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ORIGINAL ARTICLE

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Veneer strand flanged I-beam with MDF or particleboard as web material III: effect of strand density and preparation method on the basic properties

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Abstract Optimizing the manufacturing conditions of veneer strand-flanged I-beams was continued in this study and focused on the strand density and preparation method. Three levels of strand density were used, while the strands were prepared by either saw or roll-press splitter. The main results indicated that: within the compaction ratios (1.4–2.3) investigated in this study, the strand with lower density showed slight improvement in the dimensional stability and the bond strength between web and flange, but not in bending properties of the I-beams. The strand preparation method was concluded to be dependent on species for akamatsu, sugi, and bamboo strands; roll-press splitter-prepared strands tended to negatively affect dimensional stability and mechanical properties of the I-beams. When using akamatsu or sugi strands, low density allowed the possibility of using lower resin application rates between strands.

Key words I-beam · Strand density · Preparation method · Basic properties

Introduction

In the first part[1] of this series of studies, a new forming and pressing method for fabricating veneer strand flanged I-beam was developed and its technical feasibility was confirmed. The new I-beam consists of a flange part made from veneer strand, while the web part is either prefabricated medium-density fiberboard or particleboard. In the second part[2] of the study series, optimization of the manufacturing conditions was investigated using different combinations of strand dimensions, resin types between web and flange, different pressing times, and different moisture content in wood resin system. The use of phenol–formaldehyde (PF) resin between strands at an application rate of 40 g/m^2 (equivalent to 8.5% resin content based on the resin solid weight and the oven-dry weight of the wood strands) and diphenyl methane diisocyanate (MDI) resin between web and flange at an application rate of 25 g/m^2 were concluded to be the optimum manufacturing conditions up to this stage. In addition, using 12% moisture content in the wood resin system was found to be the optimum level among the three levels investigated. The results also showed the possibility of shortening the pressing time from 20 to 12 min under conventional hot-pressing conditions using PF resin between strands without compromising the I-beam properties.

In the third part of this study series, the optimization of the manufacturing conditions were continued regarding the strand density, preparation method, and the interaction between low strand density and low resin application rate. Two main methods were used to prepare strands; one is the use of a roll-press splitter (which gives relatively high yield of strands compared with the second method) and the other is the use of a panel saw or circular saw. Generally, the roll-splitted strands have minor cracks, which might affect the final properties of the I-beam. This is because these cracks may absorb some resin resulting in starved joints between strands. Also the twisted appearance of the strands does not allow uniform compression of the I-beam flange part.

Generally, the final density of the formed products depends on the raw material density,[3] because a certain compaction ratio (CR) is required to obtain products with acceptable properties. Likewise, the strand density will affect the desirable final flange density of this I-beam, because a certain CR requires providing I-beams with acceptable properties.

The objectives of this part of the study were: (1) to investigate the effect of the strand density and preparation

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method on the basic properties of the I-beam produced with the optimum manufacturing conditions from the second part of the study,[2] (2) to investigate the effect of interaction between low strand density and resin application rates between strands, and (3) to confirm the interaction between low-density strands and resin application rates.

Materials and methods

Materials

Japanese red pine (*Pinus densiflora* Seib. et. Zucc) veneer strands with the dimensions of 3 × 4 × 470 mm (thickness × width × length), and densities of 0.31, 0.42, and 0.51 g/cm^3; Japanese cedar (*Cryptomeria japonica* D. Don.) veneer strands having the same dimensions, and a density of 0.34 g/cm^3; and moso bamboo (*Phyllostachys pubescent* Mazel.) having a density of 0.62 g/cm^3 were used as flange raw material having a moisture content of 10%. The strands were prepared by either saw or roll-press splitter.[4] Phenol–formaldehyde-bonded particleboard with dimensions of 450 × 470 × 9 mm and a density of 0.82 g/cm^3 was used as web material. Phenol–formaldehyde resin (D-100) with solid content of 43% and polymeric MDI (PB 1605) formulated by Oshika were used as binder.

I-beam panel fabrication

Using the same forming and pressing method described in part I[1] of this study, ten I-beam panels with a target flange density of 0.7 g/cm^3 were fabricated conventionally (200°C and 12-min pressing time) using the combinations shown in Table 1. Wood resin system moisture content was fixed at 12% for all conditions. One replicate from each condition was produced. Changes of temperature during hot pressing were measured at three positions (see Fig. 2) by means of thermocouples.

Property testing

All beams were fully conditioned at 20°C and 60% relative humidity (RH) for 1 week. Five beams from each condition were tested for bending properties of the modulus of rupture (MOR) and modulus of elasticity (MOE) using a four-point bending test method (edge-wise). The following testing conditions were used: (1) total span of 900 mm, (2) inner span of 300 mm, (3) cross head speed of 5 mm/min, and (4) the bending properties were calculated using the tapered I-shape moment of inertia. The total span was obtained by using metallic extension bars (as used in part II[2] of this study), which, from a pilot study, were found to be not significantly different from using full-span wooden beams.

After discarding the edge parts of the beam, many 40-mm-long block specimens were prepared (see Fig. 1). From these blocks, ten randomly selected specimens for each condition (having the same shape as those used in parts I[1] and II[2]) were prepared to assess the bond strength between web and flange using a block shear test parallel and perpendicular to the strand grain. The dimensional stability was examined by evaluation of the percentile thickness, width swelling, and water absorption in a 24-h water immersion test at 20°C. Ten randomly selected specimens from the above described lot for each condition were used. To assess the bending properties of the flange part, specimens that were 9 × 15 × 220 mm (thickness × width × length) were prepared from the flange part (having the shape shown in Fig. 1), and were tested using a three-point bending test (edge-wise) at clear span of 200 mm.

Results and discussion

Effect of strand density on the I-beam basic properties

Bending properties

The results of the bending tests are listed in Table 2. The result indicated that the strand density did not affect the

Table 1. Combinations of strand density, resin application rates, and strand preparation method

Species	Strand density (g/cm^3)	Resin application rate (g/m^2)		Strand preparation method
		Between strands (PF resin)	Between web and flange (MDI resin)	
Akamatsu	0.31	20	25	S
	0.31	40	25	S
	0.42	40	25	S
	0.51	40	25	S
	0.51	40	25	RS
Sugi	0.34	20	25	S
	0.34	40	25	S
	0.34	40	25	RS
Bamboo	0.62	40	25	S
	0.62	40	25	RS

PF, Phenol–formaldehyde; MDI, diphenyl methane diisocyanate; S, panel or circular saw; RS, roll-press splitter bending properties of the I-beam. The values obtained here were comparable with those obtained in part II[2] of this study series. However, these results may not represent the real values because all beams tested from the different conditions showed horizontal shear fracture of the web, which indicates that the weakest segment in this design is the web material. Further investigations on balancing the strength between flange and web were much needed.

Bond quality

As shown in Table 2, bond quality between web and flange as indicated by bond strength in the parallel direction was significantly higher when using low-density (CR = 2.26) strands than when using medium-density (CR = 1.67), or high-density (CR = 1.37) strands. This significant increase of the bond strength is mainly attributed to good contact between web and flange as a result of high compaction with increased volumetric content of low-density strands. However, the lack of a significant difference between medium-density and high-density strands may be attributed to the small difference in the compaction ratios. Compared with the bond strength reported in the second part[2] of this study, the strand density of 0.51 g/cm^3 was about 30% higher. This is probably due to the use of newly prepared PF resin on the flange part compared with that used in the previous work. In the perpendicular direction, there was no significant difference between strand density levels, because the bond strength in this direction depends mainly on the rolling shear. However, these values were also higher than those reported in the second part[2] of this study series due to the same reason mentioned above.

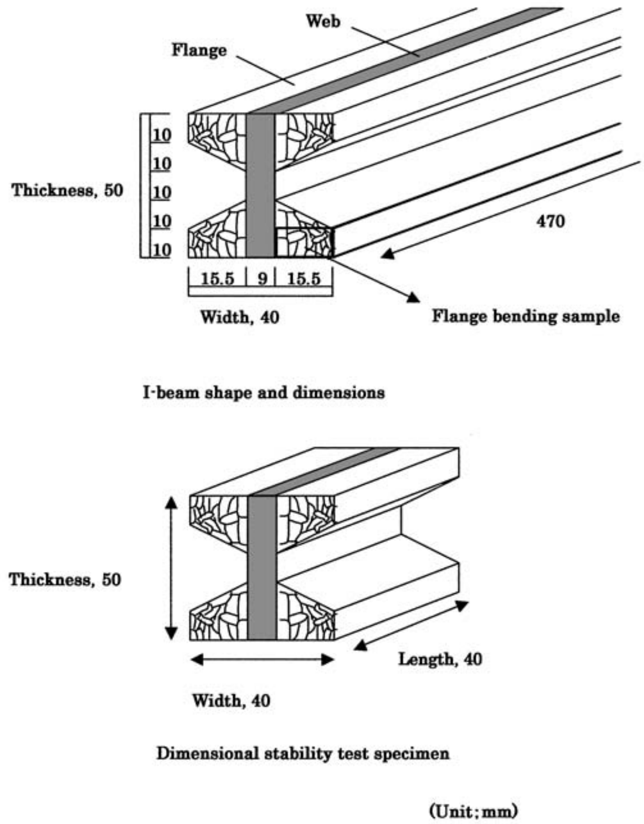

Fig. 1. I-beam cross section and dimensional stability test specimen

Dimensional stability

As listed in Table 2, the thickness swelling of the I-beam was much smaller than the width swelling. This is mainly due to the presence of prefabricated web material that helps to hold the flange part and prevent it from swelling.[1,2]

The observed width swelling was less than 10% and was improved slightly but significantly as the strand density decreased. This may be attributed to sufficient bond between strands due to good contact between strands as a result of a high compaction ratio. High compaction ratios, in general, result in fewer or no gaps between the wood elements, which consequently prevents the entry of water.[5–9] However, no significant difference of water absorption percentage was observed among the density level investigated in this study.

Effect of strand preparation method on the I-beam properties

Table 3 shows the results of mechanical properties and dimensional stability of I-beams produced with strands prepared by two different methods.

Table 2. Effect of strand density on the I-beam basic properties

Properties	Strand density (g/cm^3)		
	0.31	0.42	0.51
I-beam flange density (g/cm^3)	0.70 ± 0.01	0.70 ± 0.01	0.70 ± 0.01
MOR (MPa)	50.6 ± 7.5	50.2 ± 3.3	50.3 ± 4.6
MOE (GPa)	16.7 ± 1.5	16.4 ± 1.2	16.4 ± 1.5
Bond strength (MPa) //	9.3* ± 1.2	7.9 ± 1.7	7.9 ± 1.5
Bond strength (MPa) ⊥	4.5 ± 0.7	3.8* ± 1.2	4.3 ± 1.3
Thickness swelling (%)	0.8 ± 0.4	1.1 ± 0.8	1.0 ± 0.6
Width swelling (%)	8.5* ± 0.8	9.5 ± 1.3	9.7 ± 1.7
Water absorption (%)	32.7 ± 1.3	32.6 ± 0.9	34.8 ± 1.3

Results are given as mean ± SD
MOR, Modulus of rupture; MOE, modulus of elasticity
*$P < 0.05$ for values in the same row

Table 3. Effect of strand preparation method and species on the I-beam basic properties

Properties	Akamatsu		Sugi		Bamboo	
	Strand preparation method					
	S	RS	S	RS	S	RS
I-beam flange density (g/cm^3)	0.70 ± 0.01	0.69 ± 0.03	0.66 ± 0.02	0.65 ± 0.01	0.71 ± 0.05	0.72 ± 0.03
MOR (MPa)	50.3* ± 4.6	40.9 ± 1.1	47.9* ± 1.2	44.6 ± 2.4	44.8 ± 4.4	46.4 ± 1.8
MOE (GPa)	16.4 ± 1.5	16.3 ± 1.1	16.3 ± 1.0	15.9 ± 0.3	11.9 ± 0.7	11.7 ± 0.8
Bond strength (MPa) //	7.9* ± 1.3	4.5 ± 1.8	6.2* ± 1.4	4.6 ± 1.0	6.8 ± 2.4	7.3 ± 1.3
Bond strength (MPa) ⊥	4.3 ± 1.3	3.0 ± 1.2	4.3 ± 1.0	3.1 ± 0.7	4.4 ± 1.2	4.8 ± 1.9
Thickness swelling (%)	1.0 ± 0.7	1.1 ± 0.3	0.6 ± 0.2	0.8 ± 0.4	0.7 ± 0.2	0.6 ± 0.4
Width swelling (%)	9.7* ± 1.7	12.5 ± 1.7	8.4* ± 1.1	11 ± 2.0	4.1 ± 0.8	3.8 ± 0.4
Water absorption (%)	34.8* ± 1.3	50.4 ± 1.7	47.1* ± 2.4	55.4 ± 4.4	17.3* ± 2.2	23.1 ± 1.7

Results are given as mean ± SD
* $P < 0.05$ for values in the same row within each species

Bending properties

The MORs of the I-beams produced using sawed akamatsu or sugi strands were significantly higher than those produced using roller-splitted strands, while the MOEs were similar. It was observed that the roll-press splitter induced many minor cracks in akamatsu and sugi strands, which are thought to affect the mechanical properties of the strands. In addition, the surface roughness of the roller-splitted strands will affect the bondability of the strands, because, in general, smooth surfaces usually produce good bonding in wood-based composite.[3,10–13] The roller-splitted strands are generally twisted, which causes folding of strands during pressing. The interactions of these factors result in low MOR values of the I-beams produced with roller-splitted akamatsu or sugi strands. However, no significant difference in MOR was found between the preparation methods when bamboo was used. This may be attributed first to the saw preparation method for bamboo, which reduces the surface area of the waxy layer. Secondly, the roll-press splitter helps scratch the waxy outer layer of bamboo, thus enhancing its bondability. Thirdly, due to the straightness of fiber bundles in bamboo, roll-press splitting does not cause strands to twist.

Bond quality

The differences of bond strength between web and flange in the parallel direction were found to be significant for different strand preparation methods for akamatsu and sugi, but not for bamboo; saw-prepared akamatsu and sugi strands showed about 75% and 35% increases in bond strength over that of the roll-press splitter-prepared strands, respectively. The strand wood failure percentages on the web faces for both species were 100% and 74% for saw and roll-press splitter methods, respectively. The above increase in bond strength may be attributed to: the smooth surfaces, which allow better bondability; the absence of minor cracks, which prevent resin starvation; and the absence of folded strands, which allows better contact. In the perpendicular direction, however, no significant differences of bond strength were found between the preparation methods. The bond strength ranged from half to two thirds of those in the parallel direction. For bamboo strand I-beam, although no differences were observed between the two methods, the bond strength tended to be better when roller-splitted strands were used. The reasons may be the same as those discussed for the bending properties.

Dimensional stability

The thickness swelling of the I-beam was always better than the width swelling regardless of the preparation methods. This is because the presence of prefabricated web material helps to prevent the flange from swelling.[1,2]

The width swelling and water absorption percentages for both akamatsu and sugi were improved by changing the preparation method from roll-press splitter to saw. A possible reason may be the strong bond obtained between strands because of the smooth surfaces of saw-prepared strand. Another reason is that strand bundles before pressing into flange tend to be more massive when prepared by roll-press splitter than by saw; massive strand bundles have low bulk density and are thought to have potentially greater swelling force.

Thickness and width swelling of bamboo strand I-beams showed no differences between the preparation methods and are superior to akamastu and sugi strand I-beams. This superiority is due to the low compaction ratio of the bamboo I-beam flange (CR = 1.16), and to the lower percentage of water absorption.

Effect of resin application rate on I-beam basic properties

Table 4 shows the basic properties of the I-beams as affected by the resin application rate between strands in interaction with the low level of strand density.

Bending properties

As far as the results of this study revealed, it appears that the properties of low-density strands have strong dependence on the resin application rates. Both species

Table 4. Effect of resin application rate (between strands) on the I-beam basic properties

Properties	Akamatsu (0.31 g/cm^3)		Sugi (0.34 g/cm^3)	
	Resin application rate between strands (g/m^2)			
	20	40	20	40
I-beam flange density (g/cm^3)	0.70 ± 0.04	0.70 ± 0.01	0.67 ± 0.01	0.66 ± 0.02
MOR (MPa)	56.7* ± 7.5	50.3 ± 4.6	51.8* ± 1.4	47.9 ± 1.2
MOE (GPa)	16.7 ± 1.5	16.4 ± 1.5	16.1 ± 0.5	16.3 ± 1.0
Bond strength // (MPa)	9.3* ± 1.2	7.9 ± 1.3	8.6* ± 0.8	6.2 ± 1.4
Bond strength ⊥ (MPa)	5.0 ± 1.0	4.3 ± 1.3	5.4 ± 2.7	4.3 ± 1.0
Thickness swelling (%)	0.5 ± 0.3	1.0 ± 0.7	0.7 ± 0.2	0.6 ± 0.2
Width swelling (%)	9.5 ± 0.7	9.7 ± 1.7	9.0 ± 1.0	8.4 ± 1.1
Water absorption (%)	33.6 ± 1.5	34.8 ± 1.3	47.6 ± 2.7	47.1 ± 2.4

Results are given as mean ± SD
*$P < 0.05$ for values in the same row within each species

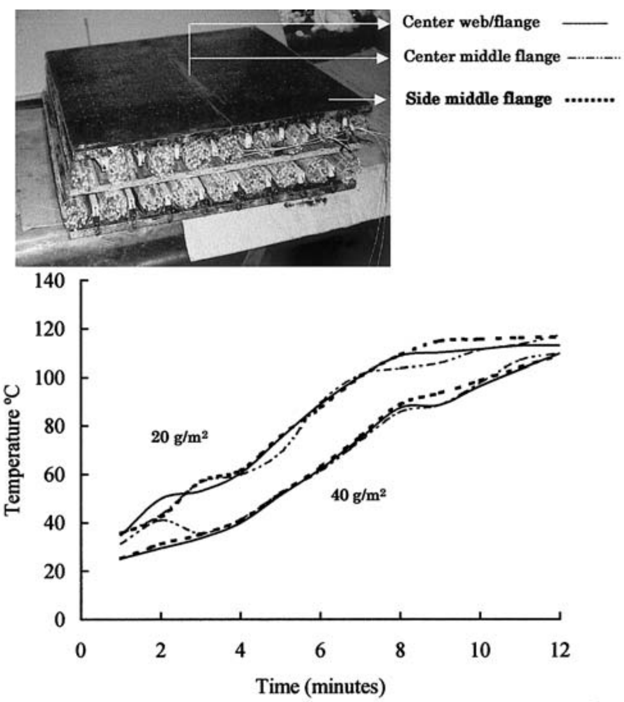

Fig. 2. Temperature rise during conventional hot pressing for panel produced with 20 g/m^2 and 40 g/m^2 resin application rates between strands

(akamatsu and sugi) showed significantly greater MOR at lower application rates than at higher application rates. This may be due to the slow temperature rise (at higher application rates, see Fig. 2) as a result of more condensed water, which negatively affects PF resin curing. On the other hand, the MOE values showed no significant differences between the resin application rates.

Bond quality

Both species showed significantly higher bond quality between the web and flange (in the parallel direction) at lower application rates. It is not easy to find a specific reason for this. However, the curing state of the MDI resin between web and flange (as a result of sufficient temperature); the cure state of the PF resin at the flange part (as a result of saved heating energy at lower application rate), and the availability of sufficient pressing time after the temperature reached 100°C (see Fig. 2) may contribute to the observed effect. In the perpendicular direction, there was a trend of improving bond strength at lower application rate, but it was not significant.

Dimensional stability

Although it is believed that increasing the amount of adhesive improves the dimensional stability,[14–18] it is interesting to note that lower application rates with low strand density showed no significant difference in dimensional stability from samples prepared with higher application rates. The reason may be mainly due to the sufficient cure state of the PF resin at the flange part as a function of sufficient available energy. Because a higher dosage of resin generates more condensed water during pressing than a low dosage, this can negatively affect the curing of PF resin. In addition, the presence of prefabricated web material helps significantly in holding flanges firmly and does not allow them to expand in the thickness direction.[1,2]

Effect of resin application rate on flange part bending properties

Figure 3 shows the results of bending tests for the flange part. The results again showed that a lower application rate had a significantly greater MOR than higher application rates and this may be attributed to the same reason discussed for the I-beam bending properties. No difference in MOE was observed between resin application rates at the same density for both species.

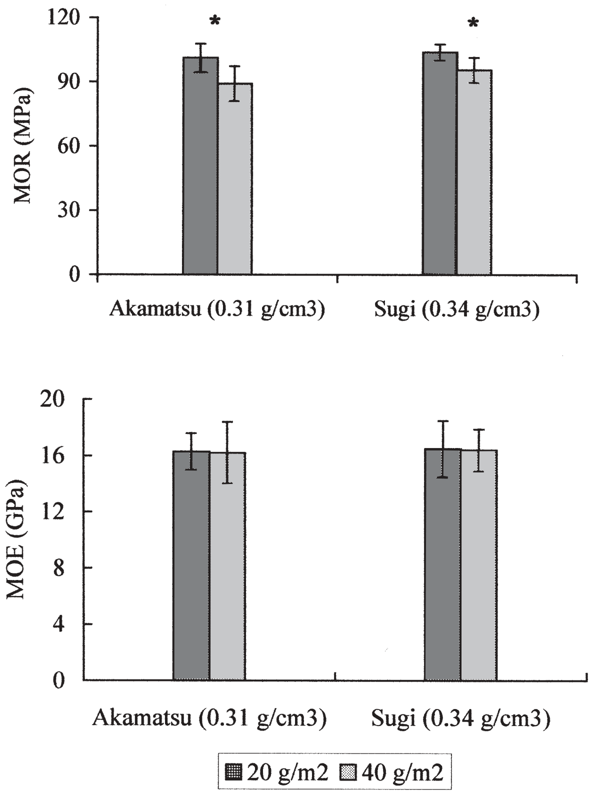

Fig. 3. Effect of the interaction between low strand density and low resin application rate between strands on the flange part bending properties Bars with *asterisks* were significantly different at $P = 0.05$. *MOR*, modulus of rupture; *MOE*, modulus of elasticity

Conclusions

Based on this study the following conclusions can be drawn:

1. Within the compaction ratios (1.4–2.3) investigated in this study, strands with lower density showed slight improvement in dimensional stability and in the bond strength between web and flange, but not in the bending properties of the I-beams.
2. Strand preparation methods were species dependent as far as using akamatsu, sugi, and bamboo strands; strands prepared using roll-press splitting tended to negatively affect dimensional stability and mechanical properties of the I-beams.
3. As far as using akamatsu or sugi strands, low-density strands tended to bond better even at lower resin application rate between strands.

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