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Veneer strand flanged I-beam with MDF or particleboard as web material IV: effect of web material types and flange density on the basic properties

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Abstract The balance of strength between the flange and web parts of veneer strand flanged I-beam was investigated by the following methods: (1) use of different web material types, such as plywood, oriented strand board (OSB), particleboard (PB), and medium density fiberboard (MDF), that have different strength properties; and (2) fabrication of I-beams with low-density flanges using low-density strands with PB web material. Replacing PB or MDF with plywood showed slight significant improvement in the modulus of rupture but not in the modulus of elasticity of the entire I-beam. However, PB and MDF showed competent performance in comparison with OSB, thus strengthening the promising future of the use of PB or MDF as web material to fabricate I-beams. Hot-pressing conditions used for I-beam production exerted slightly adverse effects on the bending properties of PB, but not on MDF, OSB, and plywood web materials. The flange density of 0.60 g/cm^3 was considered to be the lower limit that provides I-beams with balanced mechanical properties and dimensional stability.

Key words I-beam · Web material · Flange density · Mechanical properties · Dimensional stability

Introduction

In the first part[1] of this study series, 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 (MDF) or particleboard (PB) (see Fig. 1). In the second[2] and third[3] parts of this study series, I-beams with balanced mechanical properties and dimensional stability were able to be produced by conventional hot pressing using the optimal combinations among an array of strand dimension, strand preparation method, strand density, resin type between web and flange, resin application rate between strands, pressing time, and moisture content in the wood resin system.

The observed fracture mode[3] was mainly horizontal web shear or buckling, which directed our thinking power to investigate the balance of strength between web and flange parts by either using web materials having different strength properties, e.g., plywood or oriented strand board (OSB) in addition to particleboard and medium density fiberboard, or fabricating low flange density I-beam. However, reasonable compaction ratio (defined as the ratio of the flange density to the strand raw material density) was still required in order not to affect the bending properties as cited in literature.[4,5] The objectives of this part of the study were: (1) to investigate the effect of the web material type on the performance of the I-beams, and (2) to investigate the possibility of fabricating I-beams with low flange density that still have properties comparable with those of I-beams produced in the previous parts of the study (flange density 0.70 g/cm^3).

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Materials and methods

Materials

Japanese red pine (*Pinus densiflora* Seib. et. Zucc) veneer strands with dimensions of 3 × 4 × 470 mm (thickness × width × length), each having a density of 0.51 g/cm^3, and Japanese cedar (*Cryptomeria japonica* D. Don) veneer strands 3 × 4 × 470 mm, each having a density of 0.34 g/cm^3,

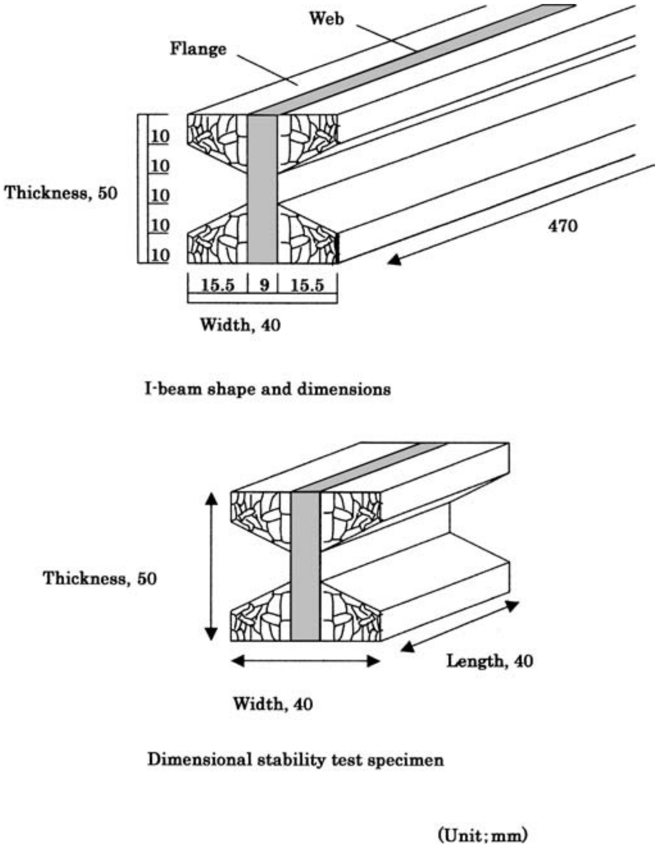

Fig. 1. I-beam cross section and dimensional stability test specimen

were used as raw material for the flange. MDF (450 × 470 × 9 mm) with a density of 0.73 g/cm^3 and particleboard having the same dimensions as the MDF and a density of 0.82 g/cm^3 were used as web materials. Also five-ply plywood with a nominal thickness of 9 mm with plies of 1, 2.5, 2, 2.5, and 1 mm thicknesses and a density of 0.57 g/cm^3 classified as type I panel by JAS[6] was used. OSB having the same nominal thickness as the above-mentioned types and a density of 0.72 g/cm^3 bonded with methyldiphenyl diisocyanate (MDI) resin was also used as web material. Phenol–formaldehyde (PF) resin (D-100) with solid content of 43% and polymeric MDI (PB 1605) formulated by Oshika were used as binders.

I-beam panel fabrication

Two experiments were conducted, using the same forming and pressing method described in part I[1] of this study series. In the first experiments, six I-beam panels (450 × 470 × 40 mm) with a target flange density of 0.7 g/cm^3 were each fabricated conventionally (200°C and 12 min pressing time) using red pine strands and four types of web material: MDF, PB, plywood, and OSB. The plywood and OSB web material were placed so that their face grains or the orientation of the strands laid either parallel or diagonal to the main axis of the I-beam. Other manufacturing conditions were the same as the optimal combinations described in the previous reports;[2,3] moisture content of 12% in the wood–resin system, 25 g/m^2 MDI resin between web and flange, 40 g/m^2 PF resin between strands, and saw-prepared strands.

I-beam panels without binder were produced using the same I-beam manufacturing conditions mentioned above to assess the effect of hot pressing on the web material strength properties; modulus of elasticity (MOE), modulus of rupture (MOR), and the internal bond strength (IB). Water was applied to the strand surfaces and between web and flange to adjust the moisture content to the same level used in panels with binder.

In the second experiment, using Japanese cedar strands as flange material and MDF as the web material, I-beam panels with target flange densities of 0.45, 0.50, 0.55, 0.60, 0.65, and 0.70 g/cm^3 were each fabricated by conventional hot pressing at 200°C. The same fixed conditions applied in the first experiment were used, with the exception that a lower application rate (20 g/m^2) of PF resin was used between the strands. Note that as concluded in the third part[3] of this study series, low density flange material required less binder to obtain the same bond strength as higher density flange material.

Evaluation of the I-beam properties

All beams with the dimensions shown in Fig. 1 were conditioned at 20°C and 60% relative humidity (RH) for 1 week. Five beams from each condition were tested for MOR and MOE using a four-bending test method as used in the previous reports.[2,3] After the bending test, the flange parts were taken and their densities were determined.

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 block shear specimens for each condition having the same shape as those used in previous reports[1–3] were prepared and tested parallel and perpendicular to strand grain to assess the bond strength between web and flange. 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, using ten randomly selected specimens from the above-described blocks.

Using the edge-wise shear test method described in ASTM 1037, shear strength (τ) was assessed for each web material type. Strain gauges were attached to some specimens to assess the shear modulus (G) for each web material type. Note that these values are indicative only, because this method does not describe the measurement of G.

The bending properties (MOE, MOR) for each web material type were assessed flat-wise and edge-wise using specimens that were 20 mm wide × 160 mm long × 9 mm thick.

The MOE and MOR of the web material were assessed before and after hot pressing in flat-wise bending tests using specimens with the same dimensions mentioned above. IB was also assessed before and after hot pressing using specimens of 50 × 50 mm according to the method specified in JIS A5908 (Japanese Industrial Standard).

Table 1. Effect of web material types and placement on the basic properties of the entire I-beam

Properties	*n*	Web material types and placement					
		Plywood		OSB		MDF	PB
		Parallel	Diagonal	Parallel	Diagonal		
Actual flange density (g/cm^3)	6	0.69 ± 0.01	0.69 ± 0.03	0.69 ± 0.02	0.69 ± 0.04	0.69 ± 0.02	0.70 ± 0.01
Modulus of rupture (MPa)	5	56.2a ± 2.2	55.3a ± 2.8	53.5ab ± 3.3	52.6b ± 2.2	49.8b ± 2.3	50.9b ± 4.9
Modulus of elasticity (GPa)	5	15.7a ± 0.92	15.3a ± 1.02	15.5a ± 1.2	15.4a ± 1.2	16.8a ± 0.45	16.4a ± 1.3
Bond strength – parallel (MPa)	10	6.2b ± 0.43	6.1b ± 0.52	6.1b ± 0.67	6.2b ± 0.26	6.2b ± 0.31	7.9a ± 1.4
Bond strength – perpendicular (MPa)	10	4.3a ± 1.03	3.9a ± 0.49	3.9a ± 0.48	3.8a ± 0.72	3.4a ± 0.61	4.2a ± 1.2
Thickness swelling (%)	10	0.79a ± 0.48	0.68a ± 0.44	0.63a ± 0.37	0.63a ± 0.38	1.6b ± 0.59	1.04b ± 0.62
Width swelling (%)	10	7.6a ± 1.1	8.6a ± 0.91	8.0a ± 1.2	8.8ab ± 1.3	8.8ab ± 1.3	9.9b ± 1.3
Water absorption (%)	10	35.7a ± 4 .8	35.8a ± 2.6	35.5a ± 3.02	35.4a ± 2.08	33.9a ± 1.9	34.7a ± 2.3

Results are given as mean ± SD. In the same row, means with the same letter/s are not significantly different at $P = 0.05$
OSB, oriented strand board; MDF, medium density fiber board; PB, particleboard

Table 2. Web material bending (flat-wise and edge-wise) and shear properties

Web material type	Placement	Bending				Shear edge-wise	
		Flat-wise ($n = 9$)		Edge-wise ($n = 9$)		Shear strength (τ) ($n = 9$) (MPa)	Shear modulus (G)[a] ($n = 3$) (GPa)
		MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)		
Plywood	Along grain axis	50.9 ± 8.4	6.5 ± 0.4	36.9 ± 3.9	5.2 ± 0.4	7.1 ± 0.4	0.5 ± 0.03
	Diagonal	–	–	–	–	7.9 ± 0.8	1.2 ± 0.1
OSB	Along grain axis	41.2 ± 7.2	7.3 ± 0.5	23.5 ± 3.3	4.7 ± 0.2	10.1 ± 0.7	1.3 ± 0.2
	Diagonal	–	–	–	–	10.8 ± 0.5	1.7 ± 0.02
MDF		28.4 ± 0.8	2.7 ± 0.1	30.9 ± 0.8	3.6 ± 0.1	10.9 ± 0.4	1.2 ± 0.6
PB		17.4 ± 1.3	3.3 ± 0.2	19.6 ± 1.0	3.2 ± 0.1	8.3 ± 0.4	1.6 ± 0.1

Results are given as mean ± SD
MOR, modulus of rupture; MOE, modulus of elasticity
[a] These values are indicative values; the method did not specify their measurement

Results and discussion

Effect of web material types and placement on the I-beam basic properties

Bending properties

The results of the bending tests are listed in Table 1. As seen in Table 2, plywood showed much higher bending properties when tested flat-wise when compared with PB or MDF; however, when tested edge-wise it showed only slightly better properties than PB or MDF. For this reason, using plywood showed slight significant improvement in the I-beam MOR but not in the MOE. This may be due to: (1) the influence of large flange portions with high elastic properties that sandwiched a small web portion with less elastic properties, and (2) better MDF and PB shear modulus compared with plywood that suppress the effect of better plywood MOE in edge-wise bending over MDF and PB (see Table 2).

It is evident from Table 1 that the placement of plywood or OSB web material showed insignificant differences for all properties studied, which is in contrast to the theoretical belief that the diagonal placement (on laminated wood flanged I-beam with plywood or OSB web material) will give I-beams with better bending properties. In Table 2, although the shear moduli of plywood and OSB were increased in the diagonal placement, the MOE values were not affected. This may be due to the influence of large flange portion with high elastic properties that sandwiched small web-portion with less elastic properties. The overall results from this section suggest a promising future of using MDF or PB as web material in such I-beams.

Bond quality between web and flange

Results for the bond strength between web and flange both parallel and perpendicular to the strand grain are listed in Table 1. As shown in Table 1, use of PB showed significantly higher bond strength in the parallel direction over the other types of web material. However, in the perpendicular direction no significant difference was observed. It was observed that during application of the resin on the web faces, MDF and plywood tended to absorb some of the resin that indicates resin starvation may have occurred, while PB did not. This observation may provide some insight for the higher bond strength in the case of PB. In the case of OSB it was observed that the surface was waxy and the applied resin tended to aggregate, which was considered to affect the bonding efficiency in some parts. This may be proved by the strand wood failure percentage on the web faces which were 100%, 92%, 90%, and 88% for PB, MDF, plywood, and OSB, respectively.

Table 3. Effect of hot pressing on the web material properties

Properties (n = 14)	Plywood		OSB		MDF		PB	
	Before	After	Before	After	Before	After	Before	After
Bending specimen density	0.57 ± 0.9	0.57 ± 1.0	0.72 ± 0.2	0.71 ± 0.2	0.73 ± 0.5	0.72 ± 1.1	0.82 ± 0.9	0.82 ± 1.2
Modulus of rupture (MPa)	63.7 ± 2.6	63.6 ± 4.5	41.2 ± 7.2	41.1 ± 13.9	31.5 ± 1.1	30.6 ± 2.7	19.6a ± 1.4	17.3b ± 1.4
Modulus of elasticity (GPa)	8.7 ± 0.5	8.4 ± 0.8	7.2 ± 0.5	6.8 ± 0.5	2.6 ± 0.2	2.4 ± 0.3	2.9a ± 0.2	2.5b ± 0.2
Internal bond (MPa)	2.05 ± 0.3	2.04 ± 0.2	0.87 ± 0.1	0.84 ± 0.1	1.04 ± 0.2	0.96 ± 0.2	1.15 ± 0.1	1.1 ± 0.1

Results are given as mean ± SD. In the same row, means with the same letter/s are not significantly different at $P = 0.05$

Dimensional stability

The results presented in Table 1 show the width swelling for all I-beams with different web material types. As stated by Abdalla et al.,[1] the total width swelling of the I-beam was mainly caused by the width swelling of the flange part. These results show that width swelling was below 10%, although there are slight differences between the web material types mainly due to the differences in the swelling percentage of the web material itself. The thickness swelling of web material, which was calculated based on the thickness before and after soaking, was found to be 0.25%, 0.3%, 0.4%, and 0.5% for plywood, OSB, MDF, and PB, respectively. The thickness swelling for all beams was less than 2%, which was excellent as compared with width swelling and this is mainly due to the presence of prefabricated web material.[1–3] No difference was observed regarding water absorption among the web material types.

Effect of hot pressing on the prefabricated web material properties

As shown in Table 3, plywood, OSB, and MDF web material properties were not affected by the hot-pressing conditions used for I-beam production. However, the MOR and MOE for PB were significantly reduced by 12% and 14%, respectively, by hot pressing. This may be because the PB surface is more susceptible to the effect of hot steam than MDF, plywood, and OSB. These results are in total agreement with the results reported in the first part[1] of this study series.

Effect of flange density on the I-beam basic properties

Bending properties

Figure 2 shows the effects of flange density on the bending properties of the I-beam, while the mean separation test results are listed in Table 4. Both MOR and MOE showed significant increasing trends as the flange density increased up to 0.6 g/cm^3. Further increase in the flange density showed insignificant increase in the MOR but not MOE, because MOE depends to a large extent on the compaction ratio (CR). The MOE increased until CR reached 1.76, after which no effect of CR increase was observed, as shown in Table 4. These results indicate that a flange density of 0.6 g/cm^3 was reasonable to produce an I-beam with good bending properties when low-density raw material such as Japanese cedar was used, in addition to favorable economical aspects such as the relatively small amount of raw material used and low energy costs.[7,8]

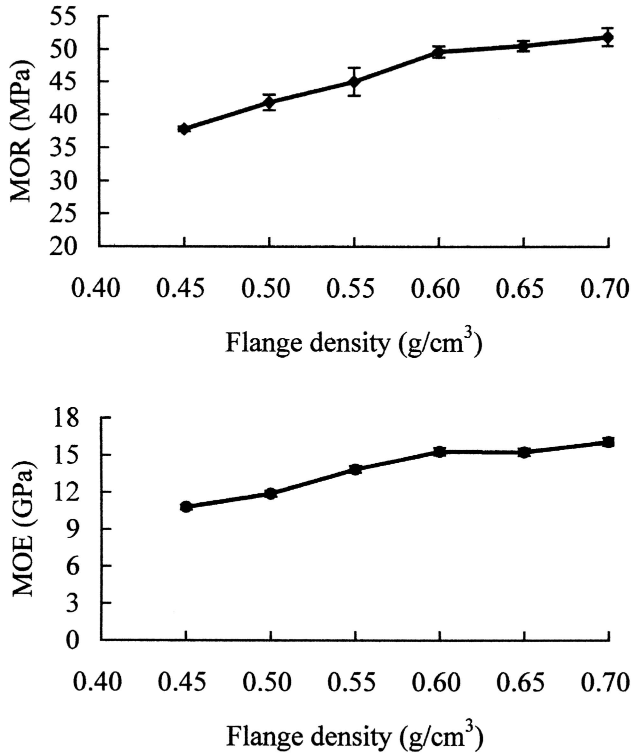

Fig. 2. Effect of flange density on the bending properties of the entire I-beam

Bond quality between web and flange

Figure 3 shows the results of the bond quality as assessed by block shear tests conducted parallel and perpendicular to the strand grain. In the parallel direction, an increasing trend in the bond strength was observed as the flange density increased. In the perpendicular direction, the values of the bond strength were half to two thirds of the values in the parallel direction, and at higher flange density (0.65, 0.70 g/cm^3) it was significantly different from the remaining levels of flange density (0.6, 0.55, 0.5 and 0.45 g/cm^3).

It was found that the strand wood failure percentage on the web faces was 100% for all levels of flange density

Table 4. Results of the mean separation tests for the effect of flange density on the bending properties and width swelling of the I-beam

Flange density (g/cm^3)	Compaction ratio	MOR (MPa)	MOE (GPa)	Width swelling (%)
0.45	1.32	37.7 e	10.7 c	5.5 c
0.50	1.47	41.86 d	11.8 c	7.6 b
0.55	1.62	45.03 c	13.8 b	9.04 ab
0.60	1.76	49.6 b	15.2 a	9.78 a
0.65	1.91	50.5 ab	15.2 a	10.05 a
0.70	2.05	51.8 a	16.09 a	10.27 a

In the same column, means with different letter/s are significantly different at $P > 0.05$

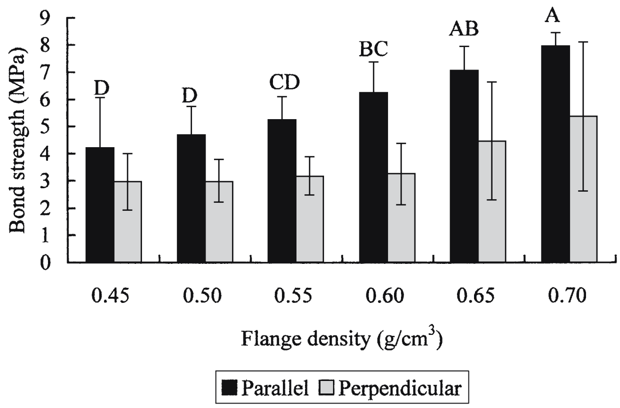

Fig. 3. Effect of flange density on the bond strength between web and flange. *Bars* with different letter/s are significantly different at $P = 0.05$; for all flange density levels the strand wood failure percentage on the web faces was almost 100%

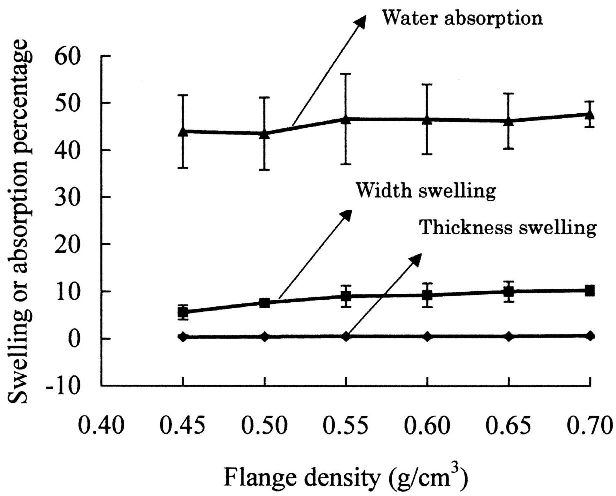

Fig. 4. Effect of the flange density on the dimensional stability of the I-beam

investigated. In addition, it was also observed that in some specimens, the failure occurred between strands or within the strands. This suggests that: (1) the real bond strength between web and flange was more than the reported values, and (2) the bond quality between web and flange depends to a large extent on wood cohesion of the strands themselves and the bond quality between strands. Therefore, bond strength reported here may indicate the bond quality of the flange part that consists of strands.

Dimensional stability

Figure 4 shows the dimensional stabilities of the I-beams, and the results of the mean separation tests for width swelling are listed in Table 4. Generally, the thickness swelling of the beams is less than 2% irrespective of the flange density. This is mainly due to the presence of the prefabricated web material,[1,3] while the presence of a good quality glue line between web and flange may also play a role.[9–11]

Width swelling showed a slight increasing trend with increasing flange density but remained in the area of about 10%, which is comparable with the results obtained in part III[3] of this study series. The increasing trend of width swelling with increasing flange density is mainly due to the differences in CR. The results listed in Table 4 show that when CR reaches 1.76 or larger, the width swelling remain nearly constant.

The overall conclusion from this section was that a flange density of 0.6 g/cm^3 is the lower limit to obtain I-beams with balanced mechanical properties and dimensional stability, when low-density raw material is used.

Conclusions

Based on the above reported results, the following conclusions can be drawn:

1. PB and MDF web materials showed competent performance comparable with that of OSB in I-beams, which suggests a promising future for the use of PB or MDF as web material.
2. Hot-pressing conditions used for I-beam production exerted slightly adverse effects on the bending properties of PB, but not on the MDF, OSB, and plywood web materials.
3. The flange density of 0.60 g/cm^3 (CR = 1.67) was found to be the lower limit that provides I-beams with balanced mechanical properties and dimensional stability when low-density veneer strand is used.

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