Effects of Decay on the Mechanical Properties of Nailed Joints in Light Wood Frame Structure

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Abstract

For this study, spruce–pine–fir (*Picea–Pinus–Abies* [SPF]) specification material, oriented strand board (OSB), and domestic twisted nails that were driven vertically and perpendicular-to-grain were selected. Referring to GB/T 13942.1-2009, nailed joints specimens were exposed both to white rot fungus and brown rot fungus for 1 month to 6 months. The monotonous loading test was applied to the specimens based on ASTM D1761-88. The holding power of the nails and weight loss of both OSB and SPF were investigated. Theoretical maximum load of the nailed joints was calculated according to Eurocode5. Results illustrated that the load, stiffness, and energy consumption of the nailed joints showed significant linear decline with the decay time. A linear decline of the ductility coefficient was not obvious, and there was no obvious difference between white rot fungus and brown rot fungus. Effect of decay on the OSB was much greater than the impact on the SPF. The decay grade of the nailed joints was established according to the linear relationship between weight loss and maximum load. Based on Eurocode5, the study calculated the maximum load of the nailed joints and introduced the correction coefficient γ to better predict the maximum load.

Light wood frame structures have gradually developed in China because of their superior structural and environmental performance (Canada Wood 2012). However, as a type of biomass material, wood degrades under the influence of decay fungi. The decay of wood will inevitably lead to a decline in the mechanical properties, which in turn affects the bearing capacity of the wood structure.

The weakest part in the shear wall of a light wood structure is the connection between the sheathing and framing members, especially the connection between the sheathing panel and the bottom plate, which usually involves nailed joints (Nairn et al. 2011). Much research has been conducted to better understand the effect of decay on the properties of nailed joints. Merrill and French (1964) studied the effect of nailhead pull-through strength at various levels of decay damage and found that a 12 to 15 percent weight loss caused an approximate 50 percent reduction in pull-through strength. Some scholars studied the relationship between nail pull-out force and the decay of nails under brown rot conditions. Studies have shown that the nailhead rust increased the pull-out force (Takanashi et al. 2017). After 1 to 9 weeks of exposure to brown rot decay, the surface of the nail obviously was rusted and the pull-out force of the nail increased significantly with the decay time (Ishiyama and Koshihara 2009).

Kent et al. (2004, 2005) studied the effects of the nailed joints of oriented strand board (OSB) panels and Douglas fir (*Pseudotsuga menziesii*) frame exposed to brown rot fungus on the mechanical properties under monotonic and cyclic conditions and found that the results began to decline after 20 weeks, and the mechanical properties of nail joints were mainly determined by the OSB plate. Toda et al. (2010, 2013) studied the influence of brown rot fungus on the mechanical properties of the nailed joints using both the

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plywood and medium-density fiberboard (MDF) connected via specifications. Their results showed that the brown rot fungus had serious decay on the sheathing board and the weight loss of the plywood was far greater than that of the MDF. In Mori et al.'s study (2014), the bolt bearing capacity, the density, and the weight loss of the materials could be used to reflect the effect of brown rot on the nailed joints.

A high moisture content will greatly reduce the mechanical properties of the joints of wood structure. Sawata et al. (2008) studied dowel-type joints that were exposed to a brown rot fungus, and found that when dowel-type joints were placed in wet conditions, compared with air-dried samples, the initial stiffness, yield load, and maximum load showed significant reduction, and decreased further with degradation of wood caused by the fungus.

The above research mainly focused on the effect of brown rot on the nailed joints and did not involve white rot. In fact, white rot fungi in the late stage of decay will decompose hemicellulose of the wood cell wall; this decomposition will lead to a rapid decline in the mechanical properties of the wood, resulting in a decrease in that of the nailed joints. Additionally, the specimens were soaked to increase the moisture content to promote the growth of decay fungi, which meant the influence of moisture content on the decline of mechanical properties from the initial decay could not be excluded.

In order to fully understand the influence of decay on nailed joints and reduce the influence of moisture content on the mechanical properties in the initial decay, this study built a laboratory decay method for the corrosion resistance of nailed joints based on Guobiao Standard GB/T 13942.1-2009. The specimens were exposed to both brown rot and white rot to study the effect of decay on the strength, stiffness, ductility, and energy consumption. Test specimens were not soaked, so the influence of moisture content on the mechanical properties could be reduced to some extent. The nails' holding power and weight loss of the OSB and the spruce–pine–fir (*Picea–Pinus–Abies* [SPF]) were used to evaluate the influence of decay on the nailed joints. The decay level of the nailed joints was also established. According to the failure modes of the nailed joints, a formula was used to predict the maximum load determined from the decayed materials based on Eurocode5.

Materials and Methods

Experimental materials

The experiment used SPF specifications, 12-mm OSB, and domestic twist steel nails. The SPF was a secondary structural material with a cross-section size of 38 mm × 89 mm and moisture content of the SPF was 13.99 percent. The OSB (exported from Brazil) had a density of 705 kg/m^3 and moisture content of 7.13 percent. The nail was 3.3 mm in diameter and 63 mm in length with a bending yield strength of 761MPa (ASTM F1575-2003 [ASTM 2013]).

Specimen design and manufacture

The SPF and OSB were 38 mm × 89 mm × 185 mm and 90 mm × 210 mm × 12 mm, respectively (Nairn et al. 2011). Specimens for the decay process were designed considering two factors, the decay time and decay fungi, and were decayed from 1 to 6 months, using both white rot fungus and brown rot fungus. The SPF and the OSB were connected by steel nails and 2-mm holes were predrilled. Table 1 shows the experimental design; and Figure 1 shows specimen details.

Decay method

Specimens were subjected to the decay fungus based on GB/T 13942.1-2009. *Gloeophyllum trabeum* (brown rot, GT) and *Coriolus versicolor* (white rot, TV) were cultivated on agar medium for 1 to 2 weeks. A 295 × 230 × 138-mm polypropylene box was used as the incubator. Eighty grams vermiculite, 80 g poplar sawdust, and 45 g corn flour were put into the incubator and then mixed evenly; and 500 ml maltose was poured into the box (Fig. 2a). The nailed joint specimens were placed on the medium and then sterilized in the high-pressure sterilization equipment at 120°C for 1 hour (Fig. 2b). After sterilization and cooling, the fungi were inoculated to the nailed joints (Fig. 2c). The box was placed in a biochemical incubator at 28°C and 75 to 85 percent relative humidity from 1 month to 6 months.

Table 1.—The specimen design.

Decay type	Decay time (mo)	No. of specimens
Brown rot (GT)	0, 1, 2, 3, 4, 5, 6	4 × 7 = 28
White rot (TV)	0, 1, 2, 3, 4, 5, 6	4 × 7 = 28

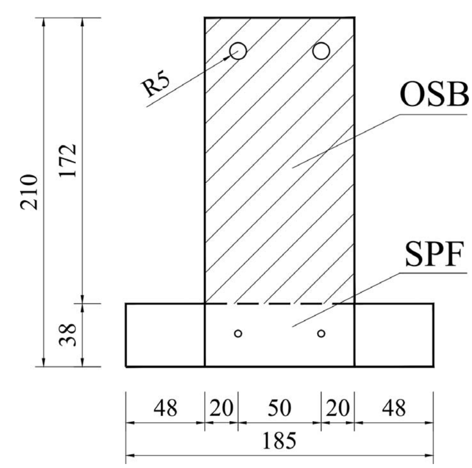
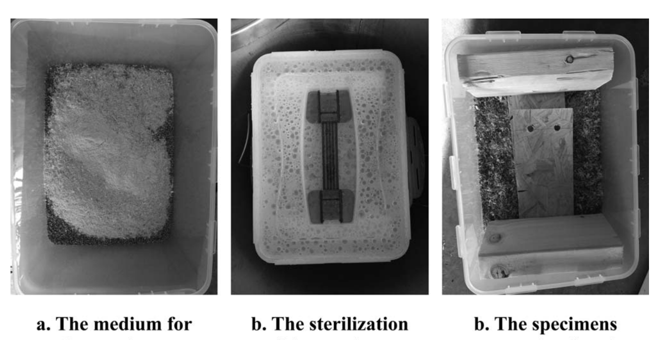


Figure 1.—The test specimen.



a. The medium for the specimen **b. The sterilization of the specimen** **b. The specimens exposed to fungi**

Figure 2.—(a–c) The specimens exposed to wood decay: (a) The medium for the specimen; (b) The sterilization of the specimen; (c) The specimens exposed to fungi.

Loading test

The monotonous test was performed under the displacement control based on ASTM D1761-88 (ASTM 2012). The decayed specimens were then conditioned under conditions of constant temperature and humidity for 1 week to keep the moisture content at 11.4 percent before testing. Loading rate was 2.54 mm/minute. The test was finished once the test load dropped to 80 percent of the maximum load or the specimens fractured. The testing equipment was a universal capability testing machine (MMW-50). Special fixtures were designed to fix the test specimens. The upper section of the specimen was bolted to the fixture, which was connected to the test machine with one bolt. The bottom end was fixed to a steel plate by two steel blocks, which covered the SPF with four bolts. The load displacement curve was recorded on a computer. Figure 3 shows the loading diagrams.

Mechanical test of the materials

The nail holding power test of the SPF.—The nail holding power of the SPF was tested based on GB/T 14018-2009 and GB 50005-2003. Samples of 50 mm × 38 mm × 150 mm size were cut from the decayed SPF. Six specimens in every condition were manufactured. Table 2 shows the specimen design. The nails were nailed at a distance of 30 mm both on the surface and side of the specimens as in Figure 4a–b. The nail was pulled out at a speed of 5 mm/minute as in Figure 4c.

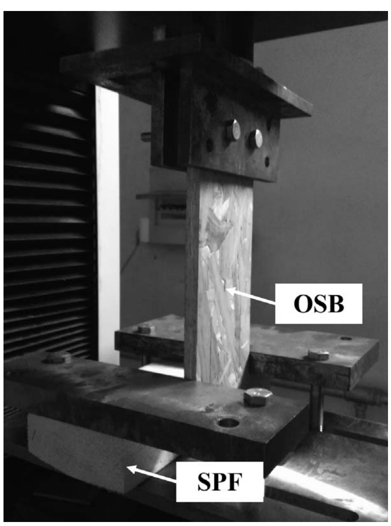


Figure 3.—The loading test.

Table 2.—The design of nail holding power test specimens.

Decay type	Decay time (mo)	No. of specimens
Brown rot (GT)	0, 1, 2, 3, 4, 5, 6	6 × 7 = 42
White rot (TV)	0, 1, 2, 3, 4, 5, 6	6 × 7 = 42

The nail pull-out force test of the OSB panel.—Nail pull-out force was tested based on GB/T 17657-2013. The OSB specimen was 75 mm × 50 mm × 12 mm. The nails were nailed at a distance of 30 mm in the center of the OSB board. The nail was aligned with the centerline of the test machine and pulled out at a loading speed of 5 mm/minute. Figure 5 shows the pull-out test, and Table 3 shows the specimen design.

Weight loss test

The SPF and OSB from the decayed nailed joint specimens and the same materials without decay were cut into small pieces of 20 × 20 × 20 mm and 20 × 20 × 12 mm, respectively. There were 10 specimens in every group. Samples were then dried to an absolutely dry condition in the oven-drying box at 103°C. Oven-dried weight of the specimens without decay was measured as W_1. Oven-dried weight of the decayed specimens was measured as W_2. The weight loss W_l was calculated via the following formula (GB/T 13942.1-2009):

$$W_l = \frac{W_1 - W_2}{W_1} \times 100\% \quad (1)$$

Results and Discussion

Fracture modes

The decay conditions.—During the decay process, both the brown rot and white rot fungi grew well. The fungi gradually spread to the nailed joints. After 1 month, the fungus began to grow. After 4 months, the fungi had substantially covered the whole surface of the specimens, and the thickness of the fungi layer gradually increased. After 6 months, blocky fungi formed on the specimens. Figure 6 shows the specimens exposed to brown rot.

The loading conditions.—Specimens decayed from 1 month to 3 months demonstrated common destructive

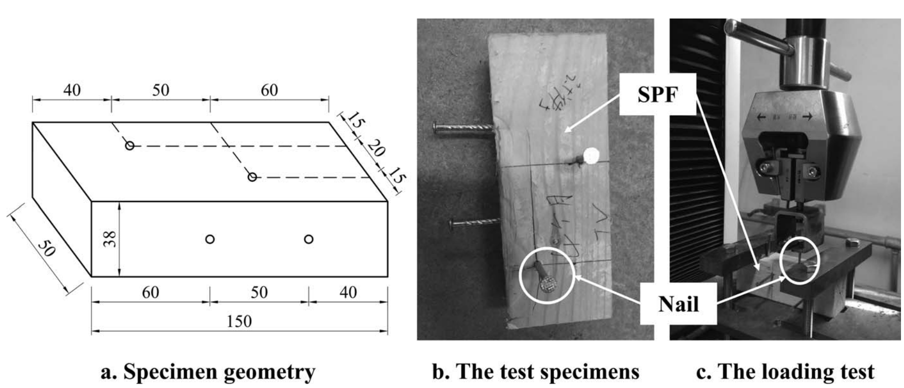


Figure 4.—(a–c)The nail holding power test: (a) Specimen geometry; (b) The test specimens; (c) The loading test.

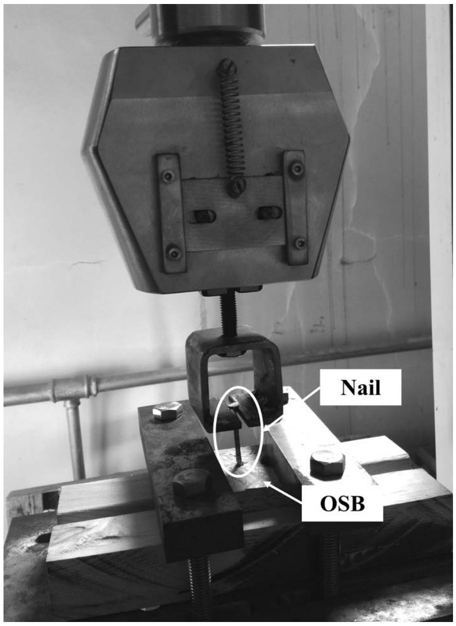


Figure 5.—The nail pull-out force test.

phenomena both for brown rot and white rot: the caps collapsed (Fig. 7a), the nail rods bent (Fig. 7b), the OSB cracked, and the SPF tore (Fig. 7c). After 4 months and 5 months, the SPF damage was tensified and the edges were torn seriously (Fig. 7d). Two test specimens exposed to white rot broke at the bolt holes of the OSB board, which led to rapid destruction of the OSB panel and failure of the nailed specimens failed. After 6 months, the OSB board cracked along the nailed joints (Fig. 7e). Almost all the specimens were destroyed; the OSB board was seriously damaged at the bolt hole and the test specimens quickly failed (Fig. 7f). Most nails did not bend (Fig. 7g), but the surface of the nailhead rusted (Fig. 7h).

Analysis of loading test results

The average maximum load and displacement of each group are shown in Table 4. The characteristics value of each load-displacement curve was calculated and averaged

Table 3.—The design of nail pull-out force test specimens.

Decay type	Decay time (mo)	No. of specimens
Brown rot (GT)	0, 1, 2, 3, 4, 5, 6	$6 \times 7 = 42$
White rot (TV)	0, 1, 2, 3, 4, 5, 6	$6 \times 7 = 42$

(Japan 2×4 Home Builders Association 2004). Results are shown in Table 5.

Comparative analysis of the load.—Figure 8 shows the comparative result of the maximum load, the yield load, and the ultimate load. Under the decay condition, the maximum load, the yield load, and the ultimate load of the nail joints began to decrease after 1 month of decay; and there was a significant linear decline trend with decay time. The linear formulas fit by the data analysis and graphing software—origin were as follows.

The maximum load:

$$\text{Brown rot}: F_{\max} = -0.23x + 2.56 \qquad R^2 = 0.91 \quad (2)$$

$$\text{White rot}: F_{\max} = -0.31x + 2.58 \qquad R^2 = 0.90 \quad (3)$$

The yield load:

$$\text{Brown rot}: F_y = -0.13x + 1.34 \qquad R^2 = 0.86 \quad (4)$$

$$\text{White rot}: F_y = -0.17x + 1.33 \qquad R^2 = 0.86 \quad (5)$$

The ultimate load:

$$\text{Brown rot}: F_u = -0.21x + 2.28 \qquad R^2 = 0.82 \quad (6)$$

$$\text{White rot}: F_u = -0.29x + 2.34 \qquad R^2 = 0.88 \quad (7)$$

From 1 to 3 months, there was no obvious difference between the brown rot and white rot load. However, after 4 months of decay, the maximum load exposed to white rot dropped rapidly by 44 percent, probably because of the broken OSB bolt hole connected to the test machine. As a result, the average value of the load obtained in the test dropped sharply. The phenomenon was not found in the specimens exposed to brown rot. After 5 months of decay, the brown rot load still showed a declining trend, but the average value of the white rot load increased compared with

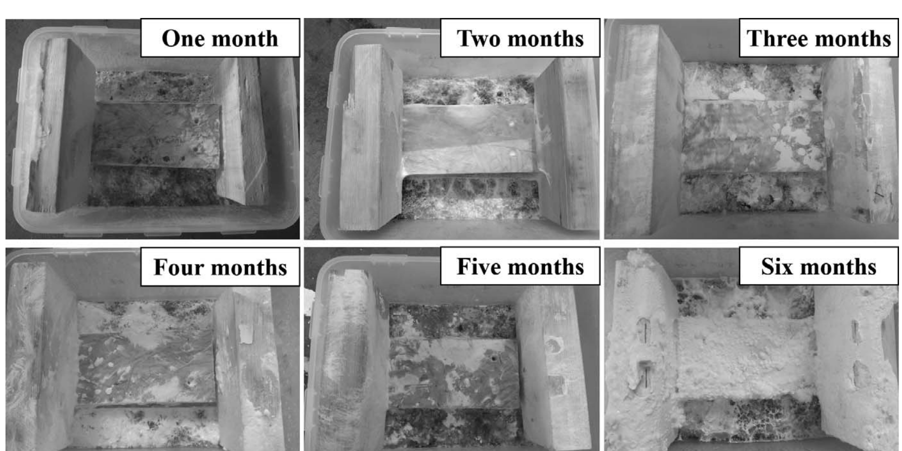


Figure 6.—The specimens exposed to brown rot after decaying from 1 to 6 months.

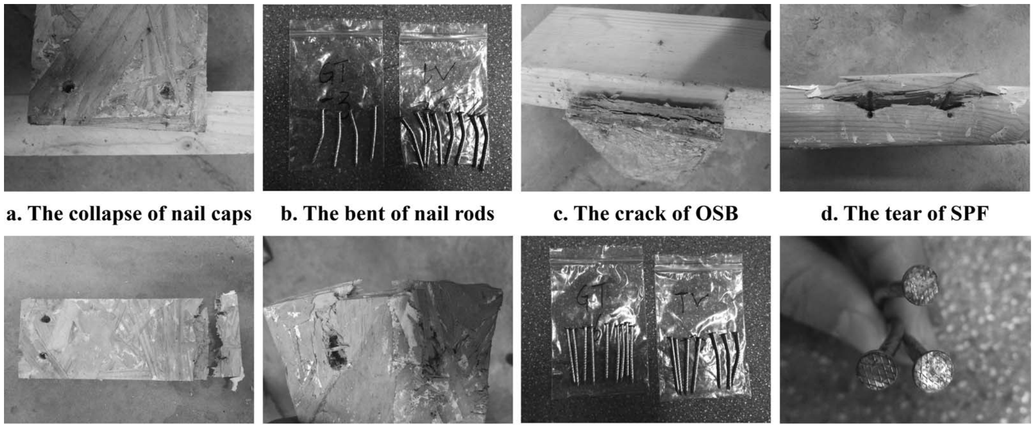


Figure 7.—(a–h) The fracture modes of the nailed joints: (a) The collapse of nail caps; (b) The bent of nail rods; (c) The crack of OSB; (d) The tear of SPF; (e) The crack of OSB; (f) The crack of OSB bolt hole; (g) The nails after 6 months; (h) The rusted nailhead.

at 4 months, probably because there was no fracture at the bolt hole of the OSB, and the OSB and SPF materials of the nailed joint specimens exposed to white rot fully functioned. After 6 months of decay, both white rot and brown rot decreased significantly. At this time, the OSB panel of the white rot and brown rot test specimens broke at the bolt hole, resulting in a rapid decrease in the load.

Comparative analysis of the stiffness.—Figure 9 shows comparative result of the stiffness analysis. Under the decay condition, the stiffness of the nailed joints began to decrease after 1 month of decay, and there was a significant linear decline trend with decay time. The linear formulas were as follows:

$$\text{Brown rot}: K = -0.04x + 0.33 \qquad R^2 = 0.90 \tag{8}$$

$$\text{White rot}: K = -0.038x + 0.32 \qquad R^2 = 0.82 \tag{9}$$

Decayed specimens exposed to brown rot exhibited slightly higher stiffness than specimens exposed to white rot. With decay time, the brown rot decreased evenly and the stiffness decreased to a minimum of 0.1 kN/mm after 6 months. Stiffness of the white rot specimens dropped sharply by 43 percent after 4 months of decay, possibly because the OSB bolt hole connected to the testing machine broke during the loading process. Only the OSB panel material provided rigidity against deformation, which caused the average stiffness to drop significantly.

Table 4.—The mechanical properties of the nailed joints.

Decay type	Decay time (mo)	Maximum load (kN)	Maximum displacement (mm)
Brown rot (GT)	0	2.67	23.22
	1	2.33	23.28
	2	1.92	21.93
	3	1.83	21.78
	4	1.67	28.02
	5	1.65	25.13
	6	1.06	22.43
White rot (TV)	0	2.67	23.22
	1	2.31	25.88
	2	1.96	22.69
	3	1.60	17.59
	4	0.91	16.16
	5	1.25	15.02
	6	0.83	14.96

Comparative analysis of the ductility.—The ductility coefficient of the nailed joints did not change significantly and increased slightly after 1 month (Fig. 10). That was because 500 mL of maltose was poured into the nutrient medium to promote the growth of decay fungi. The nailed joint specimens were in an environment of particular humidity, which made the OSB panel expand in the thickness. The expansion in thickness of the OSB panel relieved the ductility decrease to some extent. After the first month, the ductility showed a downward trend.

Comparative analysis of the energy dissipation capacity.—Figure 11 shows comparative results of the energy dissipation capacity. Under the decay condition, the energy dissipation capacity of the nailed joints began to decrease after 1 month of decay. There was a significant linear decline trend with decay time. The linear formulas were as follows:

$$\text{Brown rot}: E = -4.17x + 44.49 \qquad R^2 = 0.80 \tag{10}$$

$$\text{White rot}: E = -7.22x + 47.62 \qquad R^2 = 0.90 \tag{11}$$

In the early stage of decay after 1 to 2 months, the energy dissipation capacity of the nailed joints exposed to white rot was larger than that of joints exposed to brown rot, and the decrease of white rot in the early stage was less than that of brown rot. After 3 months, the energy consumption of white rot dropped rapidly, and the decrease was much bigger than that of brown rot. After 4 to 6 months of decay, the energy consumption of white rot was only 50 percent that of brown rot. It might be because the fracture of the OSB panel caused the nailed joints to become brittle in the late stage of decay, so the area between the load displacement curve and the axis was significantly reduced.

The nail-holding power of SPF and the nail pull-out force of OSB

The surface and side maximum load of SPF and the maximum pull-out force was recorded by the mechanical

Table 5.—The mechanical properties of the nailed joints.

Decay type	Decay time (mo)	Stiffness (kN/mm)	Yield load (kN)	Ultimate load (kN)	Ductility	Energy dissipation capacity (kN·m^2)
Brown rot (GT)	0	0.35	1.48	2.43	3.06	47.31
	1	0.30	1.19	2.11	2.96	40.65
	2	0.24	0.95	1.71	2.74	30.08
	3	0.17	0.89	1.32	2.23	29.69
	4	0.14	0.76	1.46	2.74	31.93
	5	0.16	0.80	1.47	2.33	28.13
	6	0.10	0.60	0.94	2.03	16.16
White rot (TV)	0	0.35	1.48	2.43	3.06	47.31
	1	0.29	1.15	2.11	3.21	46.41
	2	0.19	0.95	1.78	2.31	32.42
	3	0.21	0.74	1.38	2.60	21.86
	4	0.12	0.46	0.77	2.95	11.24
	5	0.14	0.63	1.10	1.90	13.83
	6	0.12	0.45	0.77	2.24	8.74

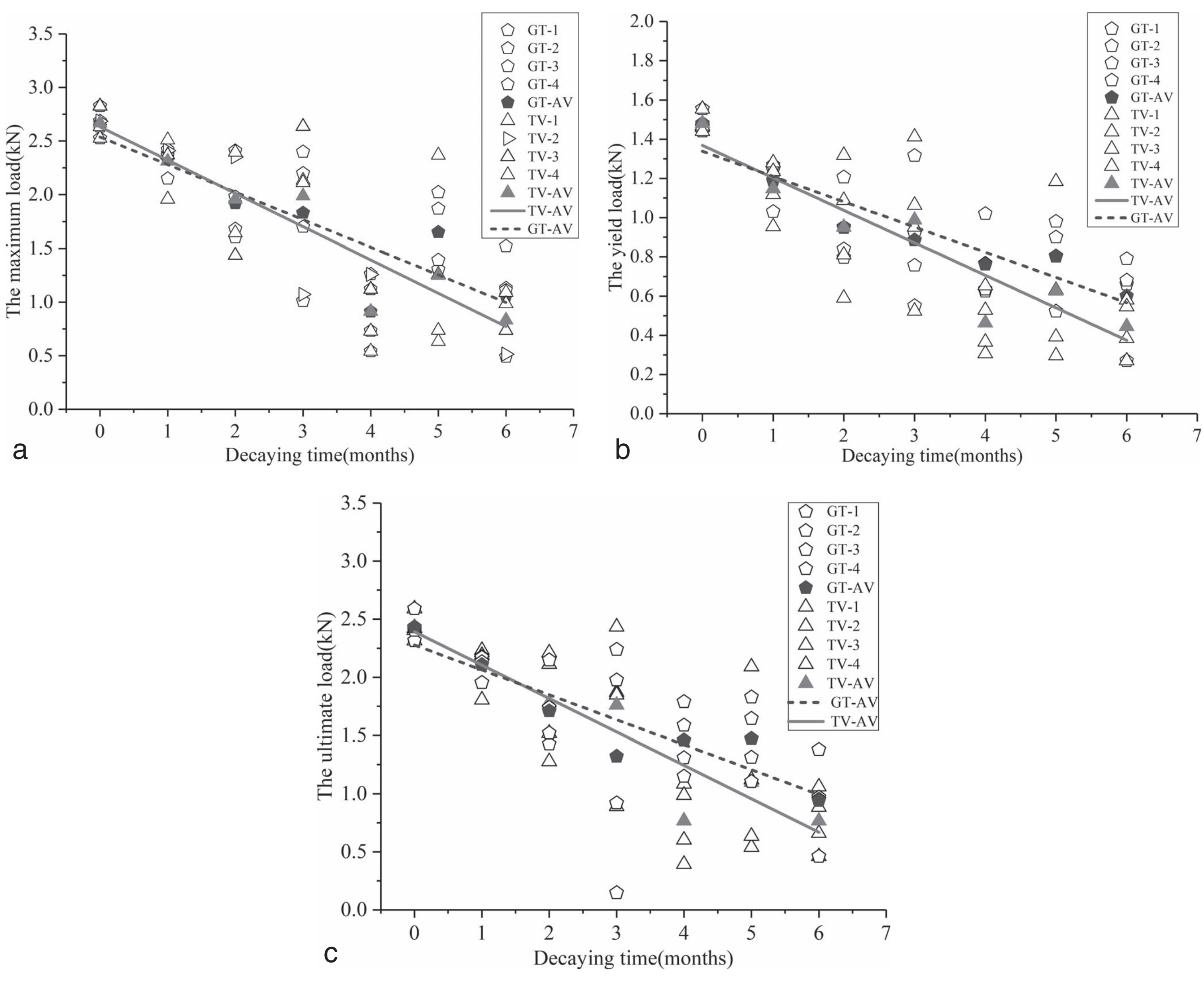


Figure 8.—(a–c) The relationship between the load and the decay time.

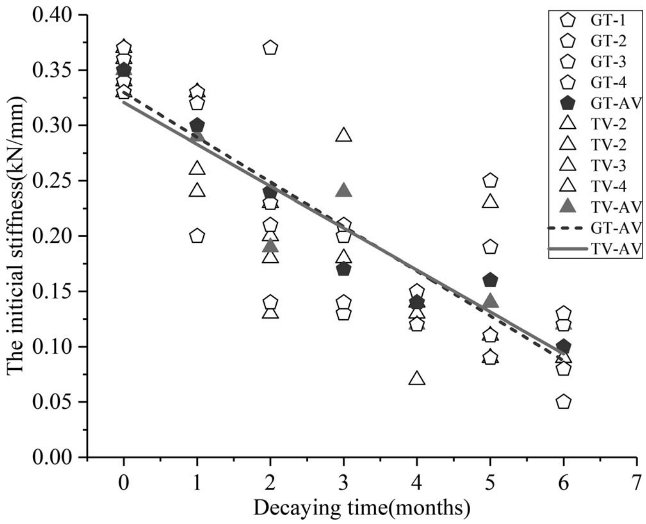


Figure 9.—The relationship between the stiffness and the decay time.

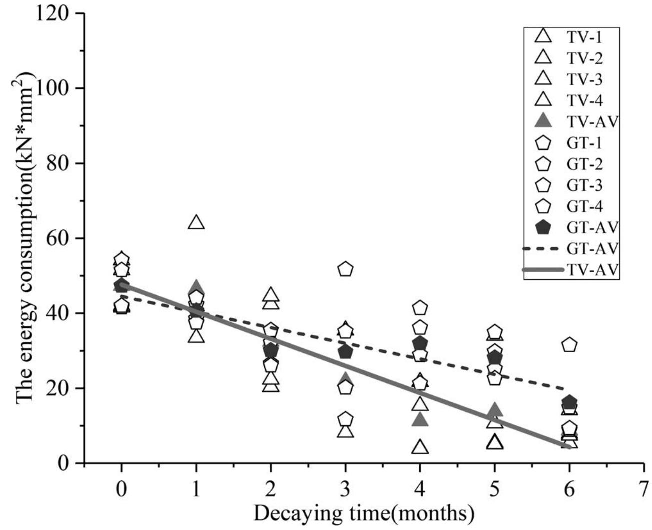


Figure 11.—The relationship between the energy dissipation capacity and the decay time.

testing machine. The nail holding power was calculated according to the following formula (12; GB/T 14018-2009). The average value is shown in the Table 6.

$$P = \frac{P_{\max}}{L} \tag{12}$$

where P is the nail-holding power, $P_{\max}$ the maximum load, and L the depth into the wood.

Figure 12 shows the change in nail holding power of the SPF with decay time. During the initial 3 months, nail holding power did not change based on exposure to white or brown rot. After 4 to 6 months of brown rot, the surface and side nail-holding power began to show a significant downward trend. The surface nail-holding power decreased notable after exposure to white rot. The side remained basically unchanged from the fourth to fifth month, but fell rapidly by 37 percent after 6 months of decay. The brown rot made the drop of the nailed joints of the SPF decrease more obviously.

The nail pull-out force of the nailed joints began to decrease after the first month of decay (Fig. 13). There was a significant linear decline trend with decay time. Under decay conditions, the linear formulas fit with the load and decay time were as follows:

$$\text{Brown rot}: P = -44.32x + 425.96 \qquad R^2 = 0.94 \tag{13}$$

$$\text{White rot}: P = -47.86x + 398.57 \qquad R^2 = 0.93 \tag{14}$$

The effect of both white rot and brown rot on the pull-out force of OSB was obvious. The pull-out resistance of brown rot was significantly higher than that of white rot and that of OSB panel decreased more obviously. The effect of decay had a much greater impact on the OSB panel than on the SPF.

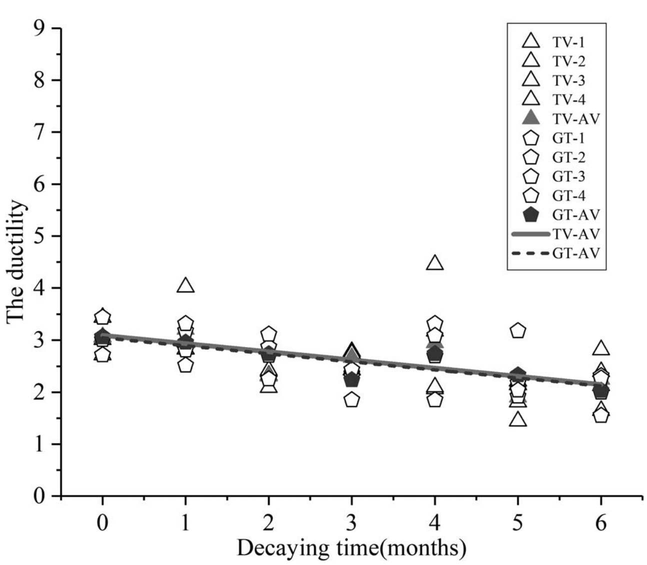


Figure 10.—The relationship between the ductility and the decay time.

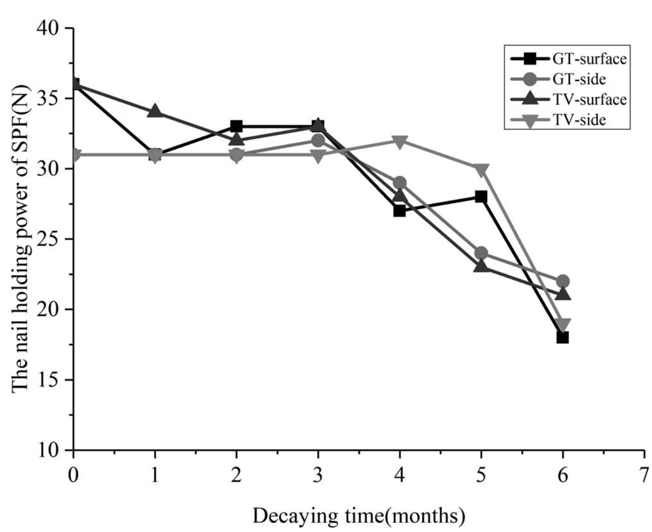


Figure 12.—The relationship between the nail holding power and the decay time.

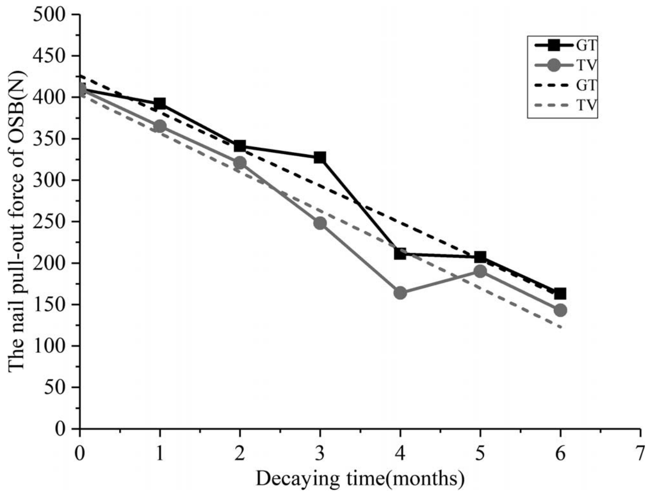


Figure 13.—The relationship between the nail pull-out force and the decay time.

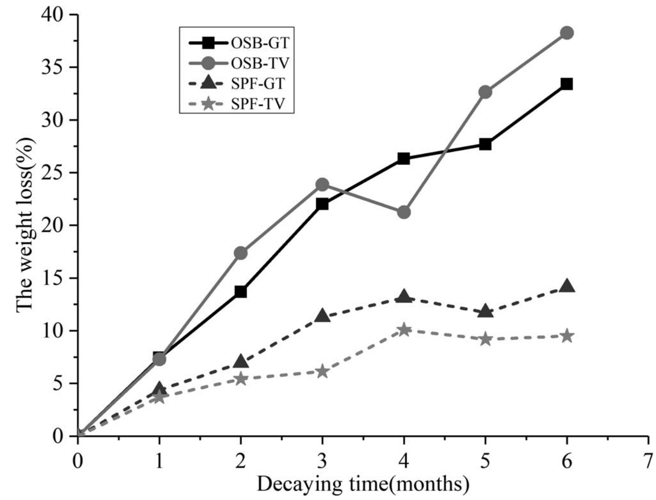


Figure 14.—The relationship between the weight loss and the decay time.

The weight loss of the SPF and OSB

Table 7 shows the average weight loss of the OSB panel and SPF specification. Figure 14 shows that the weight loss of OSB panel increased linearly with the decay time. It reached the maximum weight loss after 6 months of white rot and brown rot decay, which were 38.26 percent and 33.40 percent, respectively. Maximum weight loss of brown rot was less than 15 percent, and weight loss of white rot was less than 10 percent. The weight loss of the OSB panel changed much more than that of the SPF specification. The weight loss of the OSB panel was almost twice that of SPF when exposed to brown rot, and the weight loss of the OSB panel was three times that of SPF when exposed to white rot.

The decay resistance grade of nailed joints

Based on GB/T 13942.1-2009, the decay resistance grade of wood was divided into four levels according to the weight loss of the sample (Table 8). In the initial 3 months of decay, weight loss of SPF was below 7 percent. In the last 3 months of decay, although weight loss of SPF increased slightly, it was still much lower than the weight loss of OSB. In the loading process, the OSB panel was easily damaged and the destruction of the OSB panel led to rapid failure of the nailed joints. The mechanical properties of the OSB panel material determined the mechanical properties of the nailed joints, so the effect of SPF weight loss on the nailed joints failure was ignored (Nairn et al. 2011).

Figure 15 shows the relationship between maximum load and weight loss. The linear formulas fit with maximum load and weight loss were as follows:

$$\text{Brown rot}: F_{\max} = -0.041x + 2.65 \qquad R^2 = 0.92 \quad (15)$$

$$\text{White rot}: F_{\max} = -0.046x + 2.69 \qquad R^2 = 0.99 \quad (16)$$

When the weight loss was 10 percent, 24 percent, 44 percent, the maximum load could be calculated as in Table 9. The nailed joints laboratory decay resistance grade is shown in Table 10.

The theoretical calculation of the maximum load

The failure modes of the test specimens decayed from 1 month to 5 months were mainly that the nail bent and pulled through the panel, and the SPF was destroyed. The failure mode after 6 months was that the OSB panel cracked at the bolt hole and the nails did not bend. Chen et al. (2008) and Zhu et al. (2011) found that the results calculated by the Eurocode5 were in good agreement with the experimental results. Therefore, in this study, the maximum load of the nailed joints was calculated based on Eurocode5. According

Table 6.—The nail-holding power of the spruce–pine–fir (SPF) and the nail pull-out force of the oriented strand board (OSB). Gloeophyllum trabeum *(brown rot, GT);* Coriolus versicolor *(white rot, TV).*

Decay time (mo)	SPF-nail-holding power (N/mm)				OSB-nail pull-out force (N/mm)	
	GT		TV			
	Surface	Side	Surface	Side	GT	TV
0	36	31	36	31	410	410
1	31	31	34	31	392	365
2	33	31	32	31	341	321
3	33	32	33	31	327	248
4	27	29	28	32	211	164
5	28	24	23	30	207	190
6	18	22	21	19	163	143

Table 7.—The weight loss of the spruce–pine–fir (SPF) and the oriented strand board (OSB). Gloeophyllum trabeum *(brown rot, GT);* Coriolus versicolor *(white rot, TV).*

Decay time (mo)	SPF-weight loss (%)		OSB-weight loss (%)	
	GT	TV	GT	TV
1	4.37	3.69	7.43	7.28
2	6.95	5.42	13.69	17.36
3	11.30	6.13	22.01	23.86
4	13.13	10.08	26.32	21.23
5	11.73	9.19	27.67	32.64
6	14.12	9.49	33.40	38.26

Table 8.—The wood decay resistance grade.

Decay resistance grade	Weight loss (%)
I: High decay resistance	<10
II: Decay resistance	11–24
III: Slight decay resistance	25–44
IV: Not resistant to decay	>45

to the research conclusion of Dong (2015), when the panel was OSB and the failure mode was the nail bent and pulled through the panel, the formula (17) should be selected. When the nail did not bend and only the OSB panel was destroyed, the formula (18) should be used.

$$F_{VRx} = n_{ef}\,1.05\frac{f_{h,1,k}t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y,R,k}}{f_{h,1,k}dt_1^2}}-\beta\right]+\frac{F_{ax,Rk}}{2} \quad (17)$$

$$F_{VRx} = f_{h,1,k} \quad (18)$$

where

F_{VRx} is the theoretical calculation of maximum load, kN;
n_{ef} is the number of the nail with $n_{ef}=2$;
$f_{h,1,k}$ the strength in OSB board, d the nail diameter, t the thickness of OSB with $f_{h,1,k} = 65d^{-0.7}\ t^{0.1}$;
$f_{h,2,k}$ the strength in SPF, ρ_k the density of the SPF with $f_{h,2,k} = 0.082\ \rho_k\ (1 - 0.01\mathrm{d})$;
$\beta = f_{h,2,k} / f_{h,1,k}$;
$M_{y,R,k}$ the yield moment of nailed joints, N·mm, f_u the tensile strength of the nail with $M_{y,R,k} = 0.45 f_u\ d^{2.6}$;
$F_{ax,Rk}$ the pull-out resistance of nails in wood, N, l_{nail} the length of the nail with $F_{ax,Rk} = 20\times10^{-6}\ \rho_k^2\ d\ t_{\mathrm{pen}}$ and $t_{\mathrm{pen}} = l_{\mathrm{nail}} - t$.

The tensile strength of the nail was 700 N in this study (Dong 2015; in which nails of the same size and brand were used). The density of the SPF and the actual thickness of the OSB were measured as in Table 11. Both the brown rot and white rot made the density of the SPF decrease. The GT fungi decreased the SPF density more. Maltose caused the OSB panel to swell and became thicker.

Table 9.—The calculated maximum load. Oriented strand board (OSB); Gloeophyllum trabeum *(brown rot, GT);* Coriolus versicolor *(white rot, TV).*

	GT		TV	
Weight loss of OSB (%)	Maximum load (kN)	Decrease (%)	Maximum load (kN)	Decrease (%)
10	2.24	15	2.23	17
24	1.67	37	1.59	41
44	0.85	68	0.67	75

Table 10.—The nailed joints decay resistance grade.

Decay resistance grade	Decrease of the maximum load (%)
Brown rot (GT)	
I: High decay resistance	<15
II: Decay resistance	15–37
III: Slight decay resistance	38–68
IV: Not resistant to decay	>69
White rot (TV)	
I: High decay resistance	<17
II: Decay resistance	18–41
III: Slight decay resistance	42–75
IV: Not resistant to decay	>76

Table 11.—The density of spruce–pine–fir (SPF) and thickness of oriented strand board (OSB) panel. Gloeophyllum trabeum *(brown rot, GT);* Coriolus versicolor *(white rot, TV).*

Decay time (mo)	Density of SPF (kg/m^3)		Thickness of OSB panel (mm)	
	GT	TV	GT	TV
0	497.20	497.20	14.59	14.59
1	464.79	476.58	14.39	14.08
2	468.49	468.10	14.50	14.21
3	450.96	469.77	14.35	13.98
4	443.10	456.18	14.88	13.91
5	444.10	457.20	13.94	14.15
6	440.60	473.80	13.98	13.95

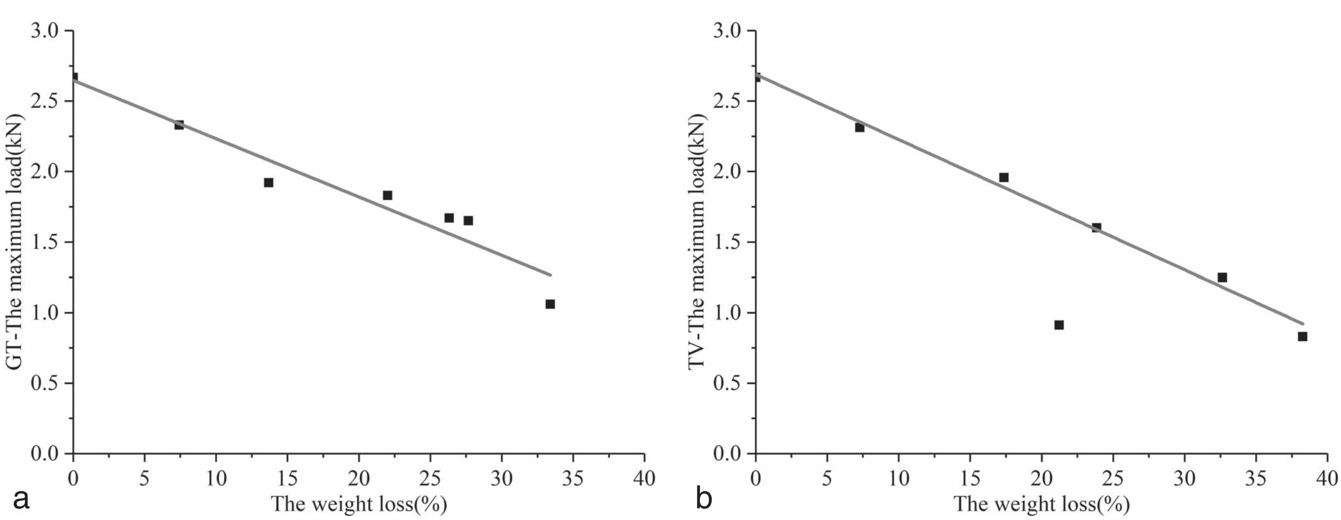


Figure 15.—(a–b) The relationship between the maximum load and the weight loss.

Table 12 shows the theoretical calculation of the maximum load. The theoretical calculation showed the error between the calculated value and the experimental value was large because the formula only considered the maximum load of nail joints without any damage. However, the mechanical properties of materials exposed to decay would decrease, which would inevitably lead to the decline of the mechanical properties of joints. Therefore, the modified coefficient γ was proposed in this experiment to calculate the maximum load after decay.

Results of the nail-holding power of SPF and the nail pull-out force of OSB indicate the decrease of the maximum load was caused by the nail pull-out force of the OSB panels, while the nail-holding power of SPF remained basically unchanged in the early stage of decay. In the later stage of decay, the failure of the OSB panels led to the rapid decline of the mechanical properties of joints, while SPF was not damaged and suppressed the decrease of the mechanical properties of joints.

When the nail-holding power of the SPF did not change,

$$\gamma = \frac{P_{\mathrm{osb-d}}}{P_{\mathrm{osb-o}}} \tag{19}$$

When the nail-holding power of the SPF decreased,

$$\gamma = \frac{P_{\mathrm{osb-d}}}{P_{\mathrm{osb-o}}} \times \frac{P_{\mathrm{spf-o}}}{P_{\mathrm{spf-d}}} \tag{20}$$

where

$P_{\mathrm{osb-d}}$ is the nail pull-out force of OSB after decay;
$P_{\mathrm{osb-o}}$ the nail pull-out force of OSB without decay;
$P_{\mathrm{spf-o}}$ the nail-holding power of SPF without decay;
$P_{\mathrm{spf-d}}$ the nail-holding power of SPF after decay.

Based on γ, the theoretical maximum load is shown in Table 13. From the test results, the error between the calculated value and the experimental value was small, and the correction coefficient γ was credible.

The decay mechanism

Brown rot and white rot are the main types of fungi that can destroy wood structure. In this study, the weight loss of SPF exposed to brown rot fungi was greater than that of white rot fungi, which can be attributed to the decay mechanism of different fungi. Brown rot fungi can decompose cellulose and hemicellulose in wood, but its degradation of lignin is limited. White rot fungi can decompose almost all the components in wood, and its degradation of lignin, especially syringyl lignin, is faster than degradation of cellulose and hemicellulose. In contrast, guaiacyl lignin, the main type of lignin in softwood, can hardly be degraded when exposed to white rot fungi (Ding et al. 1997). Therefore, the degradation of SPF exposed to brown rot was more obvious than that of white rot, which was in agreement with Curling et al's (2000, 2001, 2002) and Yang et al.'s (2010) research.

The nail holding power of SPF exposed to brown rot was smaller than that of white rot tested in this study because cellulose acts as the matrix material of the cell wall, and its degradation can lead to the decrease of the strength. A small amount of hemicellulose degradation will also make the mechanical properties of wood decline sharply. The degradation of lignin has a relatively small effect on strength.

Softwood lignin appears to vary little between species, but the structure of hardwood lignin varies greatly from one species to another (Santos et al. 2012). In addition to the composition, the anatomical characteristics of different species largely determines the severity of decay and the loss of strength as well. Similarly, the degradation ability of fungi vary greatly in genus and species (Li et al. 2012). Exposed to the brown rot, the weight loss of OSB panel was slightly smaller than the white rot and the nail pull out force of OSB panel was slightly larger than white rot, which is different from SPF.

Table 12.—The theoretical maximum load based on Eurocode5.

Decay time (mo)	Brown rot (GT)			White rot (TV)		
	Theoretical value (kN)	Experimental value (kN)	Error (%)	Theoretical value (kN)	Experimental value (kN)	Error (%)
0	2.606	2.67	−2.40	2.606	2.67	−2.40
1	2.439	2.32	5.13	2.515	2.31	8.87
2	2.442	1.92	27.19	2.469	1.96	25.97
3	2.391	1.83	30.66	2.499	1.60	56.19
4	2.314	1.67	38.56	2.454	0.91	169.67
5	2.405	1.65	45.76	2.434	1.25	94.72
6	1.693	1.06	59.72	1.688	0.83	103.37

Table 13.—The theoretical maximum load based on γ.

Decay time (mo)	Brown rot (GT)			White rot (TV)		
	Theoretical value (kN)	Experimental value (kN)	Error (%)	Theoretical value (kN)	Experimental value (kN)	Error (%)
0	2.61	2.67	−2.24	2.61	2.67	−2.24
1	2.44	2.32	5.17	2.24	2.31	−3.03
2	2.03	1.92	5.73	1.93	1.96	−1.53
3	1.91	1.83	4.37	1.51	1.60	−5.63
4	1.28	1.67	−23.35	0.98	0.91	7.69
5	1.55	1.65	−6.06	1.13	1.25	−9.69
6	0.95	1.06	−10.37	0.96	0.83	15.66

The decay mechanism of fungi varies considerably, so the decline degree of nail-holding power of SPF and the nail pull-out force of OSB were different. In this study, the nail-holding power of SPF was relatively higher in the white rot decay, but its nail pull-out force of OSB was lower. On the contrary, in the brown rot decay, the nail-holding power of SPF was lower, but its nail pull-out force of OSB was higher. The performance of nailed joints depends on both the nail-holding power of SPF and the nail pull-out force of OSB. As a result, white rot decay and brown rot decay had similar effects on the overall performance of nailed joints.

Conclusions

During the test, the load, stiffness, and energy dissipation capacity of the nailed joints showed a linear downward trend with decay time. The ductility coefficient increased slightly after the first month, and after that decreased significantly, but the linear downward trend was not obvious. The difference between white rot and brown rot was not obvious.

The influence of decay on OSB panel was much greater than that on SPF specifications. The nail pull-out force of the OSB panel decreased linearly with decay time. The weight loss of OSB panel increased significantly with decay time. The nail-holding power of SPF began to decrease after 3 months. The weight loss of SPF was much smaller than the OSB.

The laboratory test method based on GB/T 13942.1-2009 for the decay resistance of nail joints was feasible, which could ensure the normal growth of decaying fungi on the test specimens. The decay grade of the nailed joints was determined based on the maximum load decrease.

Based on Eurocode5, the study calculated the maximum load value of the nailed joints. The error between the noncorrosion value and the theoretical calculation value was small and the correction coefficient γ was credible.

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