

# Deterioration of wood-based boards subjected to outdoor exposure in Tsukuba

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**Abstract** Various types of wood-based boards were analyzed for deterioration after being exposed to an outdoor environment for 5 years in Tsukuba, Japan. In phenol-formaldehyde resin bonded particleboard (PB(PF)) and aspen oriented strand board (OSB(aspen)), longer exposure caused a greater reduction in the modulus of rupture and internal bond strength, an increase in the coefficients of variation, and a decrease in 95 % lower tolerance limit at the 75 % confidence level (95TL). Nail-head pull-through and lateral nail resistance were also reduced by outdoor exposure, but their coefficients of variation and 95TL were not significantly affected. In contrast, methylene diphenyl diisocyanate bonded medium density fiberboard (MDF(MDI)) only showed a slight deterioration of these properties even after 5-year exposure, and the coefficients of variation and 95TL hardly changed. After 5-year exposure, the retention of shear load in one-plane at relative displacement of 1.0 mm was high in MDF(MDI) and OSB(aspen) at 93.5 and 78.5 %, respectively, but low in PB(PF) at 41.1 %. As with PB(PF), OSB(aspen) also showed a sharp decrease in the modulus of rupture and internal bond strength, but only slightly reduced shear load in one-plane.

**Keywords** Outdoor exposure · Wood-based board · 95 % tolerance limit · Nail joint property · Deterioration

## Introduction

Wood-based boards are generally not used under outdoor exposure. However, such exposure is a common method of assessing the durability of wood-based boards [1–3], and it has been frequently reported in countries other than Japan [4–7]. Outdoor exposure testing in Japan has mainly focused on plywood [8], and the first wood-based panel outdoor exposure project was initiated in 1991 to assess the durability of such boards [9, 10].

The circumstances surrounding wood-based boards have changed considerably since 1991. For example, the raw materials used for producing particleboard in Japan have rapidly shifted to wood waste generated from the demolition of houses, etc. The binder has also been changed to resins that discharge a minimum of formaldehyde emission and methylene diphenyl diisocyanate (MDI) to prevent sick house syndrome. The tree species and binders used for manufacturing oriented strand board have also diversified over the past 10 years. It is, therefore, important to clarify the effects of outdoor exposure on the durability of the latest boards.

Very few outdoor exposure tests have been conducted to assess nail joint property, and the first project included no such testing. Since boards are nailed when used for structural purposes, it is also important to clarify the effects of outdoor exposure on such property.

In order to collect the data of outdoor exposure test on the latest boards manufactured by factories and then supplement the data on nail joint property, the second wood-based panel outdoor exposure project was recently conducted in eight areas of Japan: Asahikawa, Morioka, Noshiro, Tsukuba, Shizuoka, Okayama, Maniwa, and Miyakonojo. Details on the project can be found in Ref. [11]. The present report summarizes some of the test results

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obtained from Tsukuba (36°N, 140°E). In Tsukuba, the mean annual temperature was 14.3 °C with mean annual precipitation of 1,368 mm from 2004 to 2009.

## Experiments

### Outdoor exposure

The tested wood-based boards were particleboard (PB), oriented strand board (OSB), and medium density fiberboard (MDF). For each type of board, about 30 boards (each measuring 900 × 1,800 mm) were cut into about 540 specimens (each measuring 300 × 300 mm). Twelve 300 × 300 mm specimens were collected as one set for use in the 5-year outdoor exposure test. The weight of each 300 × 300 mm specimen was measured, so as to roughly correspond to the weight of each set when twelve 300 × 300 mm specimens were collected. One set was used for testing the modulus of rupture; another set was used for testing nail joint property. The 300 × 300 mm specimens were set on an exposure stand that faced south at an angle of 90° to the ground, and then four 300 × 300 mm specimens were collected for testing every year. Two 300 × 300 mm specimens were for the modulus of rupture and another two 300 × 300 mm specimens were for nail joint property. The boards were commercial products that did not include such detailed information as binder content. Table 1 lists the abbreviations and basic properties of the boards exposed outdoors. Further details are provided in Ref. [11].

The cut edges of the 300 × 300 mm specimens used for the modulus of rupture were coated with enamel paint as a waterproof agent before outdoor exposure.

No method of assessing the nail joint property of boards exposed outdoors has been established. In this study, stainless steel nails (SUS304, 50 mm in length, 6.3 mm in head diameter, 2.75 mm in shank diameter) were driven into 300 × 300 mm specimens of PB(PF), MDF(MDI), OSB(aspen), and OSB(pine), and then the specimens were exposed outdoors (Fig. 1). Stainless steel nails were used to prevent rusting. This study focused on the degradation of nail joint property caused by the deterioration of nailed boards due to outdoor exposure. Figure 2 shows the points where nails were driven in. The cut edges of the 300 × 300 mm specimens used for nail joint property were not coated with waterproof agent.

### Property tests

The 300 × 300 mm specimens collected from the exposure stands were conditioned in a constant temperature and humidity room (at temperature of 20 °C and relative humidity of 65 %) for about 1 month. Table 2 lists the moisture content of the specimens after conditioning. The specimens (measuring 280 × 50 mm) used for the modulus of rupture were removed from the 300 × 300 mm specimens (Fig. 2). After modulus of rupture testing, the specimens (measuring 50 × 50 mm) for testing internal bond strength (thickness change) were cut from the modulus of rupture specimens (Fig. 2). The modulus of rupture and internal bond strength were then conducted in

**Table 1** Abbreviations and basic properties of boards exposed outdoors

Abbreviation	Board type	Binder	Density (g/cm <sup>3</sup> )		Initial thickness (mm)	TC after 5-year exposure (%)	Raw materials	Classification/Category
			Initial	After 5-year exposure				
PB(PF)	Particleboard	PF	0.75	0.66	12.6	15.2	Wood waste	18P <sup>a</sup>
PB(MDI)	Particleboard	MDI	0.80	0.76	12.0	4.01	Wood waste	18P <sup>a</sup>
OSB(aspen)	Oriented strand board	PF	0.63	0.51	12.1	15.6	Aspen	Class 3 <sup>b</sup>
OSB(pine)	Oriented strand board	PF	0.67	0.57	11.5	10.7	Pine	Class 3 <sup>b</sup>
MDF(MDI)	Medium density fiberboard	MDI	0.71	0.71	9.00	−0.13	M. L. H. and wood waste	30M <sup>c</sup>
MDF(MUF)	Medium density fiberboard	MUF	0.76	0.71	12.1	2.01	M. L. H. and wood waste	30M <sup>c</sup>

PF phenol–formaldehyde resin, MDI methylene diphenyl diisocyanate, MUF melamine urea formaldehyde resins, TC thickness change after 5-year outdoor exposure, M. L. H. mixed light hardwoods

<sup>a</sup> In compliance with JIS A 5908

<sup>b</sup> In compliance with JAS for structural panel

<sup>c</sup> In compliance with JIS A 5905

compliance with JIS standards [12, 13] after the conditioning. The numbers of specimens were 8 and 13 from two  $300 \times 300$  mm specimens (Fig. 2). The thickness change was measured using internal bond strength specimens. The modulus of rupture of OSB, which showed in-plane anisotropy, was measured parallel to the surface fibers (Fig. 2). 30 specimens each were initially used for the modulus of rupture and internal bond strength tests, respectively. Nail-head pull-through and lateral nail resistance tests (at 12 mm from the edge) were conducted in compliance with ASTM D-1037 [14]. Shear load in one-plane (at 12 mm from the edge) was tested as shown in Fig. 3. The specimens used for testing nail-head pull-through, lateral nail resistance, and shear load in one-plane were removed from nailed  $300 \times 300$  mm specimens, and the size of the specimens were measured as  $50 \times 50$  mm,  $50 \times 90$  mm, and  $65 \times 90$  mm, respectively (Fig. 2). The numbers of specimens were 8, 6, and 6 from two  $300 \times 300$  mm specimens. The shear load in one-plane test used two specimens per measurement and spruce-pine-fir (SPF) dimension lumber of  $2 \times 4$  in. (with air-dried density of  $0.48\text{--}0.52$  g/cm<sup>3</sup>). The head speed of the testing machine was 2 mm/min in the tensile direction. There was little friction between the panels and SPF. OSB, which is in-plane anisotropic, was tested along fibers on the surface for lateral nail resistance and shear load in one-plane



**Fig. 1** Outdoor exposure test on boards with stainless steel nails driven in

(Fig. 2). The initial numbers of test specimens used for testing nail-head pull-through, lateral nail resistance, and shear load in one-plane were 30, 30, and 12, respectively. The shear load in one-plane test evaluated the initial stiffness under shear load at relative displacement of 1.0 mm. Since two nails were used in the test, shear load in one-plane is the shear load per nail, which was determined by dividing the measurement by two.

In this study, the mean and standard deviation were calculated for each property, such as the modulus of rupture, as well as for retention of the initial value, coefficient of variation, 95 % lower tolerance limit at a 75 % confidence level (95TL) [15], and retention of 95TL.

## Results and discussion

### Modulus of rupture

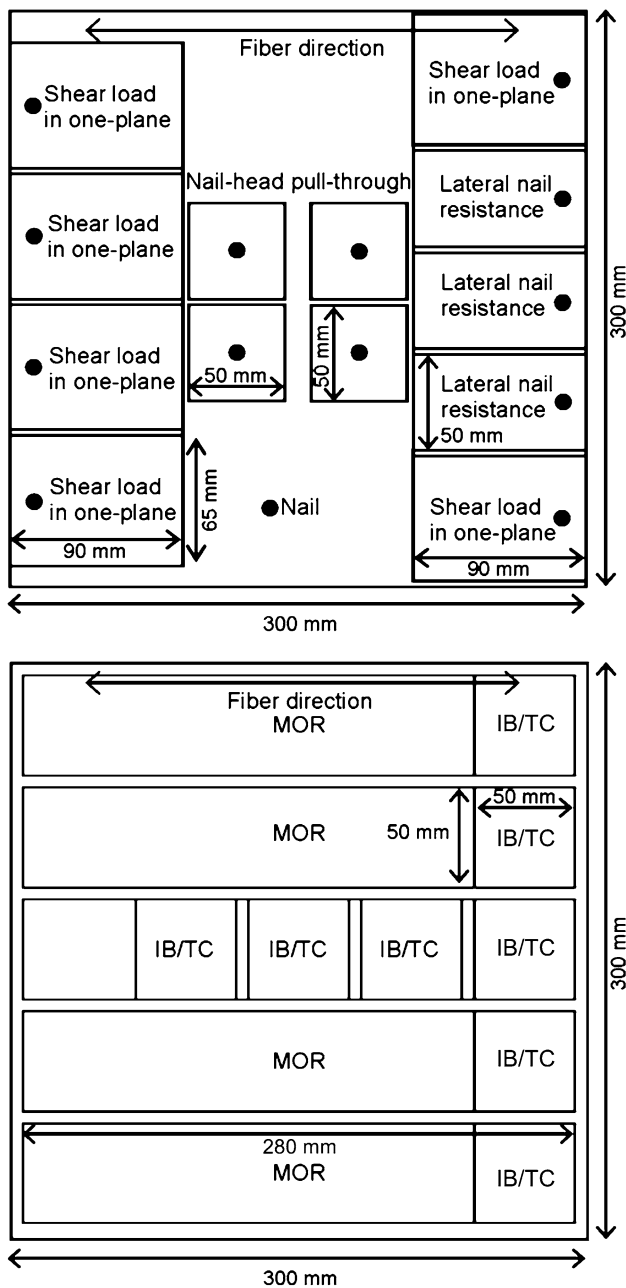
Fig. 4a–e show the changes in modulus of rupture and its 95TL for outdoor exposure. Table 3 lists the retention of initial value, the coefficient of variation, and the retention of 95TL for modulus of rupture. Before exposure, the initial modulus of rupture of PB(PF) was 20.3 MPa, and then decreased to 7.70 MPa during the first 4 years (Fig. 4a). In PB(MDI), the modulus of rupture was 28.8 MPa before exposure, and then decreased during the first 3 years to about 20 MPa (Fig. 4a). PB(PF) retained 46.5 % of the initial modulus of rupture after 5 years, while PB(MDI) retained a higher value of 70.6 % (Table 3). In PB(PF), the coefficient of variation was 11.3 % before exposure, and then increased to 27.1 % after 5 years, resulting in a sharp reduction to 24.0 % of the initial 95TL. On the other hand, the coefficient of variation in PB(MDI) was 7.30 % before exposure, but was hardly affected by exposure, and then was 6.70 % after 5 years. Consequently, its 95TL retained a higher value of 69.8 %.

Both types of OSB showed a similar trend regarding a further reduced modulus of rupture due to longer exposure (Fig. 4b, c). The modulus of rupture of OSB(aspens) and

**Table 2** Moisture content of the specimen after conditioning at temperature of 20 °C and relative humidity of 65 %

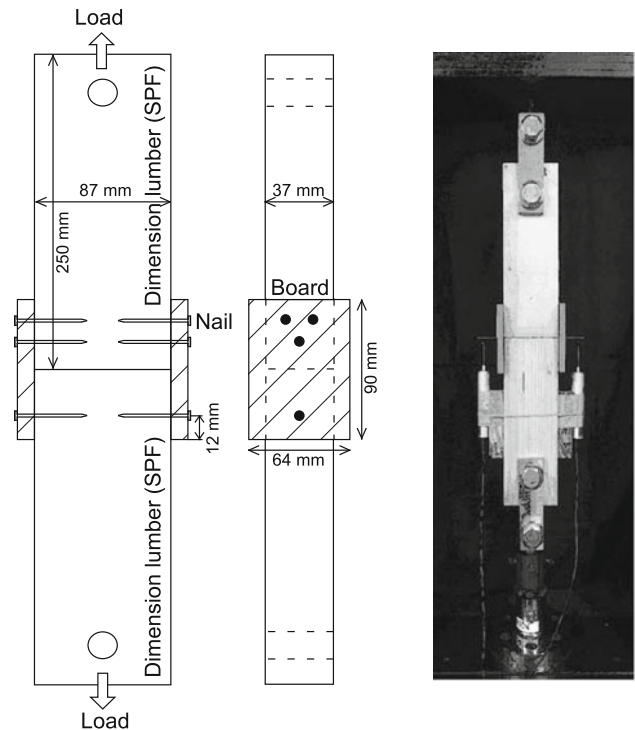
Years of exposure	Moisture content (%)				
	1	2	3	4	5
PB(PF)	10.9 (0.14)	10.2 (10.6)	10.5 (0.18)	11.0 (0.72)	9.57 (0.17)
PB(MDI)	9.67 (0.18)	9.79 (9.76)	9.73 (0.08)	9.65 (0.12)	9.00 (0.09)
OSB(aspens)	10.6 (0.17)	10.3 (10.4)	10.3 (0.61)	11.0 (0.99)	9.16 (0.20)
OSB(pine)	10.1 (2.43)	9.54 (9.66)	9.92 (0.22)	10.4 (4.02)	9.29 (0.23)
MDF(MDI)	8.53 (0.12)	7.94 (8.26)	8.29 (0.09)	8.18 (0.17)	7.86 (0.08)
MDF(MUF)	8.06 (0.11)	7.90 (8.01)	8.51 (0.05)	8.03 (0.13)	7.91 (0.07)

See Table 1 for the abbreviations; the numbers in parentheses indicate standard deviations



**Fig. 2** Trimming of specimens for MOR (50 × 280 mm), IB/TC (50 × 50 mm), nail-head pull-through (50 × 50 mm), lateral nail resistance (50 × 90 mm), and shear load in one-plane (65 × 90 mm) from base specimen (300 × 300 mm) and the specimen nailing points. MOR modulus of rupture, IB internal bond strength, TC thickness change

OSB(pine) before exposure was 39.2 and 36.8 MPa, respectively, and then decreased to 15.3 and 17.9 MPa, respectively, after 5 years. The modulus of rupture of OSB(aspens) retained 39.1 % after 5 years; and that of OSB(pine) retained 48.5 % (Table 3). The coefficient of variation in OSB(aspens) and OSB(pine) before exposure was 17.3 and 21.0 %, respectively. After 5 years, it was

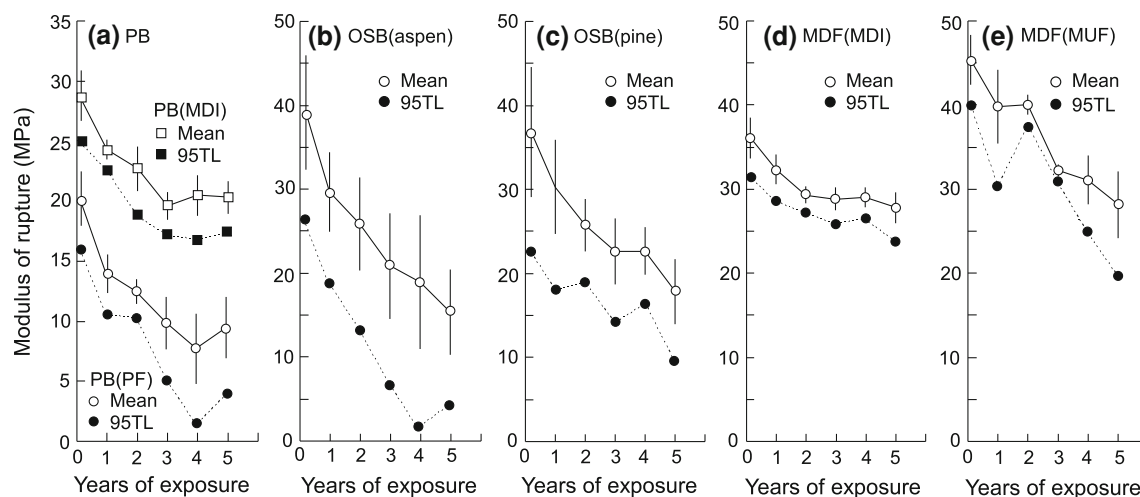


**Fig. 3** Description of shear load in one-plane test

33.2 and 21.7 %, respectively, thus showing a higher increase in OSB(aspens). Therefore, OSB(pine) retained 42.0 % of the initial 95TL even after 5 years, but OSB(aspens) retained only 15.8 %.

The modulus of rupture of MDF(MDI), which was 36.1 MPa before exposure, decreased for 2 years, and then subsequently stabilized at around 30 MPa (Fig. 4d). In contrast, the modulus of rupture in MDF(MUF) was 45.4 MPa before exposure, and then decreased to 28.2 MPa after 5 years (Fig. 4e). MDF(MDI) retained 77.1 % of the initial modulus of rupture after 5 years, but retention of MDF(MUF) reduced to 62.0 % (Table 3). In MDF(MDI), the coefficient of variation did not increase due to exposure but remained constant. Conversely, the coefficient of variation in MDF(MUF) increased from 6.47 % before exposure to 9.44 and 14.0 % after 4 and 5 years, respectively. These increases were smaller, however, than those in PB(PF) and OSB(aspens). Therefore, 95TL in MDF(MUF) lowered to a lesser extent, with 48.8 % of the initial level being retained after 5 years.

The analysis showed that longer exposure caused a greater reduction in the modulus of rupture in PB(PF), OSB(aspens), and OSB(pine). The exposure also increased the coefficient of variation in PB(PF) and OSB(aspens), resulting in a lower 95TL. Hayashi et al. obtained similar results for the same types of boards [16]. However, the



**Fig. 4** Changes in modulus of rupture and its 95TL for outdoor exposure. 95TL denotes 95 % lower tolerance limit at 75 % confidence level. See Table 1 for the abbreviations. Vertical bars denote standard deviations

modulus of rupture in PB(MDI), MDF(MDI), and MDF(MUF) was not significantly affected. Thus, the coefficient of variation did not increase much, and 95TL did not decrease sharply.

#### Internal bond strength

Fig. 5a–e show the changes in internal bond strength and its 95TL for outdoor exposure. Table 3 lists the retention of initial value, the coefficient of variation, and the retention of 95TL for internal bond strength. The retention of internal bond strength that exceeded 100 % was recorded as 100 %. When 95TL was a negative value, it was assumed to be 0 MPa and retention was recorded as 0 %. Both types of PB showed a steady decrease in internal bond strength due to exposure (Fig. 5a). In particular, the internal bond strength of PB(PF) was 0.83 MPa before exposure, and then decreased to 0.14 MPa after 5 years, showing retention of only 16.9 % (Table 3). The coefficient of variation also increased sharply to 81.9 % in 5 years. Therefore, 95TL decreased sharply, and the retention was 0 %. In contrast, the internal bond strength of PB(MDI) was 2.19 MPa before exposure, and only decreased to 1.48 MPa after 5 years, showing retention of 67.6 %. The coefficient of variation increased to 17.8 % in 5 years, but was much lower than that of PB(PF). Therefore, the retention of 95TL of PB(MDI) in 5 years was much higher than that of PB(PF), with retention of 51.1 %.

The internal bond strength of OSB(aspen) and OSB(pine) before exposure was 0.56 and 0.64 MPa, respectively, and then decreased to 0.18 and 0.31 MPa, respectively, after 5 years (Fig. 5b, c). After 5 years, OSB(aspen) and OSB(pine) retained 32.8 and 48.5 %, respectively, and thus showed a lower retention in

OSB(aspen) (Table 3). The coefficient of variation of OSB(aspen) increased throughout exposure, particularly in 5 years, reaching 78.0 %. Therefore, 95TL lowered sharply to 0 MPa (Fig. 5b), and retention of 95TL became 0 %. The coefficient of variation of OSB(pine) hardly changed during the first 4 years, but suddenly increased in 5 years to 47.9 %. Therefore, 95TL lowered sharply to 0 MPa (Fig. 5c), and retention of 95TL reduced to 3.28 % significantly.

Unlike PB and OSB, MDF showed no major changes in internal bond strength during the exposure (Fig. 5d, e). After 5 years, MDF(MDI) and MDF(MUF) retained 96.7 and 87.8 %, respectively, of their initial internal bond strength (Table 3). The coefficient of variation increased only slightly, and was 7.39 and 17.3 % in MDF(MDI) and MDF(MUF), respectively, after 5 years. Therefore, 95TL did not change, and MDF(MDI) and MDF(MUF) retained 100 and 85.2 % of the initial 95TL, respectively, even after 5 years. The reason why MDF did not lose internal bond strength is most likely because its fine and smooth surface prevented rainwater from penetrating into the boards, thus preventing internal deterioration [17].

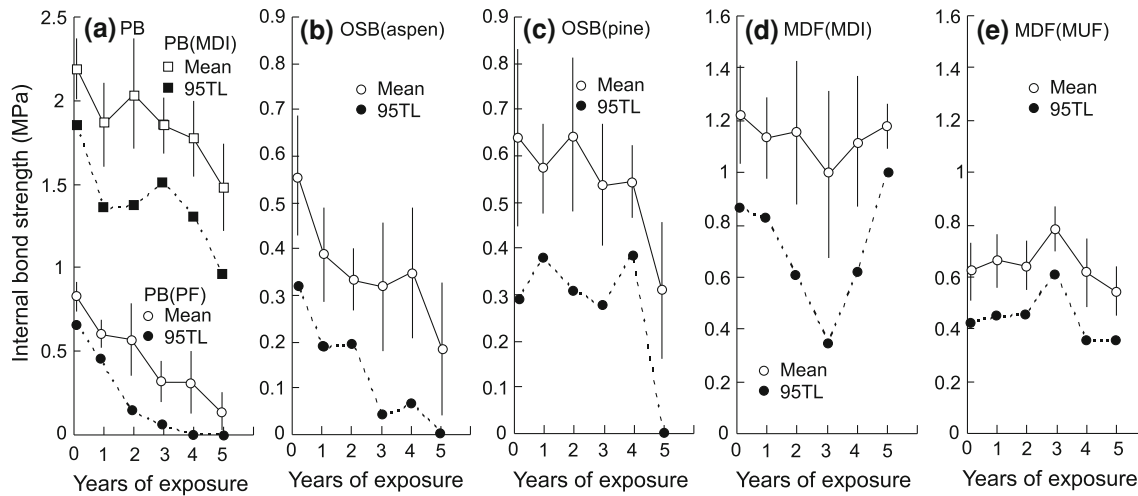
#### Nail-head pull-through

Fig. 6a–d show the changes in nail-head pull-through and its 95TL of PB(PF), OSB(aspen), OSB(pine), and MDF(MDI) for outdoor exposure. Table 4 lists the retention of initial value, the coefficient of variation, and the retention of 95TL for nail-head pull-through. The nail-head pull-through in PB(PF), which was 1.70 kN before exposure, decreased throughout the exposure and decreased to 1.04 kN after 5 years (Fig. 6a), showing retention of 60.9 % (Table 4). The reduction in nail-head pull-through

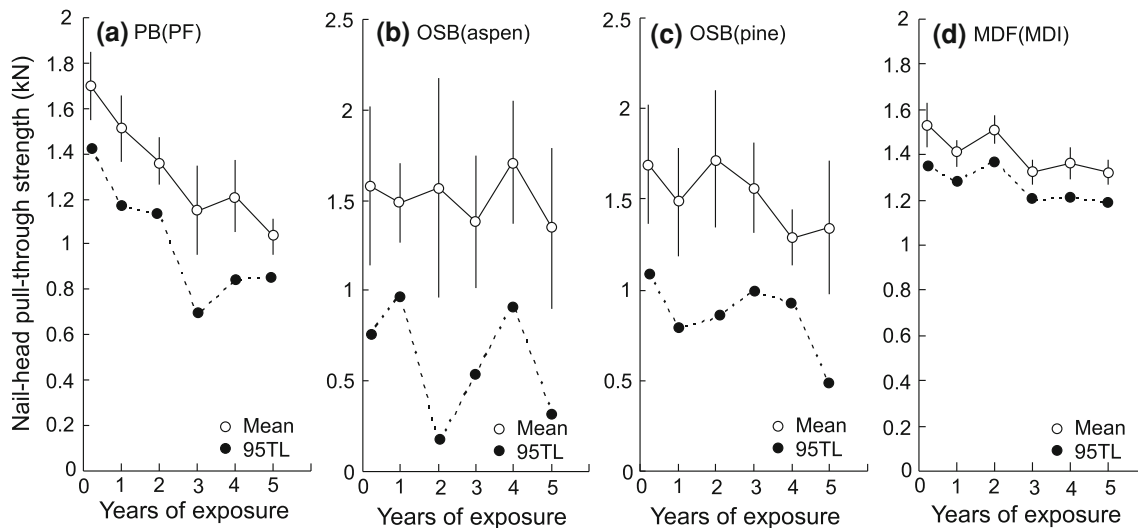
**Table 3** Retention of initial value, coefficient of variation, and retention of 95 % lower tolerance limit at 75 % confidence level for modulus of rupture and internal bond strength

Years of exposure	MOR			IB		
	MOR retention (%)	CV (%)	95TL retention (%)	IB retention (%)	CV (%)	95TL retention (%)
<i>PB(PF)</i>						
Initial		11.3			10.8	
1	69.3	11.4	65.9	72.9	14.3	64.9
2	61.8	8.08	64.5	69.0	37.7	20.5
3	48.6	21.9	32.1	38.4	39.6	9.53
4	38.0	37.8	8.30	38.5	58.5	0
5	46.5	27.1	24.0	16.9	81.9	0
<i>PB(MDI)</i>						
Initial		7.30			8.22	
1	84.4	3.38	90.5	84.9	13.5	72.9
2	78.9	8.12	75.1	93.2	16.3	73.7
3	68.1	5.82	68.8	84.3	9.08	81.3
4	71.2	8.20	67.7	80.9	12.9	70.7
5	70.6	6.70	69.8	67.6	17.8	51.1
<i>OSB(aspen)</i>						
Initial		17.3			23.2	
1	75.8	16.1	72.5	69.5	26.1	57.9
2	66.1	21.6	51.5	59.7	20.4	61.8
3	53.3	30.1	26.9	56.6	43.8	11.3
4	57.9	12.6	5.51	62.5	40.2	20.4
5	39.1	33.2	15.8	32.8	78.0	0
<i>OSB(pine)</i>						
Initial		21.0			29.7	
1	82.2	18.5	80.5	89.6	16.8	100
2	69.9	12.2	84.5	100	25.8	100
3	61.4	17.2	63.2	84.0	24.4	95.5
4	61.6	12.6	73.4	85.0	14.1	100
5	48.5	21.7	42.0	48.5	47.9	3.28
<i>MDF(MDI)</i>						
Initial		6.76			15.6	
1	89.7	5.36	90.7	93.1	13.8	94.7
2	81.2	3.32	86.2	94.5	23.7	69.2
3	79.9	4.72	82.0	81.3	32.3	39.6
4	80.4	4.15	83.6	91.8	22.3	70.9
5	77.1	6.54	75.6	96.7	7.39	100
<i>MDF(MUF)</i>						
Initial		6.47			17.7	
1	87.6	11.0	75.6	100	16.1	100
2	88.2	2.91	94.0	100	15.0	100
3	70.9	2.26	76.7	100	10.6	100
4	68.4	9.44	61.8	99.0	21.2	84.3
5	62.0	14.0	48.8	87.8	17.3	85.2

See Table 1 for the abbreviations. *MOR* modulus of rupture, *IB* internal bond strength, *CV* coefficient of variation, *95TL* 95 % lower tolerance limits of 75 % confidence level



**Fig. 5** Changes in internal bond strength and its 95TL for outdoor exposure. 95TL denotes 95 % lower tolerance limit at 75 % confidence level. See Table 1 for the abbreviations. Vertical bars denote standard deviations



**Fig. 6** Changes in nail-head pull-through and its 95TL of PB(PF), OSB(aspens), OSB(pine), and MDF(MDI) for outdoor exposure. 95TL denotes 95 % lower tolerance limit at 75 % confidence level. See Table 1 for the abbreviations. Vertical bars denote standard deviations

was less conspicuous as compared to internal bond strength. 95TL did not decrease much even after 5 years, and its retention was 60.0 %. OSB(aspens) and OSB(pine) did not show sharp reductions in nail-head pull-through during exposure (Fig. 6b, c). The nail-head pull-through in MDF(MDI) was 1.53 kN before exposure, and then decreased to 1.32 kN after 5 years (Fig. 6d), thereby retaining 86.3 % (Table 4). The coefficient of variation changed only slightly, and therefore, 95TL did not decrease significantly. 95TL retained 88.4 % after 5 years. The coefficient of variation in MDF(MDI) and PB(PF) was smaller than that in both types of OSB. 95TL did not deviate from the mean in MDF(MDI) and PB(PF). Conversely, both OSBs showed large coefficients of variation and large deviation of 95TL from the mean.

#### Lateral nail resistance

Fig. 7a–d show the changes in lateral nail resistance and its 95TL of PB(PF), OSB(aspens), OSB(pine), and MDF(MDI) for outdoor exposure. Table 4 lists the retention of initial value, the coefficient of variation, and the retention of 95TL for lateral nail resistance. The lateral nail resistance in PB(PF), which was 1.74 kN before exposure, decreased sharply during exposure and decreased to 0.49 kN after 5 years (Fig. 7a), thus retaining 28.0 % (Table 4). The retention of lateral nail resistance showed a trend similar to that of internal bond strength, and both were sharply reduced by 5-year exposure. However, changes in the coefficient of variation differed between lateral nail resistance and internal bond strength. The coefficient of

**Table 4** Retention of initial value, coefficient of variation, and retention of 95 % lower tolerance limit at 75 % confidence level for nail-head pull-through and lateral nail resistance

Years of exposure	Neal-head pull-through (NHPL)			Lateral nail resistance (LNR)		
	NHPL retention (%)	CV (%)	95TL retention (%)	LNR retention (%)	CV (%)	95TL retention (%)
<i>PB(PF)</i>						
Initial		8.82			13.8	
1	88.9	9.76	82.2	72.9	26.7	36.9
2	80.4	7.55	79.3	52.0	23.7	31.3
3	67.7	17.3	48.3	41.3	8.32	44.8
4	71.4	13.2	59.2	38.3	9.21	40.5
5	60.9	7.55	60.0	28.0	12.4	26.8
<i>OSB(aspen)</i>						
Initial		27.9			27.7	
1	93.8	14.9	100	75.9	23.4	71.5
2	99.3	38.9	19.0	78.2	26.8	60.5
3	87.4	26.2	70.7	66.0	32.2	34.0
4	100	19.8	100	53.6	24.2	48.3
5	85.3	32.9	41.1	54.2	17.6	66.2
<i>OSB(pine)</i>						
Initial		19.3			30.7	
1	87.5	20.1	72.6	88.0	35.7	34.5
2	100	22.1	77.0	80.6	29.4	59.5
3	92.3	15.9	90.9	70.0	22.0	79.8
4	76.0	12.0	85.8	82.6	14.1	100
5	79.3	27.6	44.0	72.6	17.8	99.8
<i>MDF(MDI)</i>						
Initial		6.60			8.35	
1	91.8	4.07	94.8	100	5.82	100
2	98.7	3.93	100	100	9.80	97.8
3	86.2	4.08	89.0	97.2	4.45	100
4	88.9	5.01	89.6	100	7.00	100
5	86.3	4.37	88.4	87.7	19.6	56.3

See Table 1 for the abbreviations. CV coefficient of variation, 95TL 95 % lower tolerance limit at 75 % confidence level

variation of internal bond strength in PB(PF) increased by 5-year exposure (Table 3), but that of lateral nail resistance was not increased. Therefore, retention of 95TL of internal bond strength was 0 % after 5 years (Table 3), but that of lateral nail resistance was as high as 26.8 %.

The initial lateral nail resistance values of OSB(aspen) and OSB(pine) were 1.81 and 2.08 kN, respectively. In 5 years, those values decreased to 0.98 and 1.51 kN, respectively (Fig. 7b, c). The retention was 54.2 and 72.6 % in OSB(aspen) and OSB(pine), respectively (Table 4). The coefficient of variation did not change much in OSB(aspen), but was decreased by exposure in OSB(pine). Therefore, the retention of 95TL after 5 years was as high as 99.8 % in OSB(pine).

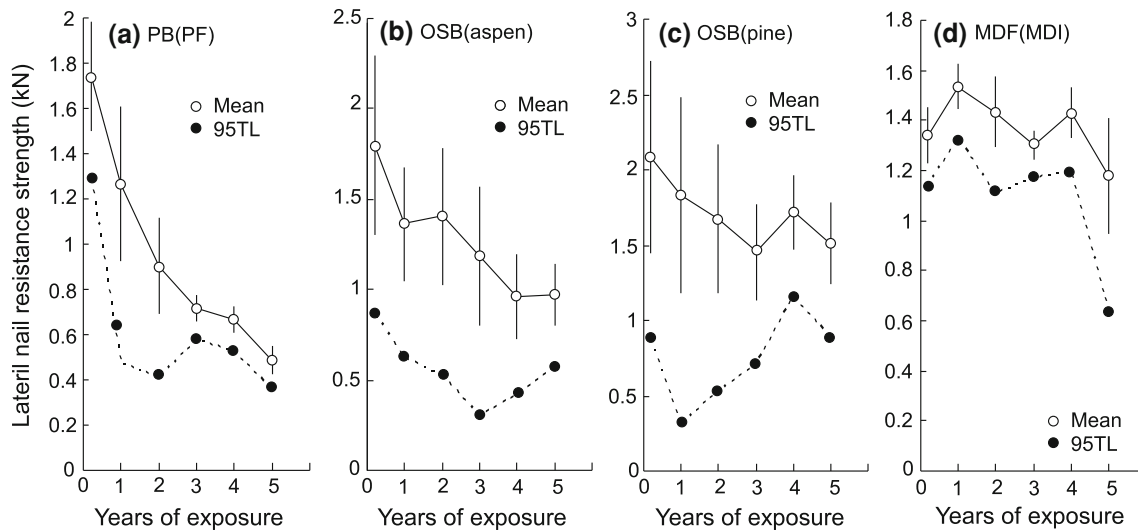
MDF(MDI) did not show conspicuous reductions even after 5 years (Fig. 7d), and maintained a high retention

(Table 4). No large change was observed in the coefficient of variation until 4 years, but marked 19.6 % in 5 years, showing a 2.3-fold increase from the initial value. This resulted in a sharp reduction in 95TL. Up to 4 years, 95TL retained about 100 % of the initial value, but decreased in 5 years. An ongoing investigation will determine whether 95TL is further reduced by continued exposure. The coefficients of variation in MDF(MDI) and PB(PF) were generally smaller than those in both OSBs. 95TL largely deviated from the mean in both OSBs, but did not deviate much in MDF(MDI) and PB(PF).

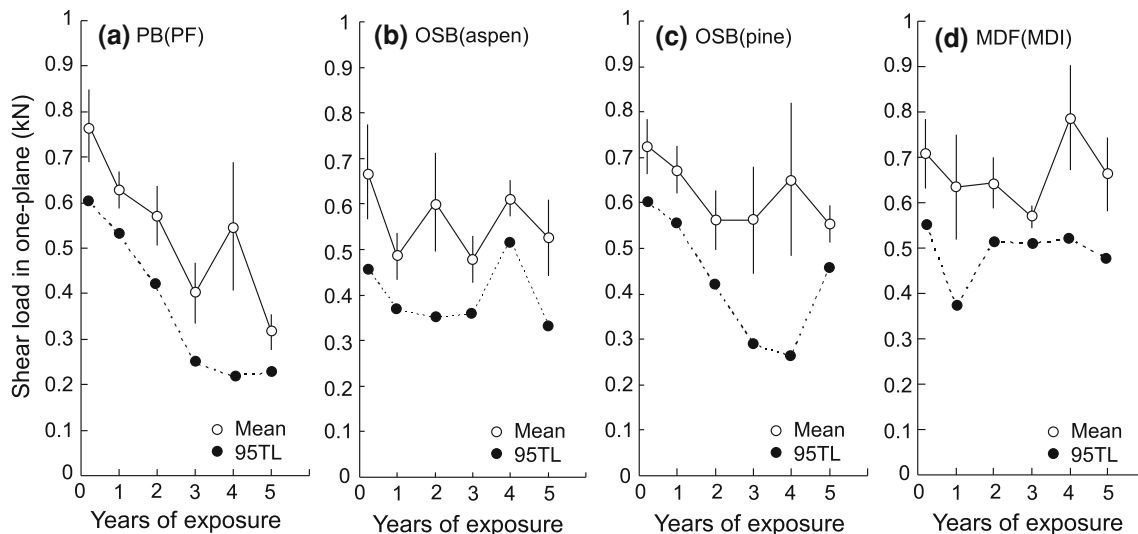
Shear load in one-plane

Fig. 8a–d show the changes in the shear load in one-plane at relative displacement of 1.0 mm and its 95TL of PB(PF),





**Fig. 7** Changes in lateral nail resistance and its 95TL of PB(PF), OSB(aspen), OSB(pine), and MDF(MDI) for outdoor exposure. 95TL denotes 95 % lower tolerance limit at 75 % confidence level. See Table 1 for the abbreviations. Vertical bars denote standard deviations



**Fig. 8** Changes in shear load in one-plane at relative displacement of 1.0 mm and its 95TL of PB(PF), OSB(aspen), OSB(pine), and MDF(MDI) for outdoor exposure. 95TL denotes 95 % lower tolerance

limit at 75 % confidence level. See Table 1 for the abbreviations. Vertical bars denote standard deviations

OSB(aspen), OSB(pine), and MDF(MDI) for outdoor exposure. Table 5 lists the retention of initial value, the coefficient of variation, and the retention of 95TL for shear load in one-plane at relative displacement of 1.0 mm. Most of the boards were destroyed along the edges as shown in Fig. 9, showing that the boards were deteriorated by exposure. In all boards, the coefficient of variation generally did not increase significantly. Therefore, 95TL did not deviate much from the mean. MDF(MDI), OSB(aspen), and OSB(pine) did not show a large deterioration of shear load in one-plane even after 5 years (Fig. 8b–d). Conversely, shear load in one-plane in PB(PF) decreased after

5 years (Fig. 8a). Before exposure, PB(PF) showed the highest value, but showed the lowest after 5 years. The retention in 5 years was high in MDF(MDI), OSB(aspen), and OSB(pine) at 93.5, 78.5, and 76.4 %, respectively, but low in PB(PF) at 41.1 %.

MDF(MDI) retained high levels of the properties in this study, even after 5 years. Therefore, it is understandable that the board also retained a high level of shear load in one-plane. The low retention of shear load in one-plane in PB(PF) is also understandable given the sharp reduction in the shown properties. On the other hand, both OSBs showed a low retention of the modulus of rupture and

**Table 5** Retention of initial value, coefficient of variation, and retention of 95 % tolerance limit at 75 % confidence level for shear load in one-plane at relative displacement of 1.0 mm

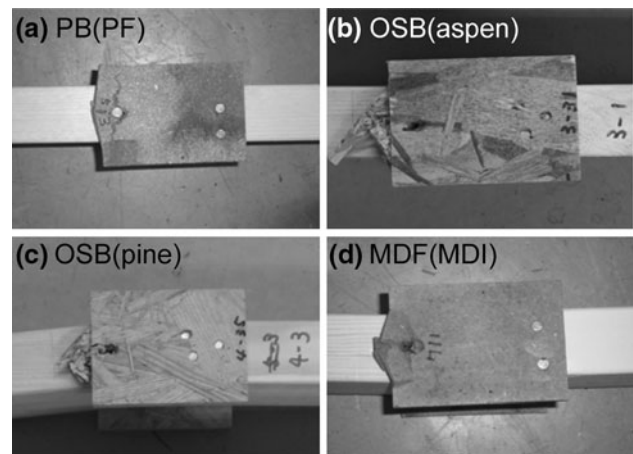
Years of exposure	Shear load in one-plane <sup>a</sup>		
	Shear load in one-plane retention (%)	CV (%)	95TL retention (%)
<i>PB(PF)</i>			
Initial		10.3	
1	81.5	6.50	87.5
2	74.2	11.5	68.7
3	52.3	16.6	40.5
4	71.3	25.8	35.9
5	41.1	12.6	36.8
<i>OSB(aspen)</i>			
Initial		15.4	
1	72.4	10.4	80.1
2	90.1	18.1	76.1
3	71.4	10.7	78.4
4	91.5	6.53	100
5	78.5	15.8	72.4
<i>OSB(pine)</i>			
Initial		8.28	
1	92.8	7.75	91.5
2	77.5	11.4	68.5
3	77.4	20.9	47.8
4	90.1	25.8	43.2
5	76.4	7.47	75.9
<i>MDF(MDI)</i>			
Initial		10.7	
1	89.5	18.2	66.0
2	90.8	8.78	92.5
3	80.2	4.34	92.3
4	100	14.6	93.8
5	93.5	12.2	85.7

See Table 1 for the abbreviations. CV coefficient of variation, 95TL 95 % lower tolerance limit at 75 % confidence level

<sup>a</sup> Strength at relative displacement of 1.0 mm per one nail

internal bond strength. In particular, the retention in OSB(aspen) was as low as that in PB(PF). However, OSB(aspen) showed a high retention of shear load in one-plane. This is possibly attributable to the shape of raw materials (i.e., very long strands in the fiber direction) used for OSB.

Even after many bonding points among strands were destroyed by exposure, nails still passed through the strands, and the strand strength due to fiber strength was manifested. In other words, the density of OSB(aspen) was 0.63 g/cm<sup>3</sup> before exposure, and then decreased to 0.51 g/cm<sup>3</sup> after 5 years (Table 1). The thickness change increased to 15.6 % (Table 1). The reduced density and increased thickness



**Fig. 9** Board destruction caused by shear load in one-plane of PB(MDI), OSB(aspen), OSB(pine), and MDF(MDI) subjected to outdoor exposure

change suggest the destruction of bonding points. However, the strand strength was effectively manifested and showed high nail resistance, and thus OSB retained high levels of shear load in one-plane even when only a few bonding points remained. On the other hand, particleboard is manufactured from particles that are much smaller than strands, and nails rarely pass through the particles. Therefore, particle strength due to fiber strength is rarely manifested. Before exposure, PB(PF) showed the highest shear load in one-plane because PB(PF) had a higher density than the other boards (Table 1). However, the density of PB(PF) was reduced to 0.66 g/cm<sup>3</sup> after 5 years, and the thickness change increased to 15.2 % (Table 1). The reduced density and increased thickness change suggest the destruction of bonding points between particles. Unlike strands, particles lack the fiber strength. This is why shear load in one-plane decreased in PB(PF). On the other hand, MDF is manufactured from fibers that are as small as particles, but the fibers are intertwined and have mutually high adhesion [17]. As a result, the bonding points were not destroyed, and MDF maintained both high density (Table 1) and nail resistance even after exposure.

Nail joint property is a key element of structural boards. The outdoor environment to which the boards were exposed was very severe. The small decreases in shear load in one-plane in OSB(aspen), OSB(pine), and MDF(MDI) provide valuable data when applying the boards for structural purposes.

**Conclusions**

Various types of board were exposed outdoors for 5 years in Tsukuba, and then the board properties were analyzed for deterioration. The following results were obtained:

1. In PB(PF), OSB(aspen), and OSB(pine), the modulus of rupture decreased further with longer exposure. The coefficient of variation increased significantly in PB(PF) and OSB(aspen), resulting in a lowered 95TL. In contrast, the modulus of rupture in PB(MDI), MDF(MDI), and MDF(MUF) was hardly reduced, and the coefficient of variation increased only slightly.
2. In PB(PF) and OSB(aspen), the internal bond strength decreased further with longer exposure. The coefficient of variation increased significantly, and 95TL was sharply decreased. In both MDFs, however, the internal bond strength decreased only slightly and the coefficient of variation did not change much. Therefore, the retention of 95TL was high.
3. The nail-head pull-through of PB(PF) decreased during exposure, but not as conspicuously as seen in the modulus of rupture and internal bond strength. In MDF(MDI), OSB(aspen), and OSB(pine), nail-head pull-through was only slightly reduced.
4. In PB(PF), the lateral nail resistance decreased as sharply as the internal bond strength. In OSB(aspen) and OSB(pine), the lateral nail resistance decreased moderately. MDF(MDI) retained a high level of lateral resistance.
5. In OSB(aspen), OSB(pine), and MDF(MDI), shear load in one-plane was not significantly reduced even after 5 years, but was sharply reduced in PB(PF). OSB(aspen) showed low levels of the modulus of rupture and internal bond strength, but showed a high level of shear load in one-plane. In PB(PF), the retention was low for the modulus of rupture, internal bond strength, and shear load in one-plane.

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