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Veneer strand flanged I-beam with medium density fiberboard or particleboard as web material I: the forming method and fundamental properties

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Abstract I-beams flanged with veneer strands with medium density fiberboard (MDF) or particleboard as web material were produced by hot pressing. The forming and pressing method used a special metallic mould that allowed flanges to be formed and bonded to the web at the same time. Many I-beams were able to be produced in a single hot pressing cycle and this method allows the utilization of residues and wastes from wood and wood-composite industries. The forming and pressing method was found to be technically suitable for the production of such I-beams. The fundamental properties of the specimens produced were assessed and the results indicated that the I-beams had promising mechanical properties; for example, the modulus of rupture ranged from 40 to 56 MPa depending on the flange density. The bond quality between the web and flange was found to have a critical effect on the strength of the entire I-beam. The I-beams were found to have relatively high bond strengths between the web and flange, ranging from 3.3 to 5.0 MPa in the parallel direction. The dimensional stability of the I-beams was found to be excellent in the thickness direction of the beam, but not in the compression (width) direction.

Key words I-beam · Long wood strands · Forming method · Biomass waste

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Introduction

Glued engineered wood products have shown remarkable growth in the past few decades because these products are cost effective, easy to use, environmentally friendly, and strong. In addition, their predictable qualities leads to less rework so that builders are increasingly accepting the performance advantages of these products as building materials.[1] The decreased forest area in many countries of the world or the small area available for growing trees, as in the case of Japan,[2] has pressured wood technologists to find innovative methods to maximize the utilization of the available fiber resources to satisfy human needs for excellent wood products. Among these products are the I-beams or wood I-joists. Prefabricated wood I-joists are structural, load-carrying products used in residential and light commercial construction, especially in North America. The flange material for I-joists is typically dimension lumber or laminated veneer lumber (LVL), and the web material is plywood or oriented strand board (OSB).[3]

The proposed forming and pressing method invented in this study has three main characteristics: flanges are formed and bonded to the web at the same time; many I-beams can be produced during a single hot pressing cycle and this method allows the utilization of residues and wastes of wood and wood-composite industries. The method also has a unique pressing direction that is in the width direction of the I-beam, contrary to the normal pressing method used to produce I-beams.

The I-beam produced in this study is of a special type. The flange material is a long wood strand derived from waste veneer, and the web material is either melamine–urea–formaldehyde bonded medium density fiberboard (MDF) or alkali phenol–formaldehyde bonded particleboard (PB). Production of such I-beams was proposed to allow efficient utilization of the available biomass material, especially wood. Raw materials for the flange can easily be obtained from many sources such as waste veneer, small diameter crooked wood species, under-utilized wood species, and scrapped lumber, allowing many timber processing factories to strive toward zero emission of carbon dioxide.

The objectives of the present work were to (1) technically investigate the suitability of the proposed forming and pressing method for production of I-beams, (2) investigate the suitability of using long veneer strands as flange material in combination with MDF and/or PB as web material, (3) investigate the effect of hot pressing on the prefabricated web material properties, and (4) assess the fundamental or basic properties of the produced beams.

Materials and methods

Forming method

Figure 1 shows the forming and pressing method invented in this study. In stage A, the flange material (strands) was made into bundles to fit the metallic mould. In stage B, the web material was placed on the strand bundles after applying resin on both faces of the web material. Areas covered with Teflon bars were not coated with resin. In stage C, the whole set was covered by the upper plate that contained the other half of the flange material. In stage D, the whole set was loaded into the press and compressed to the required thickness. Side press plates were used to keep the side strand bundles in the mould. The I-beam panel was obtained in stage E after removing the metallic mould and the I-beams obtained by cutting the panel (stage F).

Figure 2 shows the details of the special metallic mould plate and the final shape and dimensions of the I-beam. The upper and lower plates each contain eight repeated units of two triangular sloping supports spaced 10 mm from each other. The function of the triangular sloping support was to provide uniformly compressed flanges and to make it easy to delaminate the mould from the panel. Each space between the triangular sloping supports was fitted with a movable Teflon bar in order to keep the strands in the proper position and to prevent them from spreading horizontally. The repeated units were spaced 23 mm from each other. According to this configuration one panel can give eight I-beams with the shape and dimensions shown in Fig. 2.

Manufacture of the I-beam

Japanese red pine (*Pinus densiflora* Seib. et. Zucc) was used as flange raw material. It was prepared in the form of 3-mm thick veneer sheets and was then cut in the form of long wood strands 3 × 6 × 470 mm using a panel saw. The average wood density was 0.52 g/cm^3. The strands were carefully hand sorted to exclude the shorter strands. Melamine–urea–formaldehyde bonded MDF with a density of 0.73 g/cm^3 and phenol–formaldehyde bonded particleboard with a density of 0.82 g/cm^3 were used as web materi-

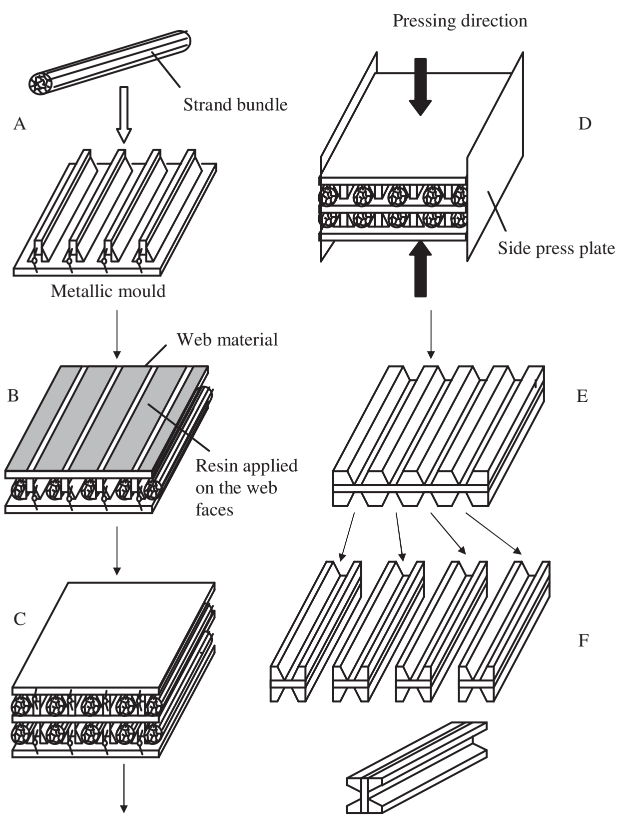

Fig. 1. The forming and pressing method. For full explanation, see text

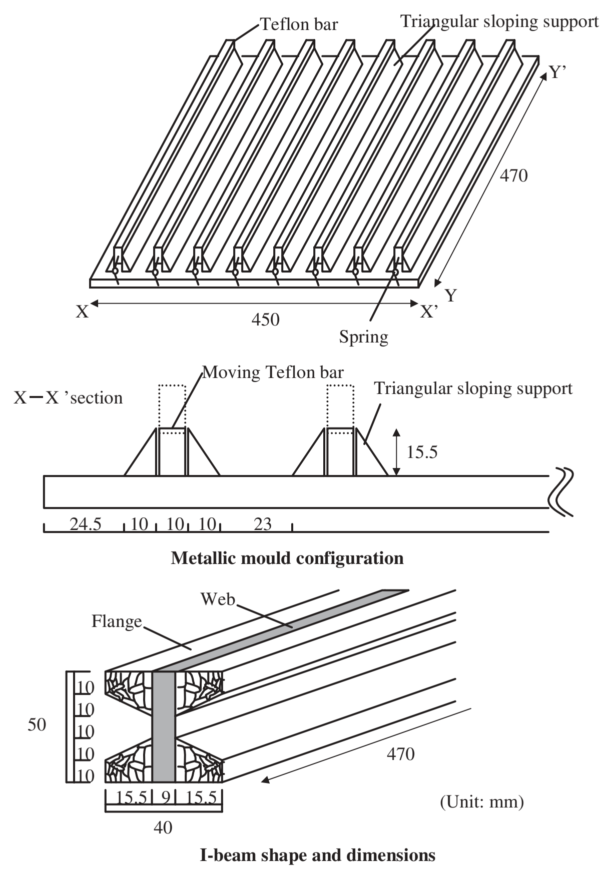

Fig. 2. Metallic mould configuration and I-beam shape and dimensions

Table 1. Combinations of flange density, web material type, and resin application rates

Target flange density (g/cm^3)	Web material type	Resin application rates (g/m^2)				
		Between strands[a]	Between web and flange[b]			
0.6	MDF	20	–	–	100	200
0.7	MDF	20	–	50	100	–
0.8	MDF	20	0	50	100	–
0.8	PB	20	–	50	–	–

MDF, Medium density fiberboard; PB, particleboard
[a] Application rate of 20 g/m^2 is equivalent to 4.3% resin content based on the oven-dried weight of the strand
[b] Resin application rate on the web materials

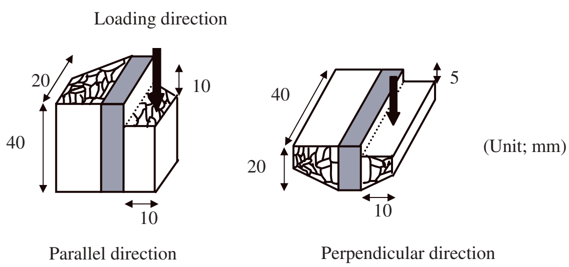

Fig. 3. The shape and dimensions of the block shear test specimens

als after preparation in the form of 450 × 470 mm boards. The nominal thickness of the boards was 9 mm. Phenol formaldehyde (D-100, Oshika) with resin solid content of 43% was used as binder between the flange strands, as well as between the web and flange.

Eight conditions using three target density groups were produced using 20 g/m^2 resin spread rate between strands (calculated based on the resin solid weight and total strand surface area) and different resin application rates between the web and flange as shown in Table 1. MDF was used as web material in seven conditions, and particleboard was used in the remaining condition.

A conventional hot press with a platen of 450 × 470 mm equipped with a platen position control system and side press plates was used. Pressing temperature was 200°C and the total pressing time of 20 min included the press closure. The press time of 20 min was selected after a preliminary study showed that it took about 13 min for the core part of the I-beam panel to reach 100°C. One replicate from each condition was produced.

Property testing

The specimens produced were fully conditioned at 20°C and 60% relative humidity. Five replicates from each condition were tested for bending properties, mainly modulus of elasticity (MOE) and modulus of rupture (MOR) using a three-point bending test method (edge-wise), over a span of 400 mm. Both MOR and MOE were calculated using the I-shape moment of inertia. The actual flange density for each specimen was calculated by measuring the volume and weight of the flange.

Many block specimens 40 mm (long) × 40 mm (wide) × 50 mm (thick) (see Fig. 4) were prepared from the beams and the both edge blocks were discarded. The bond strength between the web and flange was evaluated by conducting block shear tests parallel and perpendicular to the strand grain using ten specimens (for each direction) obtained from the above-mentioned blocks, having the shape and dimensions shown in Fig. 3. After the test, each failed specimen was assessed by eye.

The dimensional stability of the beam, in particular thickness and width swelling, was assessed by an accelerated aging test using wet and dry cycles. Ten specimens were randomly selected from the above-mentioned blocks of I-beam with MDF web. The specimens were initially conditioned at 20°C and 95% relative humidity for 4 weeks, before being soaked in water at 20°C for 20 h. The specimens were then dried at 60°C for 20 h. This wet–dry cycle was repeated seven times. Thickness and width swellings were calculated based on the initial dimensions using the measuring points located at the two positions shown in Fig. 4.

Two I-beam panels with flange densities of 0.8 g/cm^3, one with MDF web and the other with PB web, were produced without binder to assess the effect of hot pressing on the mechanical properties of the web material. The pressing condition was the same as that used for the I-beam panel with binder. Water was applied between strands and between the web and flange to adjust the moisture content of the panel as if 20 g/m^2 (between strands) and 100g/m^2 (between web and flange) of resin were applied. For bending properties, nine specimens of 9 × 20 × 200 mm (thickness × width × length) were selected before and after pressing and were tested using a three-point bending test method (edge-wise) over a span of 160 mm. Fourteen specimens were tested for internal bond strength (IB) before and after hot pressing, using specimens of 50 × 50 mm according to the method specified in JIS A5908 (Japanese Industrial Standard).

Results and discussion

Bond strength

The bond between the web and flange has a critical effect on the bending properties of the I-beam, especially on the

MOR.[4] Generally, the shear strength of wood is strongly affected by the test direction. Shear strength in the direction perpendicular to the wood grain is approximately one third of that in the parallel direction due to the rolling shear.[5,6] For this reason, the bond strength of the I-beams was measured in directions both parallel and perpendicular to the strand grain. Generally, in the perpendicular direction, the average bond strength of beams prepared under different experimental conditions presented in Table 2 are comparable with those of plywood cited in the literature (1.7–2.06 MPa[4] and 1.36–1.71 MPa).[7] It is interesting to note that the beams in this study show excellent bond strength in the perpendicular direction (2.1 MPa–2.8 MPa, in the density group of 0.8 g/cm^3) compared with plywood taking into consideration the lower resin spread rate used to produce these beams.

In the parallel direction, the beams showed reasonable bond strength between the web and flange compared with the block shear bond strength (5.25 MPa)[8] of akamatsu wood bonded at a much higher resin application rate (300 g/m^2) (see Table 1). The I-beams showed bond strengths of about 61%–66%, 81% and 77%–94% of the reported values corresponding to the density groups of 0.6, 0.7, and 0.8 g/cm^3, respectively.

In the perpendicular direction, the average bond strength of the beams ranged from 0.79 to 2.8 MPa depending on the flange density. The average value of the bond strength and wood failure percentage in the parallel direction varied from 3.25 to 4.96 MPa and from 41% to 100%, respectively, depending on the flange density. Generally, the results show the trend of increasing bond strength as the flange density increases. This can be attributed to the perfect contact area between the web and flange that is obtained when higher density flange was formed. The ratio of the bond strength in the perpendicular direction to that in the parallel direction ranged from 0.46 to 0.64 with an average value of 0.53, except for the condition 0.6–100 which showed 0.24. (Notation such as 0.6–100 denotes a target flange density of 0.6 g/cm^3 and a resin application rate between web and flange of 100 g/m^2). It is interesting that the bond strength of the I-beams in the perpendicular direction was half that in the parallel direction, which, in turn, is about 200% higher than that of wood itself. This might be attributed to the property differences between the web and flange materials.

Within the low and medium density group, increasing the resin application rate between the web and flange did not affect the bond strength in the parallel direction. However, in the higher density group, increasing the application slightly increased the bond strength. For example, increasing the resin application from 0 g/m^2 to 100 g/m^2 resulted in an increase in the bond strength of approximately 10%. This result indicates that using a low application rate (but not as low as 0 g/m^2) is sufficient to produce good bond strength between the web and flange of these beams.

Use of PB as the web material showed similar bond strength to cases using MDF as web material. However, there is a great difference regarding the wood failure of strands on the web surface between PB (51%) and MDF (99%). This may be attributed to the different surface characteristics of PB and MDF. The MDF has high-density faces that allow the formation of good bonding between the web and the adjacent strands.

Bending properties

The flange densities of the bending specimens and the results of the bending tests of whole beams are shown in Table 3. The actual flange densities were closer to each other than originally designed.

The results showed that at the same resin application rate, I-beams with high flange densities tended to have high bending properties. The results also showed that in the low-density (0.6 g/cm^3) and medium-density (0.7 g/cm^3) groups no significant differences were found between the resin-application rates for MOE and MOR. For the high-density group (0.8 g/cm^3), applying no resin between the web and

Table 2. Effect of resin application rate and flange density on the bond strength between web and flange

Designation[a]	Flange density (g/cm^3)	Bond strength (MPa)		Percentage of wood failure[b]	n
		∥	⊥		
0.6–100	0.64 ± 0.03	3.25 ± 0.94	0.79* ± 0.63	41 ± 29	12
0.6–200	0.65 ± 0.02	3.47 ± 1.48	1.84 ± 1.23	69 ± 42	13
0.7–50	0.68 ± 0.03	4.26 ± 0.47	1.97 ± 0.49	93 ± 17	14
0.7–100	0.69 ± 0.02	4.24 ± 0.84	2.11 ± 0.71	83 ± 29	12
0.8–0	0.75 ± 0.03	4.02* ± 1.09	2.09* ± 0.94	80 ± 33	14
0.8–50	0.75 ± 0.03	4.96 ± 0.62	2.80 ± 0.46	99 ± 3	14
0.8–100	0.74 ± 0.03	4.43* ± 0.61	2.45 ± 0.76	100 ± 0	13
0.8–50-PB	0.75 ± 0.04	4.14* ± 0.92	2.63 ± 0.74	51 ± 36	14

Results are given as mean ± SD

* $P < 0.05$ for values in the same column and within each density group

[a] For designations such as 0.6–200, the first number is the target flange density (g/cm^3) and the second is the resin application rate between web and flange (g/m^2)

[b] Wood failure refers to failure of strands on the web material faces

flange showed the same MOE and MOR values as those for the lower density groups. This can be attributed to the good contact area obtained when a high density flange is formed which results in reasonably strong bonds between strands as well as between the web and flange. This result confirms the influence of the bond strength between the web and flange on the bending properties of the beams. This was also indicated by the fracture modes shown in Table 4 in which most of the failure occurred between the web and flange in this test method.

Bending tests were conducted with small span/height ratio which induces shear effects on the tested beams. Therefore, different fracture modes were observed as shown in Table 4. The main fracture mode was delamination between the web and flange, followed by breaking at the middle of the web. This indicates that the bond strength between the web and flange and the strength of the web material itself are very important factors that influence the bending properties of the beams. In addition, the combinations with high bond strengths (Table 2) showed low incidence of delamination between the web and flange while the others showed delamination of the web material itself.

Although the use of PB as web material exhibited fracture modes a little different from those of MDF, as shown in Table 4. There was no significant difference in the I-beam bending properties between PB and MDF webs, as shown in Table 3.

Dimensional stability

Figure 4 shows some results of the wet and dry cycle tests. Generally, the dimensional stability of the long strand flanged I-beams was found to be excellent in the thickness direction, but not in the compression (width) direction. The total width swelling of the I-beam was mainly caused by width swelling of the flange part, because the swelling and shrinkage of the MDF was found to be less than ±0.5% throughout the treatment cycles. Width swelling of the beams tended to be higher as the density increased and this can be attributed to the fact that during hot pressing, applying high pressure to achieve the target panel thickness while the target density was high resulted in great deformation and shrinkage of the wood cells. When the compressed

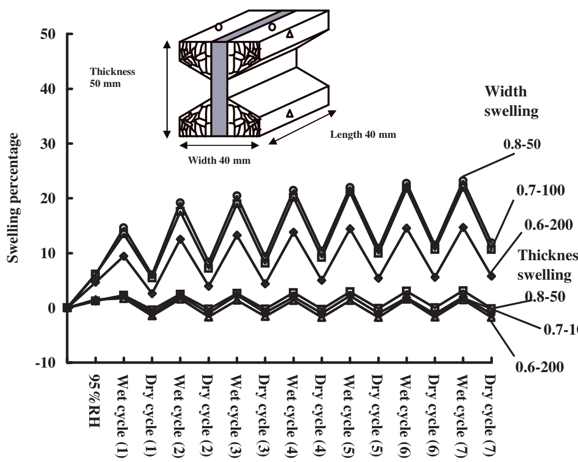

Fig. 4. I-beam thickness and width swelling percentage as influenced by the flange density and resin application rate between the web and flange. (*Open circles* on the specimen indicate the flange thickness measurement points. *Open triangles* indicate the flange width measurement points. For designations such as 0-8-50, the first number is the target flange density (g/cm^3) and the second is the resin application rate between web and flange (g/m^2)

Table 4. Fracture modes and their observed frequency in the I-beam bending test

Designation	DWF	DW	WS	DS
0.6–100	4/5	1/5		
0.6–200	4/5	1/5		
0.7–50	3/5	2/5		
0.7–100	3/5	1/5	1/5	
0.8–0	3/5	2/5		
0.8–50	1/5	3/5	1/5	
0.8–100		4/5		1/5
0.8–50-PB	2/5	1/5	2/5	

DWF, Delamination between web and flange; DW, delamination within the web; WS, web shear; DS, delamination between strands (flange part)

Table 3. Effect of resin application rate and flange density on the bending properties of the entire I-beam

Designation	Flange density (g/cm^3)	Bending properties		*n*
		MOR (MPa)	MOE (GPa)	
0.6–100	0.64 ± 0.03	40.5 ± 3.4	4.9 ± 0.25	5
0.6–200	0.65 ± 0.02	44.2 ± 1.6	5.2 ± 0.26	5
0.7–50	0.68 ± 0.03	42.0 ± 2.1	5.2 ± 0.16	5
0.7–100	0.69 ± 0.02	41.5 ± 3.4	5.5 ± 0.41	5
0.8–0	0.75 ± 0.03	43.5* ± 5.9	5.7* ± 0.29	5
0.8–50	0.75 ± 0.03	53.2 ± 3.6	6.1 ± 0.45	5
0.8–100	0.74 ± 0.03	56.8 ± 3.4	6.5 ± 0.38	5
0.8–50-PB	0.75 ± 0.04	49.9 ± 7.6	5.5* ± 0.43	5

Results are given as mean ± SD

MOR, Modulus of rupture; MOE, modulus of elasticity

* $P < 0.05$ for values in the same column and within each density group

Table 5. Dimensional stability properties of the I-beam with MDF web material at wet cycles 1 and 7

Designation	Flange density g/cm^3	Thickness swelling			Width swelling		
		95% RH	Cycle 1 wet	Cycle 7 wet	95% RH	Cycle 1 wet	Cycle 7 wet
0.6–100	0.64	0.7 ± 0.2	1.3 ± 0.5	0.9 ± 0.4	4.8 ± 0.5	10.5 ± 1.9	17.5 ± 3.2
0.6–200	0.65	1.3 ± 0.3	2.3 ± 1.1	2.0 ± 1.0	4.7 ± 0.5	9.4 ± 1.3	14.7 ± 1.0
0.7–50	0.68	1.1 ± 0.2	1.9 ± 0.7	1.5 ± 0.4	5.5 ± 0.6	12.6 ± 1.6	21.2 ± 2.4
0.7–100	0.69	1.3 ± 0.3	2.3 ± 0.7	3.1 ± 1.6	6.2 ± 0.5	13.5 ± 1.4	22.0 ± 1.0
0.8–0	0.75	1.5 ± 1.1	2.5 ± 1.4	2.3 ± 2.8	5.9 ± 0.5	16.2 ± 1.8	27.4 ± 3.5
0.8–50	0.75	1.5 ± 0.6	1.7 ± 0.5	1.5 ± 1.4	6.0 ± 0.5	14.6 ± 2.5	23.2 ± 3.4
0.8–100	0.74	1.4 ± 0.4	2.6 ± 0.8	3.1 ± 1.3	5.7 ± 0.6	13.6 ± 1.8	22.7 ± 2.8

Results given as mean ± SD
RH, Relative humidity

0.6-200 sample 0.8-0 sample

Fig. 5. Examples of the flange deformation after seven wet and dry cycles

wood cells were then subjected to higher moisture conditions they started to absorb water to regain their original form and shape, resulting in swelling of the I-beam in its width direction. This explanation is similar to that cited in the literature for various types of wood-composite panels.[9,10] Also from Fig. 4, it is obvious that swelling in the width direction continued to increase with increasing number of treatment cycles; however, the thickness did not show a clear increment.

As shown in Table 5, the I-beams showed small thickness swelling ranging from 0.7% to 1.5%, and large width swelling ranging from 4.7% to 6.2% when fully reconditioned at 95% relative humidity. The thickness of the high-density group beam (0.8–100) increased from 1.4% at 95% relative humidity to 2.6% at the end of the first wet cycle to 3.1% at the end of the seventh wet cycle. However, the swelling in the pressing (width) direction increased from 5.7% at 95% relative humidity to 13.6% at the end of the first wet cycle to 22.7% at the end of the seventh cycle. The reasons for the small thickness swelling compared with the width swelling are the pressing direction of the I-beam panel, and the presence of the prefabricated web material that holds the flange strand in its vicinity strongly prevents swelling.

The mode of deformation of the flange part at the end of the treatment cycles (Fig. 5) indicated that increasing the resin spread rate between strands will improve the bond between strands and prevent them from swelling caused by the elastic recovery of the wood. As a result, the swelling at the flange part will be reduced and result in a general reduction of overall thickness and width swelling. This finding is in agreement with those of other studies[11–14] that found sufficient bond strength between the wood particles in any wood-composite panel improves the dimensional stability of the panel by preventing elastic recovery. The observation of reduced swelling can be taken as an indicator of the degree of resin cure. Improvement of the dimensional stability can be achieved by steam-injection pressing. This is because heat helps elimination of the density gradient (profile) through the flange part, which allows good contact area between strands (by increasing the plasticization of wood) as well as between the web and flange.

Table 6. The effect of hot pressing on the web material properties

Web material	MOR (MPa)	MOE (GPa)	IB (MPa)
MDF Before pressing	31.5 ± 1.1	2.60 ± 0.17	1.04 ± 0.07
After pressing	30.6 ± 2.7	2.44 ± 0.25	0.96 ± 0.15
PB Before pressing	19.6* ± 1.4	2.91* ± 0.15	1.15 ± 0.07
After pressing	17.3 ± 1.4	2.50 ± 0.22	1.11 ± 0.07
n	9	9	14

Results are given as mean ± SD
IB, Internal bond strength
* $P < 0.05$ for each web material type in the same column

Web property changes

Table 6 shows the results of the statistical analysis of the mechanical properties of the web material before and after pressing. The results indicate that the IB was reduced because of the pressing temperature and pressure for both MDF and PB, but these reductions were small and not significant. The results also indicate that the MOE and MOR for PB were significantly reduced by 14% and 12%, respectively, by pressing. In contrast, no significant effect was found for the pressing method on the MDF bending properties.

Conclusions

The following conclusions can be drawn on the basis of the results obtained in this study:

1. The proposed forming method was found to be technically feasible.
2. The bond strength between the web and flange of the I-beams was found to be reasonable and promising. Further study to improve the bond strength is justified.
3. The beams showed promising bending properties that will improve through changing the test method, use of the proper span/height ratio, and improving the bond strength between strands and between the web and flange.
4. Dimensional stability was found to be excellent in the height direction of the beam, but not in the compression (width) direction. Increasing the resin spread between the strands is strongly recommended to improve the dimensional stability properties. A further suggestion for improving the dimensional stability is the production of I-beams under steam-injection pressing.
5. Pressing temperature and pressure conditions used for I-beam production exerted slightly adverse effects on the mechanical properties of PB web material, but not on MDF web material.

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