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Effect of Finger Profile on Static Bending Strength Performance of Finger-Jointed Wood[*1]

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ABSTRACT

To study the efficient usage of small diameter logs and woods containing defects such as knots, slope of the grain and decay, six types of finger-jointed woods with various finger profiles were made of poplar, pine and oak with different density. We investigated the effect of finger profile on static bending strength performances of finger-jointed woods.

The efficiency of bending MOE, MOR and deflection showed the highest value in poplar finger-jointed wood with the lowest density of three species, and the lowest value in oak finger-jointed wood with the highest density of three species. The values markedly decreased with increasing finger pitch for finger-jointed wood glued with polyvinyl acetate (PVAc) resin for all tested species, whereas for the finger-jointed wood glued with resorcinol-phenol formaldehyde (RPF) resin, the influence of finger pitch on the efficiency of MOE was not found in all tested species, and those on the efficiency of MOR and deflection indicated the same trend as finger-jointed wood glued with PVAc resin in the case of pine and oak finger-jointed wood with higher densities. It was found that the values tended to decrease with increasing density of species on the whole and the desirable finger pitches were L (6.8 mm) for poplar, M (4.4 mm) for pine and S (3.5 mm) for oak in a view of economy. For finger-jointed wood glued with PVAc resin, the fitness between a tip and a root width of a pair of fingers (δ) of 0.5 mm indicated the highest efficiency of MOE for all species. And, the influence of δ on MOR was only found in oak finger-jointed wood glued with RPF resin and the desirable δ value for oak was 0.1 mm. However, it was found that the influence of δ on the strength performance was very small.

Keywords : finger-jointed wood, pitch, species, MOE, MOR

1. INTRODUCTION

As it is difficult to import logs due to the effect of exhaustion of the superior logs, the environmental protection movement and the resource conservation policy of the country of logs production, it is necessary to use efficiently small diameter logs and the logs containing

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knots. To obtain wood-based materials such as wide boards and dimension beams from the low quality materials mentioned above, they have to be manufactured with the required dimension beams and wide boards after eliminating the defect of solid wood such as knots. Hence, the end joints which are one of important facts to determine strength performance are brought to the public attention. The end joint methods of wood and wood-based materials such as butt joint, scarf joint, beveled joint and finger joint have been utilized. The joining process by finger joint method is suitable to join short beams because the loss of material is small and is superior to the processing and joining efficiency. Furthermore, it is widely used for an end joint method of structural materials, furniture, flooring, athletic goods such as ski and musical instruments because it simultaneously has the advantages of both scarf joint and butt joint such that it is easy to press with a suitable pressure for joining, and is fit for machine process, and has comparatively higher strength performances. The extensive researches in various field have been conducted for improving the quality due to the merit of lots of production capacity.

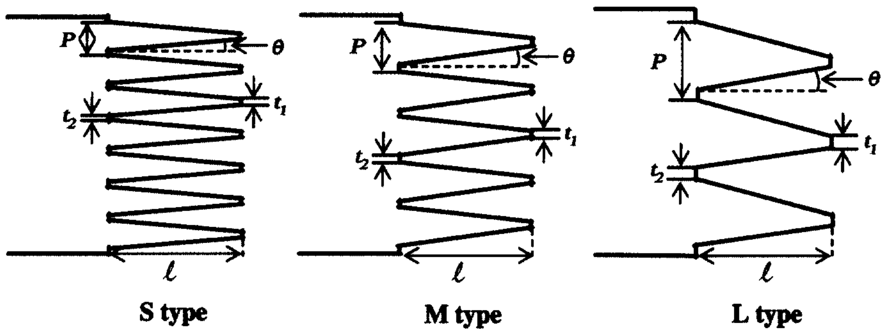
Mori *et al.* (1963) reported that the bonding strength of finger joint was determined by bonding force of scarf plane and stress concentration occurring in the part of finger angle, and the desirable slope ratio of finger scarf was 8~10. Hoshi (1972) and Hoshi *et al.* (1973, 1976) clarified that the joining efficiency of finger joint was markedly affected by finger profile and dimension as well as the adhesive used and the aspect of processing. Horie *et al.* (1981) found that finger-jointed timbers had a very high joining efficiency similar to solid wood. And Mori *et al.* (1991), Kawahara *et al.* (1991), Matsufuji *et al.* (1992, 1996) and Byeon *et al.* (1997) indicated that the efficiency of bending strength increased with increasing slope ratio of finger scarf (*l/t*) in the research on bending strength properties of sloped finger joint. Janowiak *et al.* (1993) reported that the joining efficiency had the higher value in vertical finger-jointed timber than in horizontal finger-jointed timber in the research for finger-jointed timbers made with red oak, red maple and yellow poplar. Paul (1988) indicated that there was little influence of species in the results for bending test of finger-jointed timber made with eastern white pine and eastern hemlock. Also, in the research on the effect of glue line of finger-jointed timber for tensile strength, Patrick *et al.* (1994) reported that tensile strength decreased when it has the defect of finger-jointing, the decrease of finger part glued with adhesive and finger length, and the loss of finger part. Mori *et al.* (1986) indicated that there was negative correlation between static bending strength and impact bending absorption energy because static bending strength increased with increasing tensile Young's modulus of adhesive.

As mentioned above, there have been conducting a lot of researches for finger profile, however, there are little researches for finger profile based upon density of species. Thus, in this study, six types of finger-jointed woods with different finger profile were manufactured using poplar, pine and oak with different density. We investigated the effect of finger profile on static bending strength performances of finger-jointed woods.

2. MATERIALS and METHODS

2.1. Specimen Preparation

Two hardwoods: poplar (*Populus euramericana* Gunier.) and oak (*Quercus variabilis* Bl.) and one softwood: pine (*Pinus densiflora* Sieb. et Zucc.) were selected for this study. Longitudinal elements without visible defects measuring 22(T)×22(R)×350(L) mm were cut from each of



(Unit:mm)

	S			M			L		
P		3.5			4.4			6.8	
ℓ		15.3			15.3			15.3	
$\tan^{-1}\theta$		17.59			13.48			7.57	
t_1	1.0	1.2	1.6	0.9	1.1	1.5	0.8	1.0	1.2
t_2		0.9			0.8			0.7	
δ	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5

Fig. 1. Dimension and finger profile.

Notes: P: pitch, ℓ: Length of finger, t_1: Tip width, t_2: Root width, θ: Slope angle of finger, δ: Fitness of a tip and a root width of finger(t_1-t_2), S: Small size of finger pitch (3.5 mm), M: Medium size of finger pitch (4.4 mm), L: Large size of finger pitch (6.8 mm).

three species. Density and static MOE of the species were measured, and their ranges for this study were in 0.33~0.42 Mg/m^3 and 4.97~8.34 GPa for poplar, 0.44~0.58 Mg/m^3 and 7.85~11.8 GPa for pine and 0.85~1.03 Mg/m^3 and 10.2~18.6 GPa for oak, respectively. The elements were classified without density and static modulus of elasticity (MOE) bias among three conditions for finger pitch. The center of the longitudinal elements which static MOE were measured was cut to make fingers with 3.5 mm (S), 4.4 mm (M) and 6.8 mm (L) of three pitch sizes (slope ratios of finger scarf: 17.6 (S), 13.4 (M) and 7.59 (L)) and fitness between a tip(t_1) and a root width(t_2) for a pair of fingers(δ) as shown in Fig. 1. A resorcinol-phenol formaldehyde (RPF) resin and polyvinyl acetate (PVAc) resin formulated for room temperature curewere used. The finger-jointing parts were pressed under a pressure of 3.92 MPa for 20 seconds, and cured for more than a week in a room maintained at 20 and 65% RH. And then the finger-jointed specimens of 20(T)×20(R)×300 (L) mm were completed. The number of specimen for each condition of three species was 8, respectively.

2.2. Static Bending Test

Static bending test for finger-jointed specimens were performed using universal testing machine (EHF-ED10-20L, Shimadzu) with three point loading (concentrated load at midspan and supported at its ends) method. The span was 280 mm, and the cross-head speed was set at 1.2 mm/min. Static MOE, modulus of rupture (MOR) and maximum deflection were calculated from load-deflection curve.

Table 1. Results of static bending test for finger-jointed wood made with three species

Species	A_K	P	δ (mm)	ρ (Mg/m^3)	E (GPa)	σ (MPa)	D (mm)
Poplar		Control	N	0.367	5.87	49.2	9.7
	Polyvinyl acetate (PVAc) resin	S (3.5 mm)	0.1	0.371	5.62	42.9	8.2
			0.3	0.367	5.43	37.1	7.5
			0.5	0.367	5.52	35.6	6.5
		M (4.4 mm)	0.1	0.366	5.07	38.3	7.8
			0.3	0.368	5.56	41.4	7.6
			0.5	0.370	5.66	39.5	7.2
		L (6.8 mm)	0.1	0.370	4.86	34.8	6.6
			0.3	0.368	4.93	34.6	6.2
			0.5	0.367	5.26	34.8	5.8
	Resorcinol-phenol formaldehyde (RPF) resin	S (3.5 mm)	0.1	0.364	6.16	48.3	6.4
			0.3	0.371	5.96	45.8	6.6
			0.5	0.368	6.02	43.0	6.1
		M (4.4 mm)	0.1	0.373	6.19	51.3	7.0
			0.3	0.367	6.22	50.2	6.9
			0.5	0.365	6.25	46.8	6.7
		L (6.8 mm)	0.1	0.366	6.23	50.4	7.2
			0.3	0.367	6.12	48.5	6.9
			0.5	0.367	6.15	48.6	6.8
Pine		Control	N	0.502	8.43	66.5	10.2
	Polyvinyl acetate (PVAc) resin	S (3.5 mm)	0.1	0.503	6.08	44.6	6.8
			0.3	0.501	6.68	45.1	6.4
			0.5	0.508	7.13	43.6	5.8
		M (4.4 mm)	0.1	0.509	5.65	42.4	7.2
			0.3	0.508	5.80	42.0	7.1
			0.5	0.496	6.63	43.9	6.5
		L (6.8 mm)	0.1	0.497	3.78	29.9	6.7
			0.3	0.504	3.40	28.7	6.8
			0.5	0.503	4.90	32.7	5.7
	Resorcinol-phenol formaldehyde (RPF) resin	S (3.5 mm)	0.1	0.500	8.52	60.5	6.3
			0.3	0.504	8.64	58.2	5.8
			0.5	0.502	8.54	56.5	6.1
		M (4.4 mm)	0.1	0.504	8.67	61.1	6.1
			0.3	0.501	8.71	59.8	6.0
			0.5	0.500	8.55	57.1	5.9
		L (6.8 mm)	0.1	0.498	8.40	52.4	5.1
			0.3	0.505	8.73	56.2	5.5
			0.5	0.502	8.66	51.2	4.9
Oak		Control	N	0.930	13.6	119	14.5
	Polyvinyl acetate (PVAc) resin	S (3.5 mm)	0.1	0.932	8.55	55.1	6.1
			0.3	0.925	8.57	52.5	5.6
			0.5	0.930	9.55	50.2	4.7
		M (4.4 mm)	0.1	0.936	7.77	48.8	6.1
			0.3	0.926	8.30	51.5	5.6
			0.5	0.934	9.11	49.5	5.0
		L (6.8 mm)	0.1	0.924	6.44	39.4	4.8
			0.3	0.931	7.24	41.4	4.6
			0.5	0.925	7.39	39.3	4.3
	Resorcinol-phenol formaldehyde (RPF) resin	S (3.5 mm)	0.1	0.936	12.7	107	8.6
			0.3	0.932	12.7	99.9	7.9
			0.5	0.927	12.3	98.1	8.0
		M (4.4 mm)	0.1	0.925	12.5	101	7.9
			0.3	0.930	12.9	97.8	6.9
			0.5	0.924	12.8	99.6	7.4
		L (6.8 mm)	0.1	0.928	12.7	80.0	5.0
			0.3	0.939	12.7	87.0	5.7
			0.5	0.927	12.9	87.5	5.9

Notes ; Each value is the average of eight measurements, A_K: Kind of adhesive, P: Pitch, δ: Fitness of a tip and a root width (t_1-t_2), ρ: Density, E: Modulus of elasticity, σ: Modulus of rupture, D: Deflection, N: No joint, S, M, L: See note in Fig. 1.

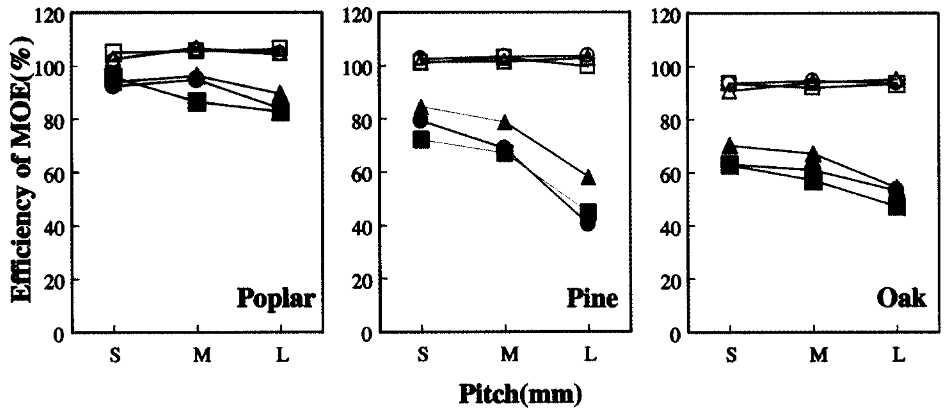


Fig. 2. Effect of finger pitch on the efficiency of MOE (%).

Legend: ■: 0.1 mm of δ for finger-jointed timber glued with PVAc resin,
●: 0.3 mm of δ for finger-jointed timber glued with PVAc rein,
▲: 0.5 mm of δ for finger-jointed timber glued with PVAc resin,
□: 0.1 mm of δ for finger-jointed timber glued with RPF resin,
○: 0.3 mm of δ for finger-jointed timber glued with RPF resin,
△: 0.5 mm of δ for finger-jointed timber glued with RPF resin.

Notes: Each value is the average of eight measurements, δ is fitness of a tip and a root width of finger, RPF and PVAc mean resorcinol-phenol formaldehyde and polyvinyl acetate, respectively. S, M, L : See note in Fig. 1.

3. RESULTS and DISCUSSION

3.1. Static Bending Modulus of Elasticity (MOE) of Finger-Jointed Wood

The results of static bending test of finger-jointed woods made with different finger profile and species are shown in Table 1 and the effect of finger profile on static bending MOE is shown in Fig. 2.

Static bending MOEs of finger-jointed woods for three species including poplar, pine and oak decreased with increasing finger pitch of finger-jointed wood glued with poly vinyl acetate (PVAc) resin. This is considered due to the decrease of the glued area of finger parts with increasing finger pitch. Luxford *et al.* (1946) indicated that the efficiency of tensile strength increased with increasing scarf ratio $\alpha(\tan^{-1}\theta)$, and the value showed 90% for α=15, and then it showed almost constant value regardless increasing of α. Mori *et al.* (1963) reported that the efficiency of tensile strength was 50% for scarf ratio α=4 and 80% for α=12 in a research to investigate the efficiency based upon scarf ratio of plain scarf joint using *Quercus mongolica* var. to detect the effect of finger scarf ratio. Also, Mori *et al.* (1991) and Byeon *et al.* (1997) reported that the efficiency of bending strength increased with increasing sloped finger ratio of finger joint. The extent of the decrease on MOE was found to have the highest value in pine finger-jointed wood and the higher value in finger-jointed wood made with softwoods than hardwoods. And the fitness between a tip and a root width for a pair of fingers(δ) of 0.5 mm showed the highest value for pine and oak finger-jointed wood. The efficiency of MOE of finger-jointed woods of three species glued with PVAc resin showed 83%~96% for poplar, 40.4%~84.6% for pine, and 53.2~70.2% for oak, respectively. These values decreased with increasing density of species on the whole.

In contrast, there was little influence of finger pitch for finger-jointed woods of three species glued with resorcinol-phenol formaldehyde (RPF) resin. The efficiency of MOE of finger-jointed woods of three species glued with RPF resin showed almost constant value of 103%~108% for poplar, 100%~105% for pine, and 92%~96% for oak regardless the finger pitch and distance between tips and roots of a pair of fingers(δ). These values were similar to the results for that the ratio of efficiency of compressive Young's modulus was 1.05, and tensile and bending Young's modulus were 0.98 by Horie *et al.* (1981). The values were markedly higher than those of finger-jointed woods glued with PVAc resin. This is considered because RPF resin has a markedly higher MOE than those of PVAc resin (Kawahara *et al.*, 1991). Furthermore, it was found that the values decreased with increasing density of species as in finger-jointed wood glued with PVAc resin, whereas the extent of decrease was lower than in finger-jointed wood glued with PVAc resin. However, it was found that there was little influence of δ for MOE of finger-jointed wood glued with RPF resin.

3.2. Bending Modulus of Rupture (MOR) of Finger-Jointed Wood

Fig. 3 shows the effect of finger profile on bending MOR. Bending MORs of finger-jointed woods for three species decreased with increasing finger pitch of finger-jointed woods glued with PVAc resin except for poplar finger-jointed wood with the lowest density of three species. This is also considered owing to the decrease of glued area with increasing finger pitch as mentioned in previous MOE section. The extent of the decrease was found to have the highest value in pine finger-jointed wood and the higher values in finger-jointed wood made with softwoods than hardwoods. The efficiency of MOR of finger-jointed timbers showed 70.4%~87.1% for poplar, 43.2%~67.8% for pine and 33.0%~46.3% for oak, respectively. It was found that finger-jointed timber with a higher density had the lower efficiency of MOR value. However, it was found that there was little influence of δ for MOR of finger-jointed wood glued with PVAc resin.

On the other hand, MOR of finger-jointed wood glued with RPF resin tended to decrease with increasing finger pitch unlike MOE of finger-jointed woods except for poplar finger-jointed wood. This is considered that MOE affected by elastic strain below proportional limit had a small influence of glued area in finger parts owing to a high MOE of RPF resin, whereas MOR affected by plasticity strain beyond proportional limit had a considerable influence of glued area in finger parts. The efficiency of MOR for finger-jointed woods of three species glued with RPF resin showed 87.3~104.2% for poplar, 77.0%~91.9% for pine and 67.2~90.1% for oak, respectively. Their values were higher than 76% reported by Paul (1988) in the results for bending test of finger-jointed timber made with eastern white pine and eastern hemlock. Also, they indicated markedly higher values than those of finger-jointed woods glued with PVAc resin. This is considered because wood failure occurred for the finger-jointed wood of three species glued with RPF resin, whereas, for finger-jointed wood glued with PVAc resin, the slippage of glue line rather than wood failure of finger-jointed wood occurred. This is correlated with the report on bending properties of sloped finger-jointed wood using red pine by Byeon *et al.* (1997). However, in a view of economy, it can be said that the desirable finger pitch was L (6.7 mm) for poplar, M (4.4 mm) for pine and S (3.5 mm) for oak. Because the difference of MOR efficiency between S and M of finger

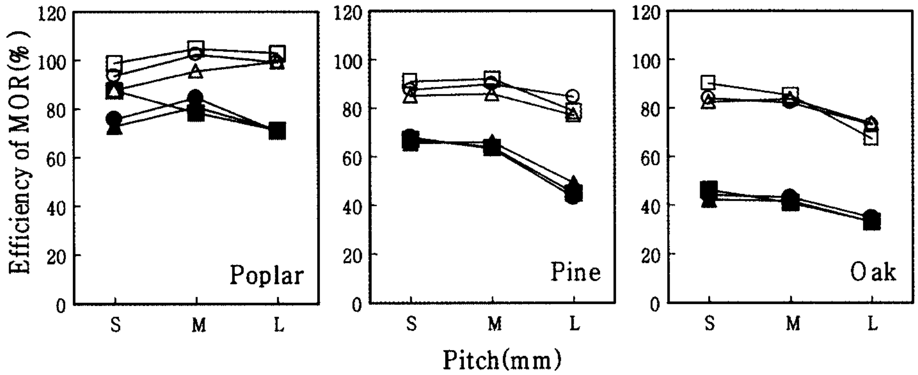


Fig. 3. Effect of finger pitch on the efficiency of MOR (%).
Legend: See legend in Fig. 2.

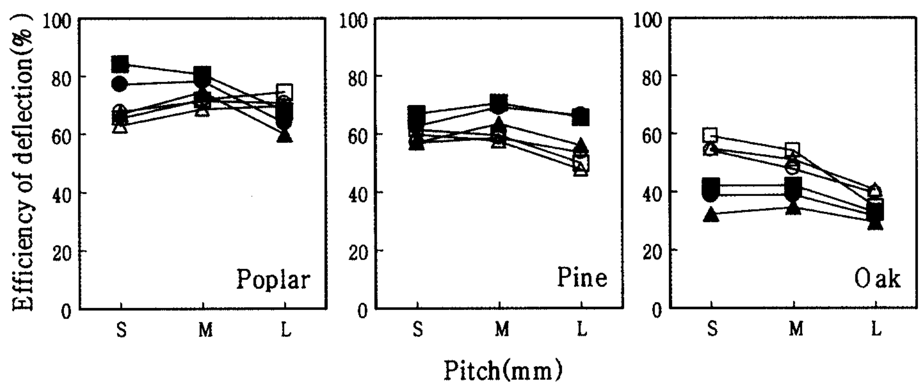


Fig. 4. Effect of finger pitch on the efficiency of deflection (%).
Legend: See legend in Fig. 2.

pitch for pine was smaller than those of oak, and the MOR efficiencies of M and L of finger pitch for poplar showed the higher value rather than those of S due to decrease of deflection caused by stress concentration occurred early owing to lots of glued area of S and there was little difference of MOR efficiency between M and L. And a desirable δ value on MOR for oak finger-jointed wood was 0.1 mm, this was correlated with the results reported by Hoshi *et al.* (1976) that finger jointed timber made with beech indicated the highest value in δ=0.13~0.27 mm and it was possible to handle before curing of glue line. However, the difference between δ values was very small and influence of δ for other finger-jointed woods was not found.

Therefore, it can be concluded that the efficiency of strength performance of finger-jointed wood was considerably affected by finger pitch size (finger scarf ratio=$\tan^{-1}\theta$) and density of species.

3.3. Relation of Deflection and Finger Profile of Finger-Jointed Wood

The effect of finger profile on deflection of finger-jointed wood is shown in Fig. 4. The deflections of finger-jointed woods for three species decreased with increasing finger pitch of

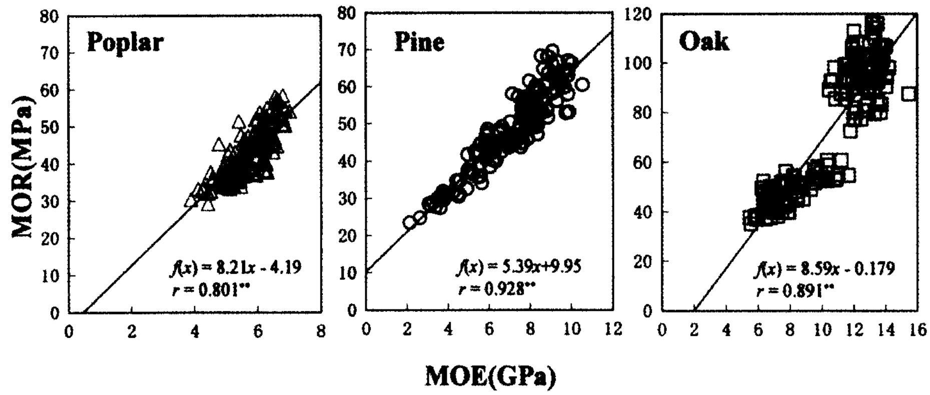


Fig. 5. Relationships between MOEs and MORs for finger-jointed woods.
Note: ** is significant at 1% level.

finger-jointed woods glued with PVAc resin. The extent of the decrease showed the highest value in poplar finger-jointed wood, but pine finger-jointed wood hardly varied. The efficiency of deflection of finger-jointed woods of three species glued with PVAc resin showed 59.8%~84.5% for poplar, 55.9%~70.6% for pine and 29.7%~42.1% for oak, respectively. The values decreased with increasing density of species. However, the influence of δ was not found like MOR.

On the other hand, the values for finger-jointed wood glued with RPF resin indicated to decrease with increasing finger pitch for oak and pine finger-jointed woods with higher densities of three species, but for poplar finger-jointed wood with the lower density, their values slightly increased. This is considered because failure caused by stress concentration early occurred in S of finger pitch due to a lot of glued area glued with RPF resin with a high MOE. The extent of the decrease showed the greatest value in oak with the highest density of three species. The efficiency of deflection for finger-jointed timbers of three species glued with RPF resin showed 62.9%~74.2% for poplar, 48.0% ~61.8% for pine and 34.5%~59.3% for oak, regardless of the fitness between a tip and a root width of a pair of fingers(δ). It was found that the values indicated to decrease with increasing density of species and the difference for both adhesives markedly decreased compared with MOE and MOR. This is considered due to the decrease of the plasticity strain of finger-jointed woods glued with RPF resin.

3.4. Relation between MOE and MOR for Finger-Jointed Woods

The least square regression analysis between MOE and MOR for finger-jointed woods of three species was conducted and the regression line and is shown in Fig 5. The correlation coefficients were 0.928 for pine, 0.891 for oak, and 0.801 for poplar. There were strong correlations among MOEs and MORs of finger-jointed woods of three species. These results were correlated with several studies for finger-jointed timber (Ayarkwa *et al.*, 2001) and solid wood (Bendtsen *et al.*, 1981, Nakai, 1984, Komastu, 1988). However, the distribution for oak finger-jointed wood was found to be divided by adhesive kind and it was found that the distribution hardly depended on density of species.

4. CONCLUSIONS

Six types of finger-jointed woods with various finger profiles were made of poplar, pine and oak with different density in order to study the efficient usage of small diameter logs and woods containing defects such as knots, slope of the grain and decay, we investigated the effect of finger profile on static bending strength performances of finger-jointed woods.

The efficiency of MOE, MOR and deflection of finger-jointed wood indicated a marked difference with finger pitch, density of species, kinds of adhesives used, whereas it was found that the influence of fitness between a tip and a root width of a pair of fingers(δ) on strength performance was very small. The desirable finger pitches for strength properties of species were L (6.7 mm) for poplar, M (4.4 mm) for pine and S (3.5 mm) for oak in a view of economy. The correlation between static MOE and MOR of finger-jointed wood was significant at 1% level for all tested species, and the correlation coefficients were found to indicate very high values of 0.801 ~ 0.928. However, their values were found to be hardly depended on density of species.

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