Veneer strand I-beam with medium density fiberboard or particleboard as web material V: Its production and performance under steam-injection pressing

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単板ストランドによる成形フランジとＭＤＦまたはパーティクルボードによるウェブから成る木質Ｉビーム（第5報）　水蒸気噴射プレスによる製造と性能

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I. Introduction

In the first part *(1)* of this study series, a new I-beam, which comprised a flange part made from veneer strands and a web part made of either prefabricated medium density fiberboard or particleboard (see Figure 1), was developed using the forming and pressing method, which was also described in the same part. In successive parts *(2-4)*, the manufacturing conditions were optimized by conventional hot pressing. In this part, an attempt is made to determine suitable combinations of manufacturing conditions so as to produce I-beams by steam-injection pressing within the shortest pressing time by utilizing the advantage of rapid temperature increase.

According to Sekino *et al.* *(5,6)*, steam treatments can be classified as 1) pretreatment, 2) steam-injection pressing, and 3) post-treatment. Many researchers *(7-10)* have stated that the main function of steam injection is to increase the core temperature rapidly and uniformly, i.e., in a short time. Other researchers *(11-15)* deduced that steam pressure, temperature, duration, and timing have a significant effect on the resin curing process and the properties of the final products. The objectives of this part of the study

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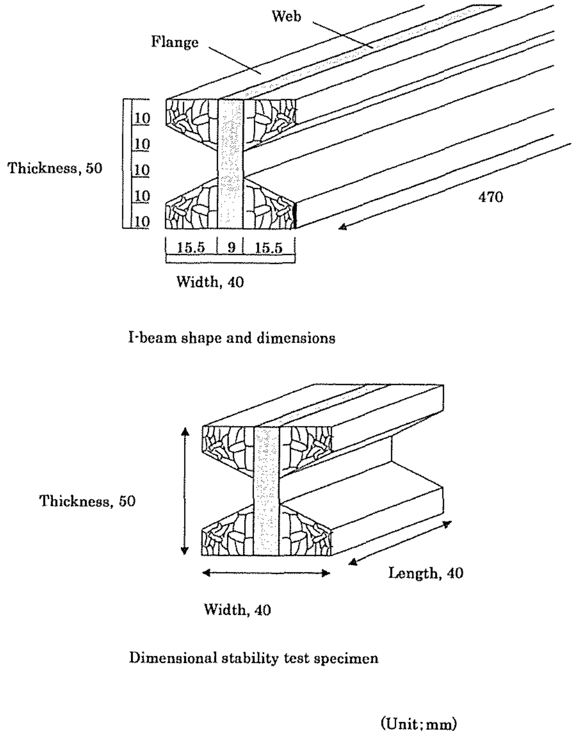

Figure 1. I-beam cross-section and dimensional stability test specimen.

are as follows: 1) comparing the performance of steam-injection produced I-beams with that of conventionally produced I-beams, and 2) developing the optimum combination of steam duration, injection position (timing), pressing time, and strand preparation method so that the I-beams are imparted properties that are comparable with those of the conventional ones.

II. Materials and methods

1. Materials

Akamatsu (*Pinus densiflora* Seib. et. Zucc) strands with a dimension of 3 × 5 × 470 mm (thickness × width × length) and a density of 0.51 g/cm^3 and sugi (*Cryptomeria japonica* D. Don) veneer strands, 3-mm thick × 4-mm wide × 470-mm long, with a density of 0.34 g/cm^3 were used as flange raw materials. All strands had a moisture content of approximately 10%, and they were prepared either by a saw or a roll-press splitter *(14)*. Particleboards with a nominal thickness of 9 mm and a density of 0.82 g/cm^3 were used

Table 1. Pressing schedules for steam-injection produced I-bean panels.

Schedule factors	A	B	C	D	E	F	G	H	J	K	L	M
Mold preheating period (T0, sec)	-	-	-	60	-	-	-	-	-	-	-	-
Injection position (Di, mm)[a]	70	75	75	75	75	75	75	75	70	70	70	75
Primary steam duration (Tp, sec)	10	15	10	5	5	8	10	10	10	10	10	10
Secondary steam duration (Ts, sec)[b]	-	-	5	5	10	7	5	-	-	5	5	5
Total pressing time (min)	8.5	6	8.5	8.5	6	6	6	6	6	6	3	6
Strand preparation method	S	S	S	S	RS	RS	RS	RS	RS	RS	RS	S

[a] Defined or measured by the distance between platens

[b] Injection while the press was closing

S stands for saw; RS stands for roll-press splitter

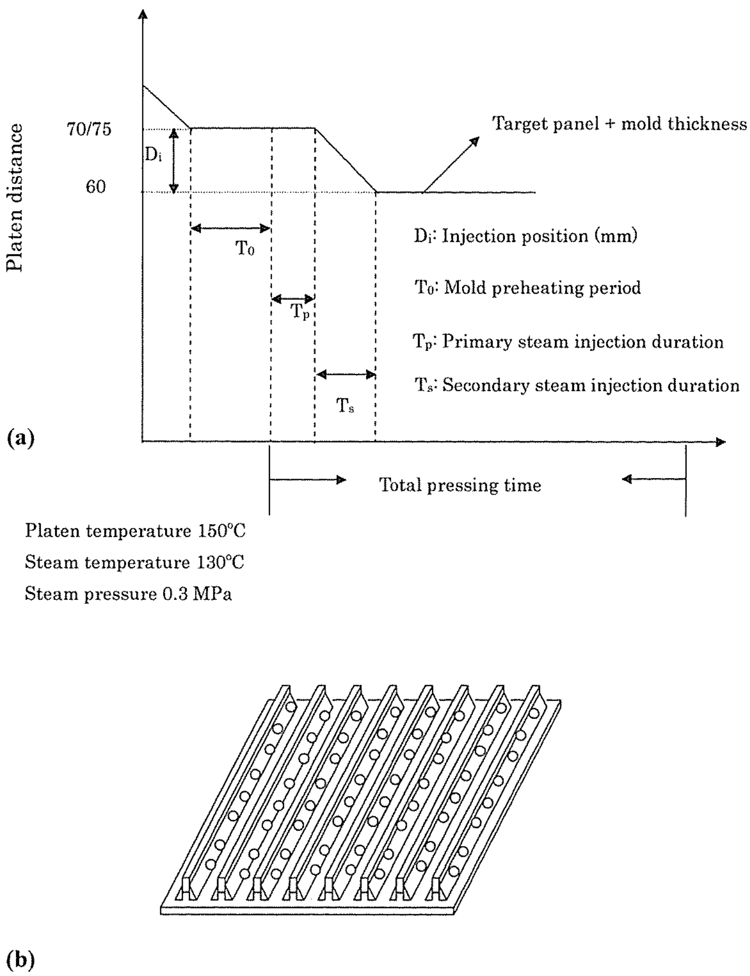

Figure 2. Schematic diagram for (a) the general pressing schedule used for producing I-beams under steam-injection pressing, (b) the hole arrangements that introduce the steam into the I-beam mat.

as web raw materials. Polymeric diphenyl-methane-diisocyanate (MDI) resin formulated by Oshika Co. Ltd. (PB 1605) was used as a binder between the strands as well as between the web and the flange for all I-beam panels fabricated conventionally or by steam-injection pressing.

2. Fabrication method

2.1 Conventionally fabricated I-beam

Three I-beam panels (450 × 470 × 50 mm) were fabricated using MDI resin between the akamatsu strands at an application rate of 20 g/m^2 and between the web and the flange at 25 g/m^2. The pressing temperature was 160℃ and the pressing times were 8.5, 10, and 12 min along with an additional 20 s for press closure time. An additional panel was fabricated at 200℃ and an 8-min pressing time with the same closure time. Under all conditions, the target flange density was 0.7 g/cm^3.

2.2 Steam-injection-fabricated I-beam

As shown in Table 1, twelve I-beam panels (sizes similar to those mentioned above) with a target flange density of 0.7 g/cm^3 (schedules A-D: akamatsu strand) and 0.6 g/cm^3 (schedule E-M: sugi strand) were fabricated using steam-injection pressing. The general pressing schedule that was applied and the methods of introducing steam into the I-beam mat are shown in Figure 2. A pair of metallic molds used for I-beam production was furnished with steaming holes with a diameter of 2 mm and an interval of 25 mm; see Figure 2(b). The following pressing conditions were applied: platen temperature: 150℃, steam temperature: 130℃, and steam pressure: 0.3 MPa. The MDI resin was applied at a rate of 20 g/m^2 between the strands and at 25 g/m^2 between the web and the flange.

The temperature increase during pressing was measured at the following four positions by using thermocouples: at the center of the panel between the web and the flange and in the middle of the flange; at the center of panel on the lower and upper surfaces of the strands; in other words, between the mold and strand surfaces. The actual upper and lower platen temperatures between the platen and the mold were also recorded using thermocouples.

2.3 Property testing

All beams, with dimensions as shown in Figure 1, were fully conditioned at 20℃ and a relative humidity (RH) of 60% for one week. For each condition, five beams were tested for modulus of rupture (MOR) and modulus of elasticity (MOE) in bending using the four-bending test method, which was previously used in parts *(2-4)* of this study series.

After discarding the edge parts of the beam, many 40-mm-long block specimens were prepared (see Figure 1). From these blocks, ten randomly selected shear specimens for each condition with the same shape as those used in previous studies *(1-4)* were prepared. The specimens were tested along directions parallel and perpendicular to the strand grain in order to assess the bond strength between the web and the flange. Dimensional stability was examined by evaluating the percentile thickness, width swelling, and water absorption in a 24-h water immersion test conducted at 20℃ using ten randomly selected specimens from those described above.

III. Results and discussion

1. Basic properties of conventionally produced I-beams

1.1 Mechanical properties

As listed in Table 2, the use of MDI resin between the strands as well as the web and the flange facilitated a further reduction in the pressing time to 8 min when compared to the use of phenol-formaldehyde (PF) resin (12 min). It also allowed for the use of a lower pressing temperature than that used for PF resin. In other words, MDI-bonded I-beams with a lower temperature and a shorter pressing time exhibited a significantly higher MOR than PF-bonded I-beams with a longer pressing time and a higher pressing temperature. The bond strength between the web and the flange exhibited a similar effect on the MOR, while no effect was observed on the MOE. This may be attributed to the strong bonding between the strands as well as between the web and the flange due to faster, and perhaps, more complete curing of the MDI resin at a temperature lower than that for the PF resin (see Figure 3).

Table 2. Conventionally produced I-beams basic properties

Pressing condition	Bond strength (MPa)		MOR(MPa)	MOE (GPa)	Thickness swelling (%)	Width swelling (%)
	Parallel	Perpendicular				
PF/12minutes/200℃[1]	4.5 ± 1.8	3.0 ± 1.2	40.9 ± 1.1	16.3 ± 1.1	1.1 ± 0.3	12.5 ± 1.7
8 minutes/200℃	9.4 AB ± 2.2	5.8 A ± 2.3	49.6 A ± 1.6	17.4 ± 0.2	0.6 ± 0.2	6.7 ± 0.9
8.5 minutes/160℃	9.1 B ± 0.3	5.2 A ± 1.2	48.3 B ± 0.8	17.9 ± 0.2	0.8 ± 0.3	6.9 ± 1.2
10 minutes/160℃	10.6 A ± 1.3	5.6 A ± 1.2	48.8 A ± 1.2	17.9 ± 0.3	0.7 ± 0.2	6.8 ± 0.9
12 minutes/160℃	10.6 A ± 1.4	6.2 A ± 2.2	49.1 ± 1.3	17.7 ± 0.2	0.6 ± 0.2	6.9 ± 2.1

[1] Part of the data published in part III, to confirm the superiority of using MDI in term of shorter pressing time and less energy consumption

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

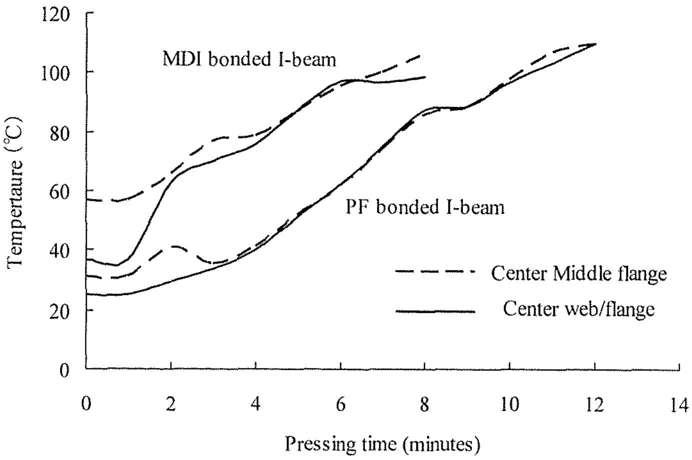

Figure 3. Temperature rises during conventional hot pressing of the I-beam using MDI and PF resin.

1.2 Dimensional stability

As shown in Table 2, the use of MDI significantly reduced the width swelling in comparison to the PF-bonded I-beam. Moreover, the dimensional stability, particularly with regard to the width swelling, showed no difference for different pressing times and temperature combinations. The results revealed that all combinations yielded excellent width swelling, and this maybe due to the excellent bonding between the strands as a result of the excellent cured state of the MDI resin at the flange part (see Figure 3).

The overall conclusion is that the replacement of PF resin between the strands with MDI resin facilitates the production of I-beams with a shorter pressing time and a lower pressing temperature.

2. Basic properties of steam-injection-produced I-beams in comparison to the conventionally produced ones

2.1 Mechanical properties

The results of the mechanical properties of I-beams with saw-cut strands produced by steam-injection pressing are listed in Table 3. The results indicated no significant differences among the different pressing schedules used; however, each schedule exhibits a unique value of the coefficient of variation, thus indicating that some schedules are superior to others. Further, the results showed in general that the MORs of the steam-injection-produced I-beams were less by 9%-13% when compared to those of I-beams

Table 3. Bending properties and dimensional stability of the I-beams produced with different pressing schedules

Pressing schedule[1]	MOR (MPa)		MOE (GPa)		Bond strength // (MPa)		Thickness swelling (%)		Width swelling (%)	
	Mean (n=5)	COV (%)	Mean (n=5)	COV (%)	Mean (n=10)	COV (%)	Mean (n=10)	COV (%)	Mean (n=10)	COV (%)
A	43.7	29	14.8	14	9.0	15	0.96	6	7.4	14
B	42.1	50	14.4	10	8.7	11	0.95	4	8.1	18
C	43.7	10	14.9	7	9.2	17	0.67	2	7.2	6
D	42.2	24	14.6	15	8.3	24	0.86	3	7.8	11
C160-8.5[2]	48.7	30	14.7	14	9.1	8	0.67	3	7.0	12

MOR, Modulus of rupture; MOE, modulus of elasticity

[1] As defined in Table 1

[2] C; conventional, 160; pressing temperature (℃), 8; pressing time in minutes

produced conventionally with a total pressing time of 8.5 min and pressing temperature of 160℃. However, the MORs lie within the acceptable range of the values reported in parts I *(1)* and II *(2)* of this study series for I-beams produced using PF resin (34.1 to 42.8 MPa), while the bond strength was comparable to that of the conventionally produced one.

As indicated by the smaller coefficient of variation in Table 3, schedule C, in comparison to other schedules, yielded I-beams with more uniform bending properties. This may be attributed to the improved timing and duration of steam injection, which results in reduced resin washout and rapid temperature increase uniformly across the panel. On the other hand, schedule B, which required the longest steam injection duration of 15 s, exhibited a considerably greater coefficient of variation of MOR and width swelling. This may be due to resin washout, which is actually observed in the second half of the injection duration. The detailed effects of the pressing schedule with the roll-press-splitter-strand I-beams will be discussed subsequently by presenting the temperature increase data.

2.2 Dimensional stability

The dimensional stabilities, particularly the thickness and the width swelling percentage for I-beams with a flange density of 0.7 g/cm^3 (schedules A to D), are listed in Table 3. Generally the results indicated no significant differences among either steam injection schedules in one side or between this group and conventionally produced I-beams. With regard to the coefficient of variation, schedule C appears to be the best not only among the four studied schedules but also in comparison to conventionally produced I-beams. On the other hand, the thickness swelling along the direction perpendicular to the pressing was considerably smaller than the width swelling mainly due to the presence of

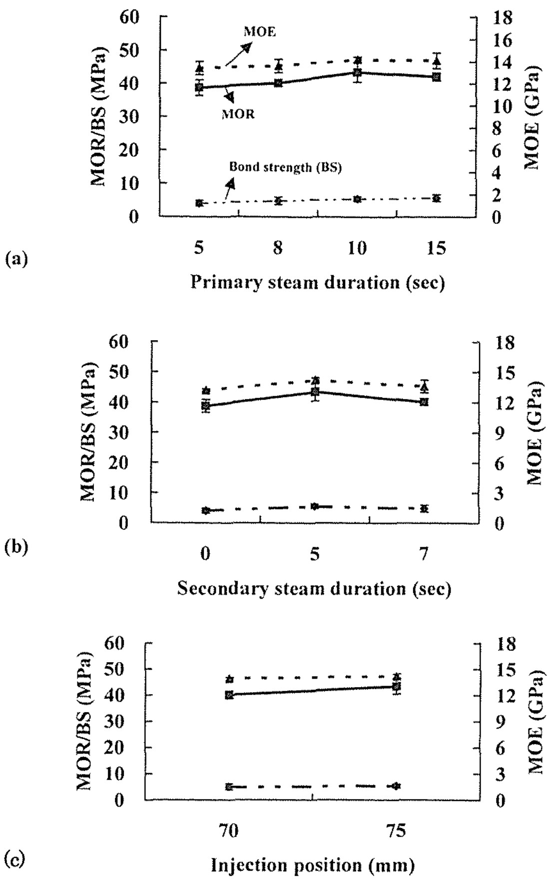

Figure 4. Effects of (a) primary steam duration (Schedules E, F, G and B), (b) secondary steam duration (Schedules H, G and F) and (c) injection position on the I-beam mechanical properties (Schedules K and G).

the web material, which prevented the flanges from swelling.

3. Detailed effect of steam-injection pressing schedule on the basic properties of the I-beam

3.1 Effect of primary and secondary steam duration and injection position on the mechanical properties

Based on the test results for the I-beams produced in schedules E, F, G, H, and K, the effects of primary (PSD) and secondary (SSD) steam duration and injection position or timing (IP) on the mechanical properties of the I-beam are shown in Figure 4. Although schedule B involves a strand preparation method and a flange density different

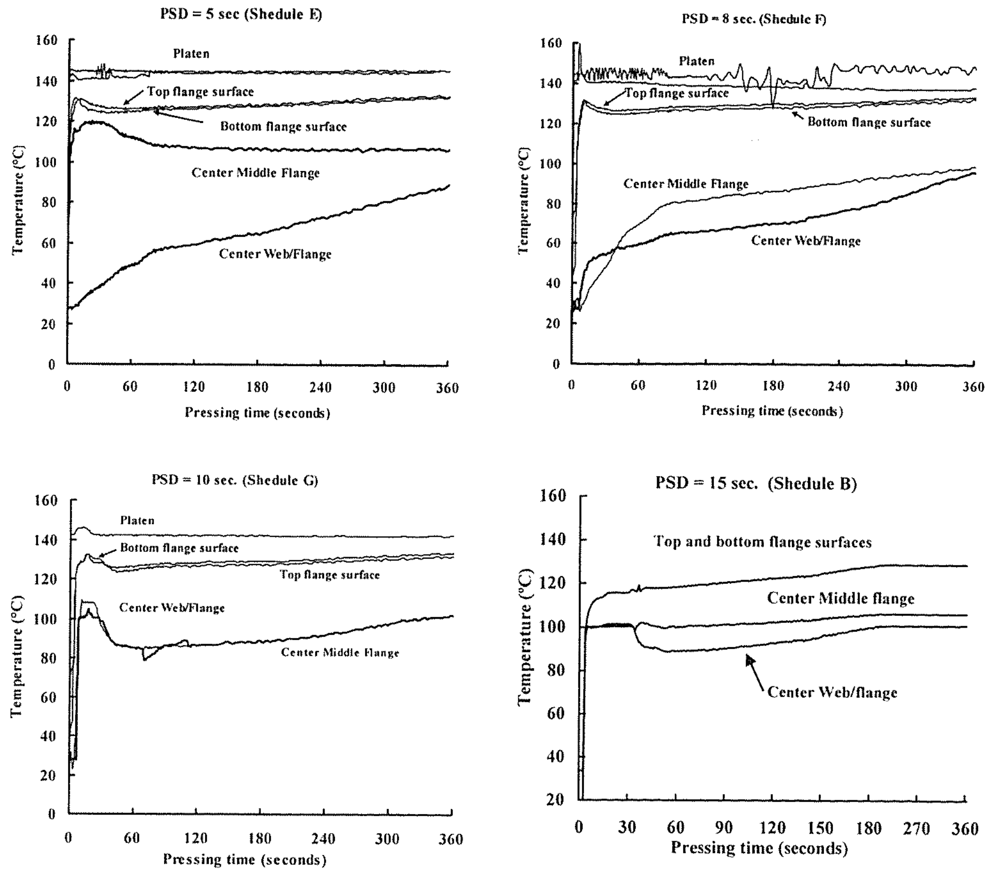

Figure 5. Temperature rises as affected by primary steam injection duration （PSD）.

from those in the abovementioned schedules, its results are included in Figure 4 for the purpose of comparison.

With an increase in PSD, MOR and MOE increased up to a duration of 10 s. Further increase in the PSD resulted in the reduction of MOR. Based on the temperature increase in the middle of the flange and between the web and the flange (see Figure 5), it appears that steam durations shorter than 8 s are not sufficient for maintaining the temperature at the level required for resin curing; the temperature remained at 90℃ or above for a short time. Although a longer steam duration of 15 s and a 10-s steam duration maintained a uniform temperature of around 100 ℃ for a long time, it caused resin washout, as mentioned before. The bond strength showed a slightly different trend from that of MOR and MOE. It increased significantly up to a PSD of 8 s; however, there was negligible increase in the bond strength with further increase in the PSD. Thus, it could

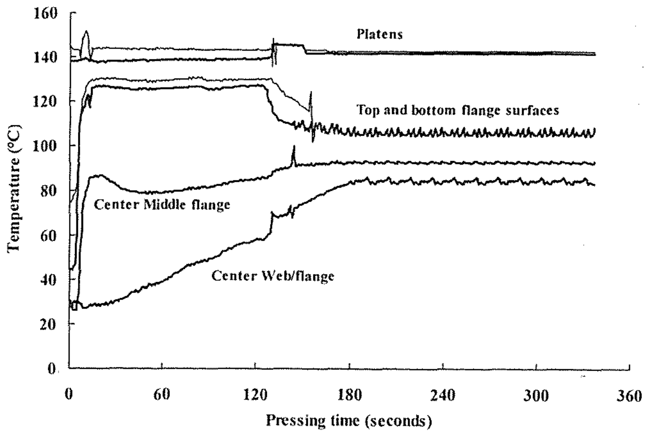

Figure 6. Temperature rises during steam injection pressing observed for the press schedule K.

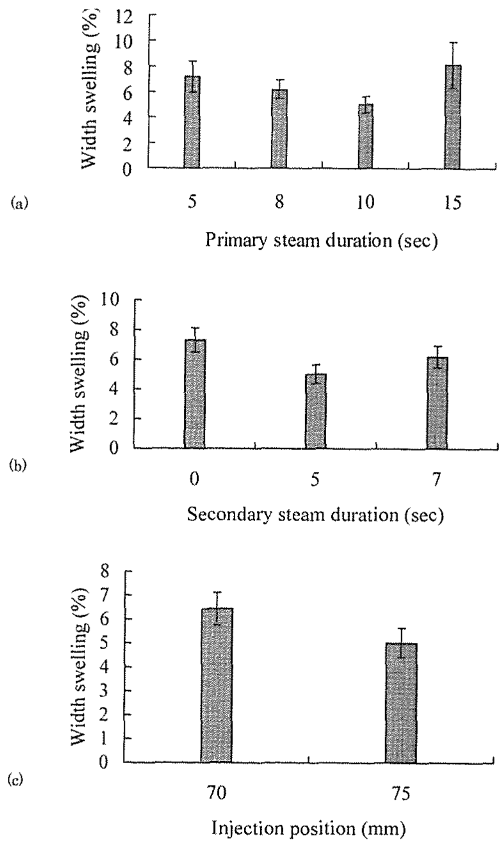

Figure 7. Effect of (a) primary steam duration, (b) secondary steam duration and (c) injection position on the I-beam width swelling. Bars show standard deviation.

be concluded that a 10-s PSD is the most reasonable among the investigated durations.

On the other hand, in Figure 4(b), when schedule H, which does not include SSD, is compared with the other schedules, it may be inferred that the second steam injection duration (SSD) is likely to play a role in enhancing the completion of the resin-curing process, thereby improving the mechanical properties. However, since the total injection duration was different in schedules H, G, and F, further investigation will be required in order to clarify the effects of SSD.

Figure 4(c) shows the effect of injection position or timing on the mechanical properties of the I-beam. It was found that steam injection at the looser flange mat (schedule G; platen distance: 75 mm) imparted better mechanical properties to the I-beams. This may be due to the difference in the steam energy introduced into the flange mat. As shown in Figure 6, the temperature increases in schedule K (platen distance: 70 mm) were slower than those in schedule G, thereby resulting in slower plasticization of strands or inferior resin curing. These results suggest that both steam-injection timing, which facilitates steam entry throughout the flange strand mat, and injection duration are important parameters.

3.2 Effect of primary and secondary steam duration and injection position on width swelling

Figure 7 shows the effect of PSD, SSD, and IP on the width swelling of the I-beam. In general, the width swelling in the steam-injection-produced I-beam was less than that in the conventionally produced I-beam. This may be attributed partly to the internal stress relief under the plasticizing action of steam and partly due to a significantly reduced capacity for water absorption, possibly caused by the high degree of wood softening.

The results showed that width swelling improved with the increase in PSD from 5 to 10 s, depending on the injection position. Injection at a loose position showed a better width swelling than that at a tied position. This could occur because a loose position allows a considerable amount of steam to enter the flange part, and therefore, the plasticizing action of steam and the degree of wood softening could be expected to be greater.

On the other hand, a further increase in PSD beyond 10 s resulted in inferior width swelling. In the case of 15-s PSD (schedule B), the designed density of the flange was slightly higher than that at other conditions; thus, it is possible that the compaction ratio of the flange also plays a role in addition to the resin washout that results in low bond strength between the strands, as mentioned previously. With regard to SSD, the results

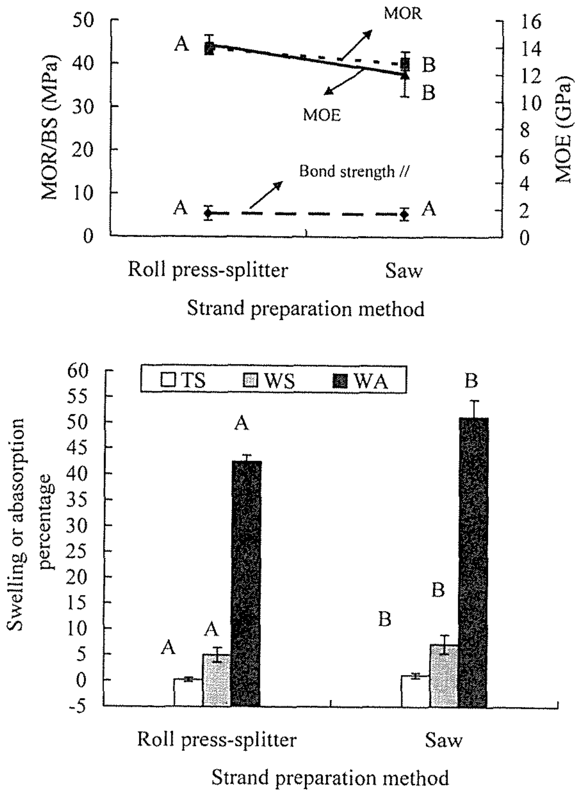

Figure 8. Effect of strand preparation method on the I-beam basic properties. TS, WS and WA stand for thickness swelling, width swelling and water absorption, respectively. Different letter/s means significantly different at P=0.05.

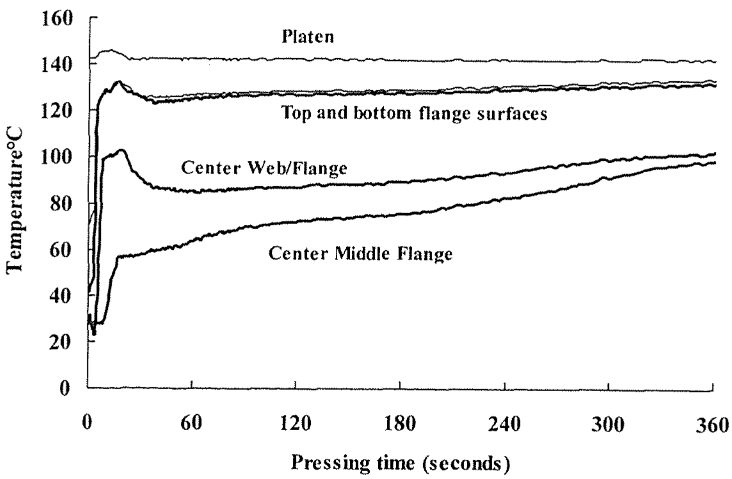

Figure 9. Temperature rises during steam-injection pressing observed for the press schedule M.

showed that the use of moderate SSD, in comparison to no SSD or longer SSD, significantly improved the width swelling. This trend shows a good agreement with that for moderate-SSD-enhanced bond strength between the web and the flange shown in Figure 4(b).

4. Effect of the strand preparation method on the basic properties of the I-beam

Figure 8 shows the effects of the strand preparation method on the basic properties of the I-beam (comparison between schedules G and M). The results indicate that the roll-press-splitter method enhances both MOE and MOR of the sugi-strand I-beams. However, in both methods, the bond strengths between the web and the flange were nearly identical to each other. In the case of the roll-splitted strand, this may be attributed to good stream entry between the web and the flange, which raises the temperature to the level required for curing the MDI resin, as indicated by the trend of the temperature measurement curves (see Figure 5, schedule G). On the other hand, in the case of sawed strand, the smooth surface and good contact between the strands on one side and that between the web and the flange on the other side result in excellent bonding between the web and the flange.

Figure 8 also shows that the roll-press-splitter method, in comparison to the saw method, provided superior dimensional stability. A possible reason for this is that the plasticizing action of steam and the degree of wood softening were greater when roll-splitted strands were used because the strands in this case possessed larger gaps than the sawed strands, which allowed a considerable amount of steam to pass and move through the flange. In fact, when the flange temperature increases are compared (see Figure 5 and 9), it is observed that roll-press-splitter strands, in comparison to saw-cut-prepared strands, maintain a higher temperature in the middle of the flange.

IV. Conclusions

The following conclusions can be drawn from the results obtained in this study.

1. The replacement of the PF resin between the strands with MDI resin facilitated a further reduction in the pressing time to 8.5 min, when compared to a reduction to 12 min in conventional hot pressing.
2. Using steam-injection pressing, veneer strand flanged I-beams with properties comparable to those prepared using conventional pressing can be produced with a pressing time

of up to 6 min.

3. It was concluded that a primary steam duration of 10 s injected at a 75-mm platen distance combined with a 5-s secondary steam duration injected while the press was closing was the optimum combination; however, long steam duration causes resin washout, thereby resulting in a poor-quality bond.

4. With regard to the steam-injection technique, the roll-press-splitter method was found to be more suitable than the saw-cut method for strand preparation.

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要　旨

一連の本研究では、単板ストランドを熱圧プレスで圧密してフランジを成形し、同時にウェブ材料との接着を完了させる木質Iビームの新たな製造方法を検討してきた。本報ではプレス時間の短縮を目的として、水蒸気噴射プレスの適用とその製造条件の最適化が検討され、以下の知見が得られた。1）MDI接着剤の使用により、従来型熱板プレスでも最短8分で製造可能であったが、水蒸気噴射プレスの適用により6分での製造が可能となった。2）水蒸気噴射による接着剤の洗流を防ぐ噴射タイミングと噴射量の重要性が明らかとなり、フランジ圧密の初期段階での10秒間噴射とそれに続く圧密継続中での5秒間噴射は、本Ｉビームの強度性能と寸法安定性を両立させる最適条件と判断された。3）単板を割裂して得たストランドは、圧密過程

で水蒸気透過経路が多く効率的な熱伝達が行われるため、鋸挽きで得られたストランドに比べて性能の優れたIビームが製造可能であった。

Summary

In this study, the optimization of the manufacturing conditions in veneer-strand-flanged I-beam production by steam-injection pressing and methods to further reduce the pressing time were investigated. The main results revealed that conventional hot pressing using diphenyl methane diisocyanate (MDI) resin between the strands as well as between the web and the flange produced I-beams within a pressing time of 8 min. This time was further reduced to 6 min by using steam-injection pressing. It was concluded that a primary steam injection duration of 10 s in the first stage of flange compression (75-mm platen distance), followed by a 5-s secondary steam injection duration while the press was closing was the optimal combination that yielded I-beams with balanced mechanical properties and dimensional stability. It was also observed that it was more appropriate to use a roll-press splitter for strand preparation instead of a saw-cutting method in the steam-injection pressing technique.