J Wood Sci (2004) 50:400–406
DOI 10.1007/s10086-003-0584-0

ORIGINAL ARTICLE

Ashraf M.A. Abdalla · Noboru Sekino

Veneer strand flanged I-beam with MDF or particleboard as web material II: effect of resin type, application rate, strand dimension, and pressing time on the basic properties

Received: April 21, 2003 / Accepted: September 17, 2003

Abstract Optimization of the manufacturing conditions of the veneer strand flanged I-beam invented in the previous study was investigated using different combinations of strand dimensions, resin types between web and flange, different pressing times, and different wood–resin moisture contents under conventional hot pressing conditions. The main results revealed that the strand dimensions have no effect on the bending properties of the flange part and the dimensional stability of the I-beam. Increasing the resin application rate between strands was found to improve the dimensional stability of the I-beams. The use of isocyanate (MDI) resin between web and flange significantly improved the bond strength between web and flange, the modulus of rupture of the I-beam, and the modulus of rupture of the flange part. Dimensional stability was also improved. Shortening the pressing time from 20 to 12 min was found to be feasible. Using low wood-resin moisture content was found to interfere with the curing of the phenol–formaldehyde (PF) resin at the flange part resulting in poor quality beams. Of the three moisture content levels tested, 12% was found to be the optimal level for producing I-beams with balanced mechanical properties and dimensional stability.

Key words I-beam · Resin type · Density profile · Pressing time · Wood–resin system moisture content

A.M.A. Abdalla
United Graduate School of Agricultural Science, Iwate University, Morioka 020-8550, Japan

N. Sekino (✉)
Faculty of Agriculture, Iwate University, 3-18-8 Ueda, Morioka 020-8550, Japan
Tel. +81-19-621-6174; Fax +81-19-621-6174
e-mail: sekino@iwate-u.ac.jp

Part of this work was presented at the 53rd Annual Meeting of the Japan Wood Research Society, Fukuoka, March 2003

Introduction

Resin adhesives are a vital part of glued wood composites, varying from a relatively small portion up to 32% of the total manufacturing cost of the item being glued and marketed in USA.[1] High-cost resin adhesive must be used at reasonable application rates catering for both the excellent properties of the product and the economical feasibility. When considering lower application rates, consideration of superior performance and quality of the composite must be maintained.

In the first part of this study, a new method for fabricating veneer strand flanged I-beams was developed and the technical feasibility of this method to produce such a type of I-beam was confirmed. Based on the results of the earlier study (part I),[2] increasing the resin application rate between strands and replacing phenol–formaldehyde (PF) resin between web and flange with isocyanate (MDI) are the main recommendations to be considered in this part of the study. In addition, reducing the moisture content (MC) of the wood–resin system is thought to somehow help in the curing of PF resin, allowing the possibility of shortening the pressing time. Using MDI resin between web and flange may not only help to improve the bond strength between web and flange but also overcome the problem of delamination of the I-beam panel from the metallic mold.

Density profile or density distribution through the pressing direction of the wood composite panel has been described as a vital characteristic, which correlates with the strength and physical properties of the composite panel.[3–6] The resulting shape of the density profile after pressing is affected by three main factors: furnish moisture content, mat structure, and the pressing environment.[7] The difference in the geometry between strands and other wood particles may affect the density profile of the I-beam. Measuring the density profile for the flange part of the I-beam will help in the interpretation and explanation of the observed results for the bond strength between web and flange.

The objectives of this part of the study were: (1) to evaluate the effect of increasing the resin application rate between strands on the mechanical properties and dimensional stability of the I-beam, (2) to study the effect of using different resin types between web and flange on the basic properties of the I-beam, (3) to examine the possibility of producing such I-beams using a short pressing time, and (4) finding the optimum wood–resin system moisture content that gives I-beams with acceptable properties after conventional hot pressing.

Materials and methods

Raw material

Japanese red pine (*Pinus densiflora* Seib. et. Zucc) veneer strands 4 mm wide and 470 mm long with thicknesses of 3, 4, and 5 mm, and density of 0.52 g/cm^3 were used as flange raw material with a moisture content of 10%. Melamine-urea formaldehyde-bonded medium-density fiberboard (MDF) (450 × 470 × 9 mm) with density of 0.73 g/cm^3 and PF-bonded particleboard (having the same dimensions as the MDF) and density of 0.82 g/cm^3 were used as web materials. PF resin (D-100) with solid content of 43% and polymeric isocyanate (PB 1605) formulated by Oshika were used as binders.

I-beam panel fabrication

The experimental approach consisted of three experiments, using the same forming and pressing method described in part I of this study.[2] In the first experiment, ten I-beam panels with target flange densities of 0.7 g/cm^3 and moisture contents of 17% were each fabricated conventionally (200°C and 20 min pressing time) using the combinations shown in Table 1. In the second experiment, five I-beam panels were fabricated using five levels of pressing time ranging from 12 to 20 min and the following fixed conditions: wood–resin system moisture content of 12%, PF resin between strands at an application rate of 40 g/m^2 (8.5% resin solid weight relative to wood strand oven-dry weight), and MDI resin between web and flange at an application rate of 25 g/m^2. In the third experiment, I-beam panels were each fabricated using 12 min of pressing time at wood resin system moisture contents of 8%, 10%, and 12% with a PF resin application rate of 40 g/m^2 between strands and 25 g/m^2 MDI resin between web and flange.

Evaluation of the I-beam properties

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 including 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) crosshead speed of 5 mm/min, and (4) the bending properties were calculated using the I-shape moment of inertia. The total span was obtained by using metallic extension bars, which, from a pilot study, were found to be insignificantly different from using full-span wooden beams. After discarding the edge parts of the beam, many 40 mm long block specimens were prepared. From each condition, ten randomly selected specimens (having the same shape and dimensions as those used in part I)[2] were prepared to assess the bond strength between web and flange using the block shear test. The dimensional stability, regarding the thickness and width swelling, was evaluated by a 24-h water immersion test at 20°C. Ten randomly selected specimens from the abovedescribed lot for each condition were used. To assess the bending properties of the flange part, specimens that were 9 × 14 × 220 mm (thickness × width × length) were prepared from the flange part (see Fig. 1) and tested using a three-point bending test method edge-wise at a clear span of 200 mm. The density profile along the width direction of the flange was evaluated by an X-ray radiography scanning machine using six randomly selected replicates having approximate dimensions of 50 × 50 × 14 mm. The samples consisted of five rectangular blocks prepared from saw-delaminated flange of 10 × 14 mm cross section.

Table 1. Combinations of strand dimensions, resin type, application rate, and web material

Strand type	Dimensions (mm)[a]	Application rate and resin type				Web material
		Between strands (g/m^2)	Between web and flange (g/m^2)			
		Phenol	Phenol	Isocyanate (MDI)		
A	3 × 4 × 470	20 (4.3%)[b]	50	–	–	PB
		40 (8.5%)	50	–	–	PB
B	4 × 4 × 470	20 (4.3%)	50	–	–	PB
		40 (8.5%)	50	25	50	PB
		20 (4.3%)	–	25	50	MDF
C	5 × 4 × 470	20 (4.3%)	50	–	–	PB
		40 (8.5%)	50	–	–	PB

PB, particleboard; MDF, medium density fiberboard
[a] Thickness × width × length
[b] Resin content expressed as percentage of resin solid weight to wood oven-dry weight

Results and discussion

PF-bonded I-beam means I-beam with flange bonded to web by PF resin, while MDI bonded I-beam implies the flange bonded to the web by MDI resin.

Effect of strand dimension, resin type, and application rate on I-beam basic properties

Bond quality

The results of the tests for bond strength between web and flange of the PF bonded I-beam are listed in Table 2. The results indicated that no significant differences were found between strand dimensions and/or the resin application rate between strands. The values were lower than those reported in part I (3.3–4.9 MPa)[2] due to insufficient cure of the PF resin. Normal curing requires 120°–140°C[8,9] and a temperature of only 100°C was recorded during the manufacturing process.

Figure 2 presents the results of the tests for bond strength between web and flange for PF and MDI bonded I-beam. Highly significant improvement was found when MDI resin was used, even at low application rates. This improvement can be explained by the fact that the temperature between web and flange was sufficient to cure the MDI resin. This result indicated that low MDI resin application rate is sufficient to produce excellent bond strength, because doubling the application rate resulted in an increase in the bond strength of approximately 20%. Also, the results showed an interesting feature that, in the perpendicular direction, the bond strength values were two thirds of the parallel values, which is higher than that of wood itself (approximately one third).[10,11]

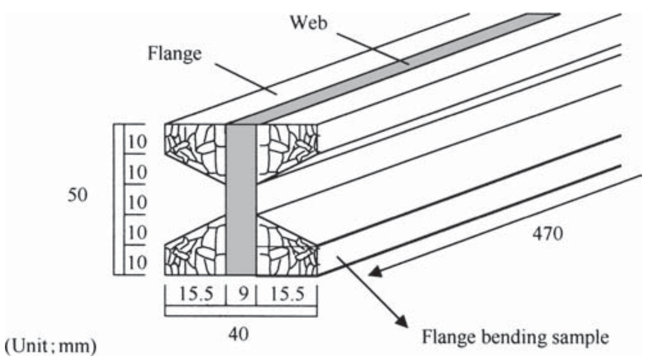

Fig. 1. I-beam shape and position from which the flange bending samples were taken

Bending properties of the I-beams

The results of the statistical analysis (SAS)[12] of the MOE and MOR for PF bonded I-beams are listed in Table 2. Regarding the MOE, no significant differences were found between either the strand dimension and/or the resin application rate between strands. Although the resin application rate was doubled, the MOR value did not improve. This was mainly due to insufficient bonding between strands as well as between web and flange because the PF resin did not sufficiently cure as a result of insufficient temperature. Thus, all beams showed delamination between web and flange in fracture.

Figure 3 shows the results for the MOE and MOR of the MDI bonded I-beam. The MOE showed little significant difference from that of PF bonded I-beam. However, the MOR showed substantial improvement over the MOR for the PF bonded I-beam, even at a low application rate of

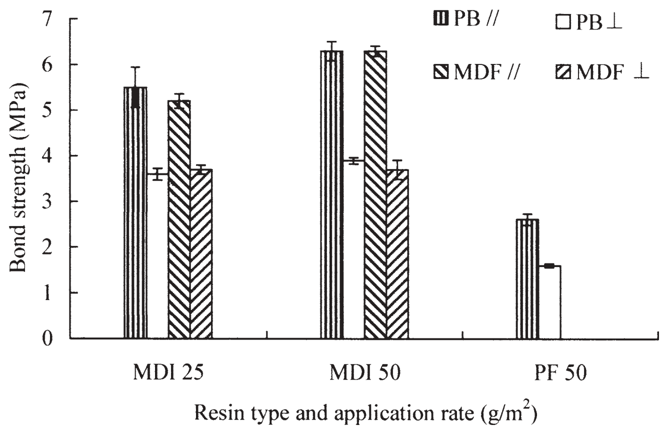

Fig. 2. Effect of resin type and application rate on the bond strength between web and flange. *PB*, particleboard, *MDF*, medium density fiberboard; *MDI*, isocyanate; *PF*, phenol-formaldehyde

Table 2. Effect of strand dimension and resin application rate on I-beam basic properties

Resin application rate between strands (g/m^2)	Strand type	MOR (MPa)	MOE (GPa)	Bond strength (MPa)		Width swelling (%)	Thickness swelling (%)
				Parallel	Perpendicular		
20	A	34.1 ± 0.21	16.00 ± 0.11	2.49 ± 0.53	1.59 ± 0.19	35.2 ± 6.20	1.5 ± 0.54
	B	34.2 ± 0.54	16.01 ± 0.22	2.51 ± 0.30	1.61 ± 0.22	31.8 ± 5.10	1.6 ± 1.50
	C	34.1 ± 1.80	16.10 ± 0.21	2.49 ± 0.32	1.58 ± 0.13	29.2 ± 1.80*	1.1 ± 0.58*
40	A	34.4 ± 0.71	16.0 ± 0.19	2.63 ± 0.39	1.62 ± 0.11	22.0 ± 3.03*	0.98 ± 0.36
	B	35.7 ± 1.90	16.01 ± 0.18	2.62 ± 0.61	1.63 ± 0.13	23.2 ± 3.80	1.01 ± 0.29*
	C	35.8 ± 1.20	16.01 ± 0.22	2.64 ± 0.63	1.63 ± 0.11	25.2 ± 2.60	0.89 ± 0.36

MOR, modulus of rupture; MOE, modulus of elasticity
* $P < 0.05$ within each resin application rate

MDI. All MDI bonded I-beams tested showed horizontal web shear fracture modes, which means that excellent or sufficient bond between strands as well as between web and flange were obtained due to satisfactory cure conditions for both PF and MDI,[13–15] because MDI cure at low temperature saves energy for PF resin curing.

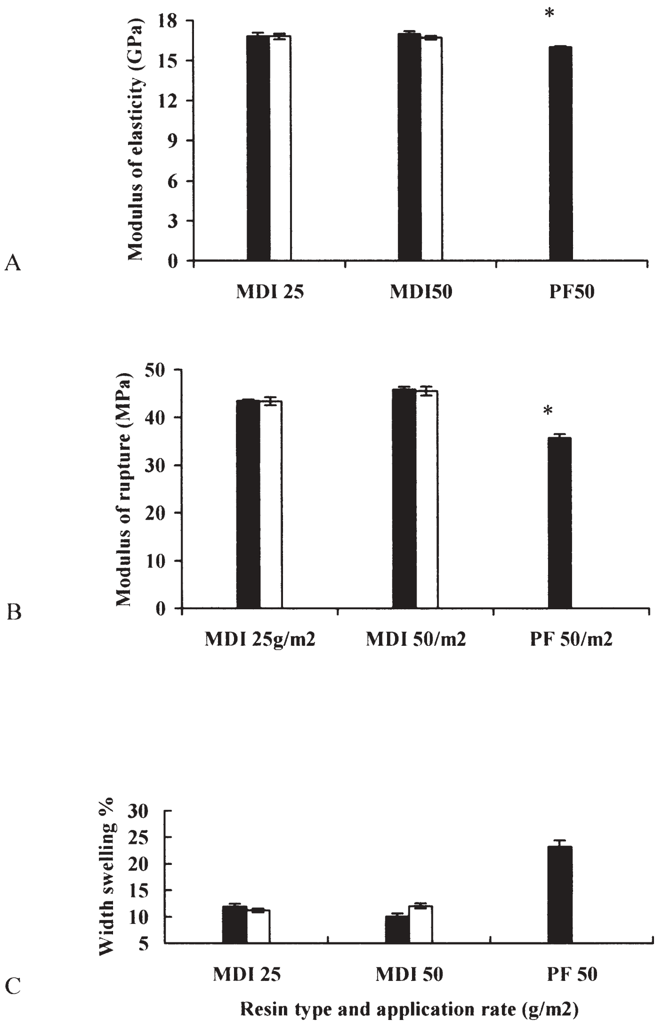

Fig. 3. Effects of resin type between web and flange on **A** the modulus of elasticity, **B** the modulus of rupture, and **C** the dimensional stability. *Asterisk*, significant difference at $P < 0.05$. *Filled bars*, PB; *open bars*, MDF

Dimensional stability

The results of statistical analysis (SAS)[12] of the percentage increase in width and thickness for PF bonded I-beams are listed in Table 2. At low application rate there was a tendency of improving the width swelling by increasing the strand dimension (thickness), while the inverse tendency was observed at high application rates, i.e., the improvement occurred with decreasing strand thickness.

In each strand dimension, significant reduction in the width swelling with increasing resin application rate was observed, which is in total agreement with previous findings[14–18] that increasing the level of adhesive decreases the width and thickness swelling as well as water absorption of flake board, particleboard, and oriented strand board (OSB). Although the thickness swelling was also reduced by increasing the resin application rate, the swelling is excellent compared to width swelling due to the presence of prefabricated web material. Figure 3 showed significant improvement of width swelling by using MDI rather than PF resin. The width swelling was reduced from 23% to 10% and this is attributed to the good bond (as a result of well-cured PF resin) between strand at the flange part preventing them from swelling and the strong bond between web and flange which holds the flange firmly to the web.

Properties of flange part

Bending properties

According to the data analysed by SAS[12] and listed in Table 3, the difference in MOE was found to be insignificant between strand dimensions and/or the PF resin application rate between strands. Increasing the PF resin application rate between strands from 20 to 40 g/m^2 showed significant increase in the MOR by 23% while using MDI resin between web and flange showed further increases in the MOR. The reason behind this increase lies in the good bond obtained between strands as result of the optimum curing environment for PF resin created by MDI through its reac-

Table 3. Effect of strand dimension, resin type, and application rate on the basic properties of the flange part

Resin application rate between strands (g/m^2)	Resin type and application rate between web and flange (g/m^2)[b]	Strand type	Density (g/cm^3)	MOR (MPa)	MOE (GPa)
20 (4.3%)[a]	PF 50	A	0.68 ± 0.001	54.8 ± 6.9	16.09 ± 0.32
		B	0.69 ± 0.002	54.7 ± 5.1	16.00 ± 0.29
		C	0.69 ± 0.004	53.9 ± 5.8	16.04 ± 0.26
40 (8.5%)	PF 50	A	0.70 ± 0.003	70.4 ± 4.2*	16.01 ± 0.17
		B	0.69 ± 0.007	69.1 ± 6.6*	16.04 ± 0.19
		C	0.70 ± 0.004	68.3 ± 8.1*	16.04 ± 0.19
40 (8.5%)	MDI 25	C	0.68 ± 0.026	93.3 ± 2.7**	16.60 ± 1.40
	MDI 50	C	0.70 ± 0.031	96.2 ± 7.7**	16.70 ± 0.33

[a] Resin content: see Table 1
[b] Resin applied on the web faces
* $P < 0.05$
** $P < 0.01$

tion with some moisture[19,20] and cure at low temperature saving energy to cure the PF resin at the flange part.

Density profile

Figure 4 shows the trend of the density profile for some representative samples, measured at the I-beam's flange part. MDI bonded I-beam showed a near-flat density distribution; the maximum density observed at the flange surface and the minimum density observed near the web surface were about only 7% higher and lower than the mean density. In contrast, when PF resin was used the density gradient was steeper than that of the MDI bonded I-beam; this trend is much clearer when small dimension strands were used.

The data listed in Table 4 shows that increased PF resin application rate between strands from 20 to 40 g/m^2 did not show clear differences in the density distribution or profile; the percentage difference between the minimum density and the mean density was almost equal for both resin application rates (between strands) within each strand type. However, no consistent trend was observed for the maximum density.

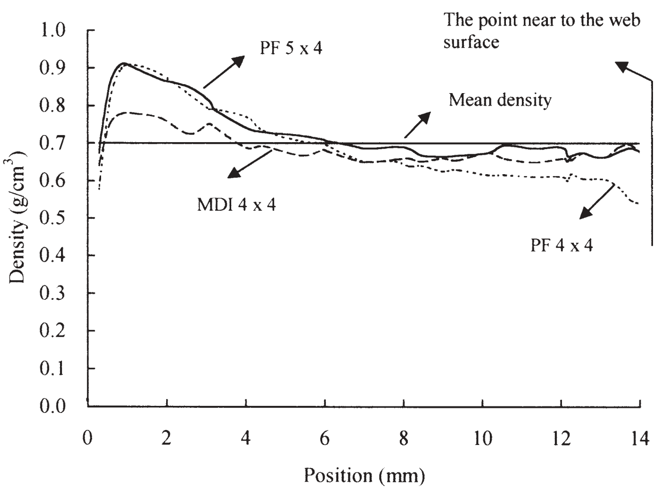

Fig. 4. Effect of strand dimension and resin type between web and flange on density profile. Dimensions are given as thickness × width

Effect of pressing time on I-beam basic properties

The bond strength between web and flange, the MOR, and MOE of the I-beam produced using different pressing times are listed in Table 5. The results showed that I-beams with acceptable mechanical properties and dimensional stability could be produced with short pressing times (e.g., 12 min).

Bond quality

Results showed that no significant differences were found between bond strengths between web and flange for different pressing times. This means the presence of good contact between web and flange plus sufficient cure state of the MDI results in excellent bond quality regardless of the pressing time.

Bending properties

Differences in MOE were found to be insignificant for different pressing times; however, the MOR showed a slight but significant difference ($P = 0.05$) with a 12-min pressing time. This result indicates that a short pressing time might be safely used to produce such I-beams. All beams showed horizontal shear fracture in the web, which indicated good bonding between strands as well as between web and flange. The good bond between strands may be attributed to the satisfactory cure state of PF resin due to the optimum curing environment created by the MDI,[19–21] because the MDI cures at lower temperature than does PF, thus saving temperature and energy for PF resin curing.

Dimensional stability

The results for the thickness and width swelling of the I-beam produced under different pressing times are listed in Table 5. The results show that the width swelling of the beams produced with a shorter pressing time (12 min) was

Table 4. Differences of the maximum and minimum density from the mean density of I-beam flange part in percentage terms as calculated from the density profile data

Symbol[a]	Density (g/cm^3)			Outer density[b] (%)	Inner density[c] (%)
	Mean	Maximum	Minimum		
A-40	0.64	0.71 (1.76)[d]	0.49 (13.96)[d]	11	23
A-20	0.69	0.91 (1.16)	0.52 (13.98)	31	24
B-40	0.70	0.92 (1.14)	0.51 (14.00)	31	28
B-20	0.69	0.92 (1.18)	0.51 (14.00)	33	26
C-40	0.70	0.91 (1.12)	0.63 (13.98)	30	10
C-20	0.69	0.78 (1.16)	0.61 (14.02)	13	12

[a] A, B, and C refer to strand types with the dimension described in Table 1. The number refers to the resin application rate between strands (see Table 1)
[b] Defined as | (mean density − maximum density)/mean density | × 100
[c] Defined as (mean density − minimum density)/mean density × 100
[d] Positions (in mm) from flange surface where maximum or minimum density were observed

Table 5. Effect of pressing time on the mechanical properties and dimensional stability of the I-beam

Pressing time (min)	Density (g/cm^3)	Bond strength between web and flange (MPa)		MOR (MPa)	MOE (GPa)	Width swelling (%)	Thickness swelling (%)
		Parellel	Perpendicular				
12	0.69 ± 0.03	4.51 ± 0.33	3.00 ± 0.24	40.9 ± 1.04*	16.7 ± 1.07	12.5 ± 1.70	0.57 ± 0.29
14	0.69 ± 0.03	4.59 ± 0.30	3.20 ± 0.39	41.1 ± 0.89	17.1 ± 1.57	11.2 ± 0.79	0.35 ± 0.22
16	0.69 ± 0.04	4.91 ± 0.75	3.32 ± 0.31	41.6 ± 0.83	17.3 ± 0.62	10.2 ± 0.80	0.24 ± 0.22
18	0.69 ± 0.02	4.93 ± 0.54	3.41 ± 0.54	42.8 ± 0.78	17.3 ± 0.29	9.6 ± 1.20	0.21 ± 0.15
20	0.69 ± 0.02	4.94 ± 0.42	3.34 ± 1.10	42.8 ± 0.50	17.3 ± 0.51	9.1 ± 0.80	0.21 ± 0.11

* $P < 0.05$

Table 6. Basic properties of I-beams produced with different moisture content in wood-resin system

Moisture content (%)	Density (g/cm^3)	MOR (MPa)	MOE (GPa)	Bond strength (MPa)		Width swelling (%)	Thickness swelling (%)	Water absorption (%)
				Parellel	Perpendicular			
8	0.64 ± 0.02	36.7 ± 1.1*	16.1 ± 0.7	4.71 ± 0.46	2.92 ± 0.4	21.7 ± 2.7	1.89 ± 0.6*	57.6 ± 4.1
10	0.63 ± 0.02	40.5 ± 2.6	17.04 ± 0.4	4.72 ± 0.52	3.06 ± 0.33	19.1 ± 4.4	1.04 ± 0.6	55.9 ± 2.8
12	0.69 ± 0.03	40.9 ± 1.04	16.6 ± 1.1	4.52 ± 0.31	3.00 ± 0.22	12.5 ± 1.7*	0.57 ± 0.3	50.4 ± 1.7

* $P < 0.05$ within the same column

inferior to that of beams produced at longer pressing times. However, in general, the width swelling of beams from short pressing times was comparable to that of beams produced with a 20-min pressing time in both this study and the previous study.[2] In general these results indicate that the possibility of shortening the pressing time to 12 min for the production of such I-beams with conventional hot pressing is promising. The thickness swelling of all conditions was found to be excellent due to the presence of the prefabricated web material, which also points toward a promising future for shortening the pressing time.

Effect of moisture content on I-beam basic properties

Table 6 shows the effects of the moisture content on the basic properties of the I-beam. Generally, the results revealed that low wood–resin system moisture content (8%) negatively affects most of the properties investigated.

Bond quality

The differences in bond strength between web and flange were found to be insignificant for different moisture levels because the MDI resin cures at low temperature resulting in satisfactory bonding between web and flange.

Bending properties

Changes in the MOE were found to be insignificant between MC levels; however, MOR showed a significantly lower value at 8% MC than at 10% and 12%. It seems that low wood–resin system MC interferes with the curing of the PF resin at the flange part due to insufficient heat transfer. This can be proved by the fracture mode observed during testing of the beam in which 80% delamination between strands occurred due to the weak bond of the PF resin.

Dimensional stability

Results showed that low MC negatively affected the dimensional stability. This adverse effect might be attributed to the insufficient bond between strands as a result of insufficient curing of PF resin. This results in many gaps between strands that allow water to enter, resulting in great width swelling as well as water absorption.

The results showed that 12% wood–resin system moisture content is the optimum level among the three tested, for production of such I-beams using conventional hot pressing.

Conclusions

To obtain I-beams with balanced mechanical properties and dimensional stability the following conditions were concluded to be optimal:

1. PF resin between strands at an application rate of 40 g/m^2 (8.5%)
2. MDI resin between web and flange at an application rate of 25 g/m^2
3. Moisture content of 12% in the wood–resin system for conventional hot pressing

Short pressing times (12 min) were found to produce I-beams by conventional hot pressing with acceptable mechanical properties. For shorter pressing times, the dimensional stability was found to be inferior to beams prepared with longer pressing times.

Acknowledgments This work was supported by a Grant-in Aid for Scientific Research (13660155) from the Ministry of Education, Culture, Sport, Science and Technology, Japan. The authors acknowledge the Oshika Company for the supply of wood adhesives, Mr. Hironori Taniuchi of the Iwate Prefectural Forestry Technology Center, Japan, for his technical assistance. Thanks and appreciation are also due to Dr. Atsushi Miyatake and Mr. Hideaki Korai, Forest and Forest Product Research Institute, Tsukuba, Japan, for preparing the strands and measuring the density profiles.

References

1. Sellers T Jr (2001) Wood adhesive innovations and applications in North America. Forest Prod J 51:12–22
2. Abdalla AMA, Sekino N, Jinbo N (2004) Veneer strand flanged I-beam with MDF or particleboard as web material I: the forming method and fundamental properties. J Wood Sci 50:223–229
3. Harless TEG, Wangner FG, Short PH, Seale RD, Mitchell PH, Ladd DS (1987) A model to predict the density profile of particleboard. Wood Fiber Sci 19:81–92
4. Winistorfer PM, Young TM, Walker E (1996) Modeling and comparing vertical density profiles. Wood Fiber Sci 28:133–141
5. Wong ED, Zhang M, Wang Q, Kawai S (1999) Formation of the density profile and its effects on the properties of particleboard. Wood Sci Tech 33:327–340
6. Winistorfer PM, Moshler WW, Wang S, DePaula E (2000) Fundamentals of vertical density profile formation in wood composite. Part I. In-situ density measurement of the consolidation process. Wood Fiber Sci 32:209–219
7. Wang S, Winistorfer P (2002) In-situ density change for in process measurement and control of hot pressing. Forest Prod J 52:77–82
8. Subiyanto B, Kawai A, Sasaki H, Kahar N, Ishihara S (1988) Studies on curing condition of particleboard adhesive I. Effect of environmental temperature and adhesive temperature on gelation time (in Japanese). Mokuzai Gakkaishi 34:333–336
9. Subiyanto B, Kawai S, Tanahashi M, Sasaki H (1989) Studies on curing condition of particleboard adhesive II. Curing of adhesives under high steam pressures or temperatures (in Japanese). Mokuzai Gakkaishi 35:419–423
10. Brown HP, Panshin AJ, Forsaith CC (1952) Textbook of wood technology, vol II. The physical, mechanical, and chemical properties of commercial woods of the United States. McGraw-Hill, New York, pp 438–439
11. Bendtsen BA (1976) Rolling shear characteristics of nine structural softwoods. Forest Prod J 26:51–56
12. SAS Institute (1996) SAS/STAT user's guide, vol 2. Version 6, fourth edn. The GLM procedure. SAS Institute, Cary, pp 891–996
13. Kelly MW (1977) Critical literature review of relationship between processing parameters and physical properties of particleboard. Gen. Tech. Report. FPL-10 USDA Forest Service, Forest Product Lab., Madison, WI (As cited by Siqun Wang, 2002, Forest Prod J, 2002, 52)
14. Deppe, HJ, Ernst K (1965) Problem of pressing-time reduction in particleboard manufacture. Holz Rho Werkst 23:441–445
15. Neusser H (1967) Practical testing of urea resin glues for particleboard. With regard to shortening of pressing time. Holzforsch Holzverw 19:37–40
16. Gardner DJ, Wagge SK, Elder TJ (1990) Bonding flakeboard with filled and extended phenol-formaldehyde resin. Forest Prod J 40:31–36
17. Wu Q (1999) In-plane dimensional stability of oriented strand panel: effect of processing variables. Wood Fiber Sci 31:20–40
18. Steiner PR, Show S, Vadja S (1980) Interaction of polyisocyanate adhesive with wood. Forest Prod J 30:21–27
19. Hse CY, Branham SJ, Chou C (1998) Adhesive Technology and bonded tropical wood products. Taiwan Forestry Research Institute, Taipei, pp 85–94
20. Bao S, Daunch WA, Sun Y, Rinaldi PL, Marcinko JJ, Phanopoulos C (2003) Solid state two-dimensional NMR studies of polymeric diphenylmethane diisocyanate (PMDI) reaction in wood. Forest Prod J 53:63–71
21. Palardy RD, Haataja BA, Shaler SM, Williams AD, Laufenberg TL (1989) Pressing of wood composite panels at moderate temperature and high moisture content. Forest Prod J 39:27–32