and branches of tree I

Trunk and branch no.		R_1 (mm) upper radius	R_2 (mm) lower radius	MFA by POM (°) *		Spring back strain (μ m/m) ($\varepsilon_s = \delta\varepsilon_s$)		Released growth strain (μ m/m) ($\varepsilon_r = \delta\varepsilon_s + \delta\varepsilon_r$)	
				Upper	Lower	Upper	Lower	Upper	Lower
Trunk	1	100	100	13.8	12.1	32	11	-535	-549
	2	55	30	-	-	16	13	-394	-414
Branch									
A	1	10	11	12.8	13.5	-313	382	32	-172
	2	10	10	-	-	-170	247	-21	-244
B	1	17	22	12.1	13.5	-382	1378	-205	16
	2	15	18	-	-	-1169	1302	-706	433
C	1	14	50	13.6	13.0	-48	-255	-191	-326
	2	10	20	-	-	-415	532	-494	23
D	1	22	55	12.9	11.5	-389	175	-669	-53
	2	24	45	-	-	-958	932	-553	-57
E	1	25	55	12.4	14.8	-892	567	-545	-212
	2	25	51	-	-	-911	1171	-520	-152

*: MFA was measured using polarizing light microscope

The spring-back strains of the branches were caused by excising the twigs. The spring-back strain was contractile on the upper side and extensive on the lower side of most branches. This is the expected response to the suppression of the gravity load, that in the standing tree tends to bend the branch downward and compress it along its length. A different behavior was the base of branch no.I-C-1, which not only produced a contraction on both side, but also a higher contraction on the lower side.

On the other hand, the released GS ranged from -706 to 433 $\mu\varepsilon$. For the trunk, the strain value was moderate and similar on both sides, indicating stable vertical growth of the whole tree. For the branches, the values of GS differed between the upper and lower sides at all positions, and various patterns were observed. The values were in most cases negative (contraction), corresponding to a low tensile growth stress typical of normal wood. In branch no. I-A and I-C-1, the upper side produced little GS (positive or negative) while the lower side contracted. In branch no. I-B and I-C-2, there were positive growth strains (corresponding to a compressive growth stress) on the lower side. Branches no. I-D and I-E produced a contraction on both sides, corresponding to a tensile growth stress, with a higher value on the upper side. Furthermore, we found that the larger growth strain occurred on the upper side opposite to eccentric growth and counteracted the gravity effect, which is unusual in angiosperms.

To clarify the biomechanical advantage of eccentric growth, we examined the relationship between the downward bending trend, quantified by the spring-back bending ($\varepsilon_{s\ lower}$-$\varepsilon_{s\ upper}$) and the eccentricity (ratio of R_2 to R_1) of the branch. As shown in Figure 1, there was a negative relationship (R^2=0.78) between both factors (except for the thinnest branch no. I-A). This suggests that eccentric growth, which appears to be a common feature of this species, resulted in a disadvantage for upright movement or stabilization of the branch orientation so that it had to be somewhat reduced when the bending load became higher.

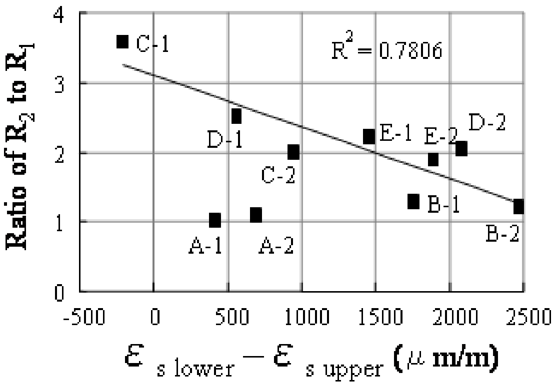

Figure 1. Relationship between the downward bending trend and eccentricity for tree I (excepting the thinnest branch no. I-A)

To inspect the results of GSs in *V. odoratissimum* branches at the first measurement, we measured the GSs in the branches of other two trees with a direct method. Table 2 shows growth eccentricity and GSs in the branches of tree II and III. Growth eccentricity displayed on the lower side for all branches. The distribution of GS showed two main patterns similar to those of tree I. One is tensile stress on the upper side and compressive stress on the lower side, most of measuring positions showed this distribution pattern; the other is high tensile stress on the upper side and slight tensile stress on the lower side, such as tension wood. Moreover, although the elastic modulus in longitudinal direction (see Table 3) of the lower side was slightly larger than that of the upper side, we can calculate that the growth stress in the upper side was larger than that in the lower side. This confirms that a larger growth stress did not occur in the eccentric growth side of branch, which is different from reaction wood.

Table 2. Growth strains in the branches of tree II and III

Branch no.		R_1 (mm) upper radius	R_2 (mm) lower radius	Released growth strain (μ m/m) ($\varepsilon_r = \delta\,\varepsilon_r$)	
				Upper	Lower
Tree II					
A	1	11	31	-445	181
	2	15	16	-304	345
B	1	12	21	-236	474
	2	12	16	-329	100
C	1	11	30	-41	220
	2	18	24	-848	35
Tree III					
A	1	12	36	1395	-91
	2	18	24	-357	-141
B	1	8	15	-471	373
	2	9	12	-466	323
C	1	14	28	-602	200
	2	12	19	-648	329
D	1	12	18	-287	279
	2	12	14	-430	392

According to the above results, we found that the eccentric growth in the lower side of the branch was a normal growth pattern for *V. odoratissimum* tree. The distribution of GS in the branch had no regular type, but the larger growth stress displayed in the upper side to fulfill biomechanical requirements. It suggests that the mechanism of eccentric growth of the branch is different from that of reaction wood. Therefore, the branches of *V. odoratissimum* formed neither tension wood nor compression wood.

Mechanical properties of the branches of *V. odoratissimum*

To clarify the physical and mechanical properties of the branch, we cut the samples from the upper and lower sides of the branches, and examined the basic density, elastic modulus in longitudinal direction (E_L), creep deformation of the samples. Furthermore, to understand the influence of microstructure, we measured the MFA with X-ray diffraction method. Table 3 shows the basic density, MFA and E_L of the branches for tree II and III. For most positions, the basic density of the upper-side wood was less than that of the lower-side wood. MFA showed a different result in tree II and III. For tree II, the MFAs of the upper side were larger than those of the lower side, whereas for tree III, the MFAs of the upper side were smaller than those of the lower side. These results indicates that the E_L of the lower-side wood should be relatively larger in tree II and the E_L of the upper-side wood should be relatively larger in tree III. However, E_L of most positions for both trees displayed a same trend: the E_L of the lower-side wood was larger than that of the upper-side wood. This means that MFA was not closely related with the mechanical properties of the branch wood, and that difference of MFA in tree II and III may be caused by the branch architecture. Relationship between MFA and E_L in *V. odoratissimum* tree suggests that the stable growth mechanism of the branch would vary from that in reaction wood.

Table 3. Basic densities, MFAs and elastic moduli in the branches of tree II and III

Branch no.	Basic density (g/mm³)		MFA by XRD (°)		Elastic modulus in longitudinal direction (GPa)*	
	Upper	Lower	Upper	Lower	Upper	Lower
Tree II						
A	0.51	0.57	21.5	17.8	3.23	5.02
B	0.48	0.51	19.6	17.9	-	-
C	0.52	0.59	23.4	22.3	4.65	5.59
Tree III						
A	0.52	0.58	19.2	20.3	3.87	5.73
B	0.47	0.51	16.5	17.9	-	-
C	0.48	0.59	15.5	18.8	5.54	6.27
D	0.51	0.48	17.7	20.4	-	-

*: The block samples[60(L)×3(T)×3(R)mm] were used.

Figure 2 shows the creep curves of green wood cut from the upper and lower sides of the branches. The creep compliance (J_t) of the upper-side sample was larger than that of sample from the lower side, meaning the upper-side sample had low relatively rigidity and high relatively fluidity. After heating, the J_t of heated sample also had the same trend as green wood. Figure 3 shows the relationship between the relative creep compliance ($J_{20000sec}/ J_{10sec}$ -1) of the samples and GS. The upper side of branch wood that produced tensile stress exhibited higher fluidity.

Effect of density on the viscoelastic property of the sample was discussed in Figure 4 because of the large basic density of the lower-side wood. We found that there was a slight relationship between both factors, meaning the density is not an important factor to influence the viscoelastic property of the branch wood.

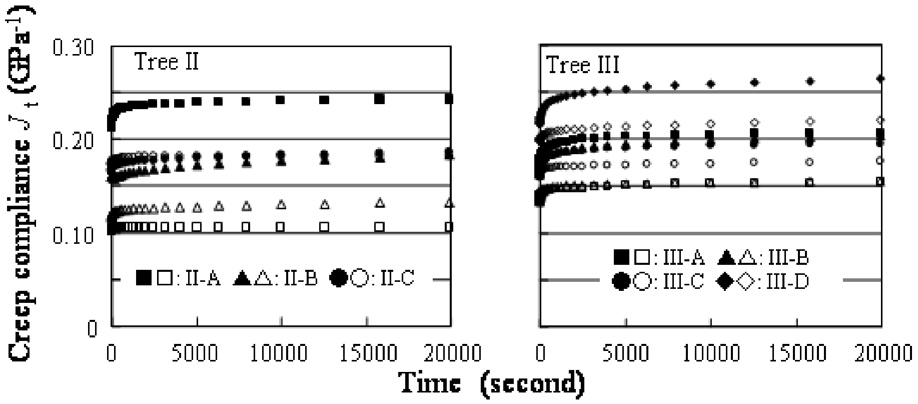

Figure 2. The creep compliance curves of green wood cut from the upper and lower sides of branches (solid mark: the upper side; hollow mark: the lower side)

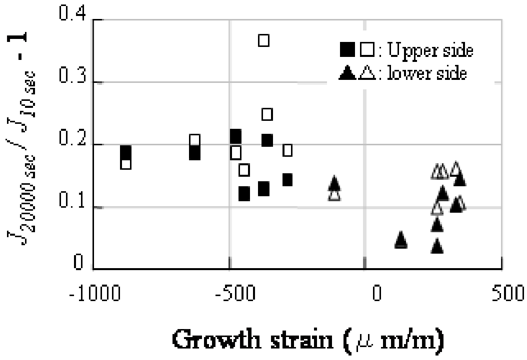

Figure 3. Relationship between the growth strain and relative creep compliance for green wood (solid mark) and heated wood (hollow mark)

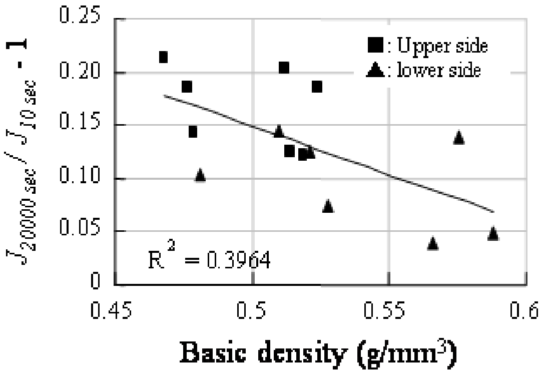

Figure 4. Relationship between the basic density and relative creep compliance for green wood

After examining the GS and the mechanical properties of the branch, we found the branch of *V. odoratissimum* have some features similar to reaction wood. From the viewpoint of GS, the branch showed a distribution of GS like tension wood because of a large tensile growth stress on the upper side. However, the eccentric growth did not occur in the upper side, and there was no anatomical feature of tension wood exhibited on both sides of the branch. From the viewpoint of the viscoelastic property, larger elasticity of the lower-side wood is similar to that of compression wood. However, microfibril angles of both sides were moderate for hardwood and did not influence the mechanical properties of the branch. Therefore, the factors which decide viscoelastic property of branch are limited in chemical components and matrix structure of S_2 layer.

At this stage, we analyzed the chemical components of the branches for tree I. We found that lignin content of the lower-side wood was about 2% more than that of upper-side wood. Distribution of lignin of the branch was similar to that of compression wood. On the other hand, the results of syringyl/guaiacyl molar (S/G) ratio showed that the S/G ratio of the upper-side wood was larger that that of lower-side wood. Moreover, softening temperature of upper-side wood was lower based on dynamic mechanical analysis (DMA). These results are the same as tension wood (Pilate et al. 2004, Placet et al. 2007). Now, we can not decide which factor support compressive stress and are advantage to improve the elasticity modulus of the lower side of the branch, however these results of chemical component suggest that the eccentric growth of *V. odoratissimum* combined some advantages of tension wood and compression wood.

Conclusion

For *V. odoratissimum*, the eccentric growth often occurred in the lower side of the branches. Generally, GSs of the branches displayed different distribution pattern: one is the values on both sides corresponded to a tensile growth stress typical of normal wood, sometimes a high tensile GS was found in the upper side similar to GS of tension wood; the other is the values on the lower side corresponded to a compressive growth stress. For both patterns, a larger growth stress was observed on the upper side of the branches Thus, the relationship between growth stress and eccentric growth is unusual in angiosperms. Furthermore, the mechanical properties of branch were not greatly influenced by MFA and BD. The upper-side wood had a low elastic modulus and a high fluidity whereas the lower-side wood had a large elastic modulus and a low fluidity. Although there was no anatomical features of reaction occurred in the upper or lower side, the chemical component of the branches exhibited some features similar to that of reaction wood.

Acknowledgements

This study was supported by a Grant-in-Aid for foreign researcher fellows (No.20.08105) provided by the Japan Society for the Promotion of Science. The authors thank Dr. Bruno Clair of Montpellier 2 University, France for microfibril angle measurement, Dr. Tomoyuki Fujii of Forestry and Forest Products Research Institute, Japan and Dr. Keiichi Baba and Dr. Takuro Mori of Kyoto University for their valuable comments, and the numbers of the Laboratory of Biomass Morphogenesis, Kyoto University for assistance with measurements.

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