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ORIGINAL ARTICLE

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Effect of decay on shear performance of dowel-type timber joints

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Abstract Monotonic and reversed cyclic loading tests were conducted on dowel-type timber joints with varying degrees of wood decay due to *Fomitopsis palustris* (Berk. et Curt.), a brown rot fungus, and the effect of decay on various shear performances of dowel-type joints was investigated. For joints affected by the brown rot fungus, the initial stiffness, yield load, and maximum load of dowel-type joints were significantly decreased, even with a small mass loss of wood. The reductions in shear performance were the largest for initial stiffness, followed by yield load and maximum load, in that order. For a 1% reduction of the yield load, initial stiffness and maximum load showed reductions of 1.15% and 0.77%, respectively. When dowel-type joints that had been exposed to the brown rot fungus were subjected to reversed cyclic loading, the gap between the dowel and the lead hole of the wood was increased and equivalent viscous damping was decreased. These results indicate that decay around the dowel lead hole especially affects the load–displacement behavior at small displacement level, and dowel-type joints under cyclic loading have very low resistance to forces acting on the wooden structure.

Key words Shear strength · Initial stiffness · Hysteresis properties · Brown rot fungus · Moisture content

Introduction

Safety and serviceability are necessary functions for wooden structures during the service period and these depend significantly on the structural performance of the elements and joints. If elements and joints are exposed to wood-decaying fungi or termites, their structural performance may be largely changed by the biological deterioration.

There have been many studies of the strength of wood exposed to wood-decaying fungi, and, as a consequence, it is well known that properties of wood are strongly affected by decay. For example, Takahashi and Nishimoto[1] and Wilcox[2] made comprehensive reports on the effect of decay on various measures of the strength of wood. The authors had also previously carried out embedding tests of wood exposed to wood-decaying fungus and had investigated the strength reduction of four wood species.[3]

In recent years, the effects of decay have been experimentally investigated not only on wood strength but also on shear performance of nailed joints,[4,5] but little data have been collected on shear performance of timber joints caused by wood-decaying fungi. Shear performance of timber joints frequently dominates the structural performance of wooden structures such that wood decay at timber joints may have a remarkable effect on the structural performance of the construction. Furthermore, the moisture intrusion required to promote decay also has an effect on the shear performance of timber joints.[6] Therefore, this study was carried out on dowel-type timber joints with high moisture content that had been exposed to the wood-decaying fungus and used monotonic and reversed cyclic loading tests to investigate the effect of decay on the shear performance of dowel-type joints.

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Materials and methods

Specimens

Shear tests of dowel-type joints were conducted on spruce (*Picea abies*) laminae. The dimensions of the specimen were 420 mm long, 105 mm wide, and 30 mm thick, and the average wood density was 474.4 kg/m^3 (standard deviation, 25.0 kg/m^3). Control and inoculated samples were prepared from the same group. Control samples comprised air-dried samples and wet samples that had been immersed in a waterbath for 2 weeks. The ranges of the moisture content for air-dried and wet samples were 12.6%–13.9% and 50.8%–86.6%, respectively. A hole with a diameter of 12 mm was predrilled in the wood.

Decay simulation

Wood samples were immersed in a waterbath for 2 weeks to increase moisture content. This study assumed the case of wood decay occurring at the dowel lead hole of dowel-type joints. Accordingly, dowel lead holes were filled with tap water, including 2% malt extract and plugged with silicon stoppers for 1 week. The samples were placed in polyethylene bags and sterilized by heating to 120°C for 60 min. Then the dowel lead hole was filled with sawdust covered with mycelium. The sawdust from spruce (*Picea jezoensis*) was inoculated with a small piece of *Fomitopsis palustris* (Berk. et Curt.) mycelium mat and nutrient solution that included 1% peptone and 2% malt extract in tap water.

The inoculated samples were incubated at 26°C and 98% relative humidity for 5, 8, and 11 weeks. One of the objectives of this study was to investigate the shear performance of dowel-type joints exposed to the fungus under wet conditions. Therefore, samples were immersed in a waterbath for 1 week after the decay procedure. The moisture content of the inoculated samples was 41.1%–115.9%.

Test methods

A diagram showing the preparation of the specimens and a summary of the preparation conditions are shown in Fig. 1 and Table 1, respectively. The steel plates and the sample were connected with a dowel of 12 mm in diameter. The steel plates and dowels were of grade SS400 according to the Japanese Industrial Standard.[7] The wood thickness/dowel diameter ratio, the end distance/dowel diameter ratio, and the edge distance/dowel diameter ratio were 2.5, 7.0, and 4.4, respectively.

Dowel-type joints under lateral loads parallel to the grain were tested by monotonic tensile loading and reversed cyclic loading. The cyclic loading protocol was defined in terms of average yield displacement obtained from the monotonic tensile tests, as shown in Fig. 2.[8] Initially, one cycle was applied for each displacement level, which was 25% and 50% of the yield displacement. Then the step of

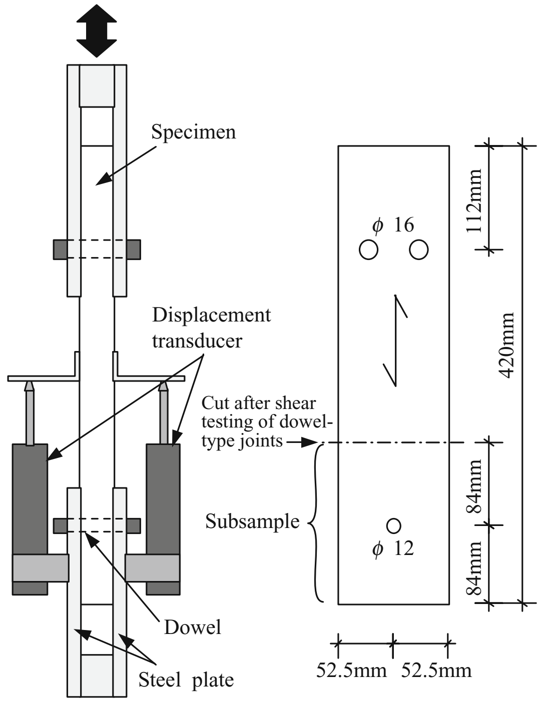

Fig. 1. Setup of dowel-type joint test

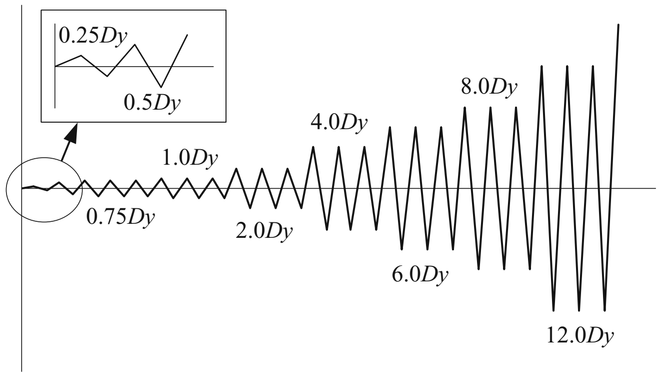

Fig. 2. Loading protocol for reversed cyclic test. D_y, Yield displacement

Table 1. Summary of dowel-type joint tests

Condition	Fungal exposure time	Loading type	Number of samples
Control sample			
Air-dry	None	Monotonic	9
		Cyclic	3
Wet	None	Monotonic	6
		Cyclic	6
Inoculated sample			
Wet	5 weeks	Monotonic	6
		Cyclic	6
Wet	8 weeks	Monotonic	6
		Cyclic	6
Wet	11 weeks	Monotonic	6
		Cyclic	6

the cyclic test was repeated three times to produce 75%, 100%, 200%, 400%, 600%, 800%, and 1200% of yield displacement.

Displacement between the steel plate and the sample was measured with two displacement transducers. Tests were carried out at a constant rate of 1.0 mm/min and were terminated when the load decreased to 50% of the maximum load or when the crack reached the end of the sample.

Results and discussion

Load–displacement relation

Load–displacement hysteresis curves of the dowel-type joints obtained from the reversed cyclic loading tests are shown in Fig. 3. The load of air-dried and wet control samples shows a linear increase up to yielding, and is almost constant after yielding. However, the shape of the load–displacement curve for the inoculated sample differs significantly, having an uncertain yield point on the load–displacement curve and showing low load until the sample fractures by splitting.

Initial stiffness (K_s), yield load (P_y), yield displacement (D_y), maximum load (P_{max}), displacement corresponding to maximum load (D_{max}), and dissipated energy up to 80% of maximum load were obtained from monotonic loading tests using evaluation methods shown in Fig. 4. Initial stiffness was defined as the line that passes through points on the curves corresponding to 10% and 40% of the maximum load. By evaluation of yield load by the 5% offset method, according to ASTM D5652,[9] the line defining initial stiffness is shifted in the positive *x*-direction by 5% of the dowel diameter, and yield load is defined as the intersection of this line and the load–displacement curve. Yield displacement was defined as the displacement on the load–displacement curve corresponding to the yield load. The results obtained from air-dried and wet control samples are shown in Table 2.

Shear performance of dowel-type joints

Shear performance of dowel-type joints for each incubation period is shown in Fig. 5. Moisture content of the wet control samples and the inoculated samples was more than 30% (near the fiber saturation point). In a previous study, the authors found that the embedding strength of wood was almost constant when the moisture content of wood was higher than 30%.[3]

Initial stiffness, yield load, and maximum load of wet control samples were 0.52, 0.57, and 0.61 times, respectively,

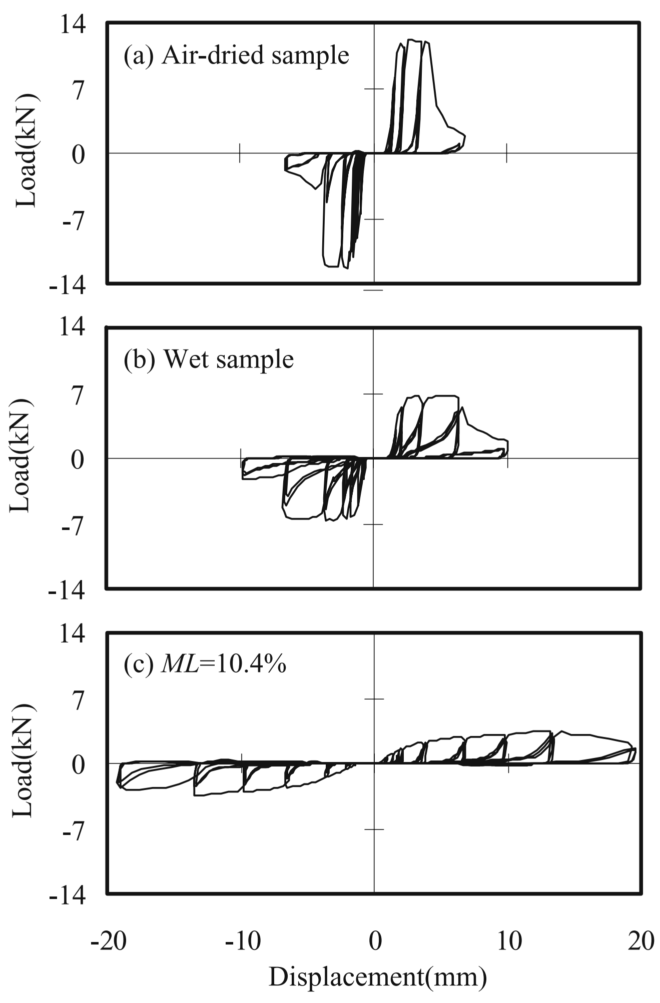

Fig. 3a–c. Load–displacement curves of dowel-type joints. **a** Air-dried control sample, **b** wet control sample, **c** inoculated sample. *ML*, Mass loss

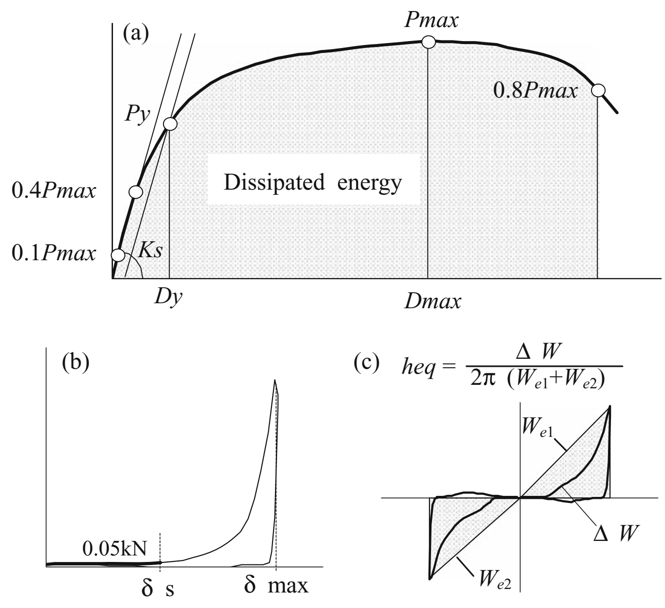

Fig. 4a–c. Method of evaluating shear performances of dowel-type joints. **a** Diagram showing the definition of K_s, P_y, P_{max}, D_y, D_{max}, and dissipated energy, **b** definition of δ_s, **c** definition of heq. K_s, initial stiffness; P_y, yield load; P_{max}, maximum load; D_y, yield displacement; D_{max}, displacement corresponding to maximum load; δ_s, displacement corresponding to 0.05 kN; δ_{max}, peak displacement; heq, equivalent viscous damping; ΔW, dissipated energy; W_{e1}, potential energy in tensile loading; W_{e2}, potential energy in compressive loading

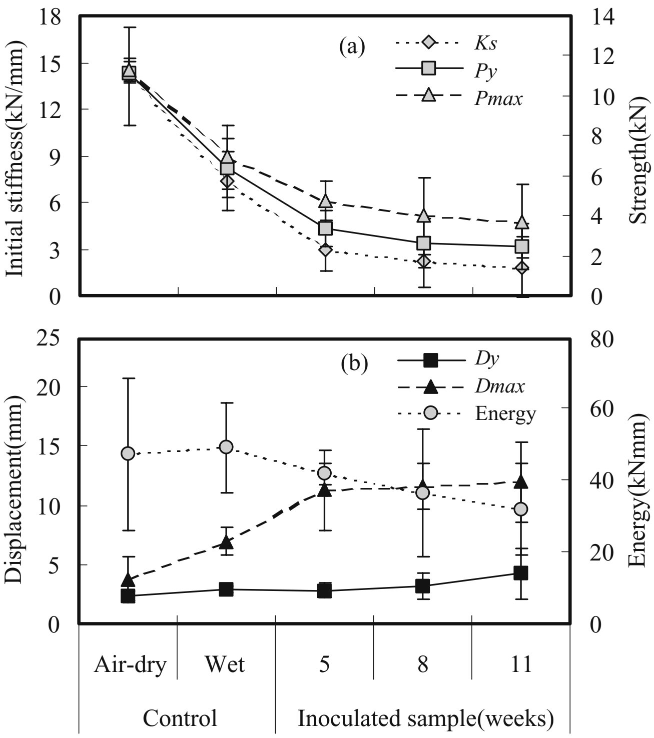

Fig. 5a, b. Relationship between shear performance of dowel-type joints and decay period. **a** K_s, P_y, and P_{max}, **b** D_y, D_{max}, and dissipated energy

those of air-dried samples. In the case of dowel-type joints with high moisture content, those that were exposed to the fungus, shear performance showed significant further reduction compared with those of air-dried samples. Shear strength of dowel-type joints is usually governed by the embedding strength of wood and the fastener yield capacity in bending.[10] Because the dowel-type joint used in this study had a small wood thickness/dowel diameter ratio (2.5), the shear strength of the dowel-type joints was determined by embedding strength. However, when decay causes significant reduction of embedding strength, the shear strength of the dowel-type joint may be determined only by embedding strength, even if the wood thickness/dowel diameter ratio is large. Therefore, the findings of this study may also be applied to the prediction of shear strength of ordinary dowel-type joints affected by wood-decaying fungi.

Although yield displacement and displacement corresponding to the maximum load of inoculated samples were higher than for air-dried control samples, the dissipated energy of inoculated samples was decreased due to significant reductions in initial stiffness, yield load, and maximum load. Initial stiffness, yield load, and maximum load of inoculated samples were divided by each mean value of wet control samples and the ratios of those shear performance values were obtained. Figure 6 shows the relationship between the ratio of shear performance values of dowel-type joints and mass loss. After shear testing of dowel-type

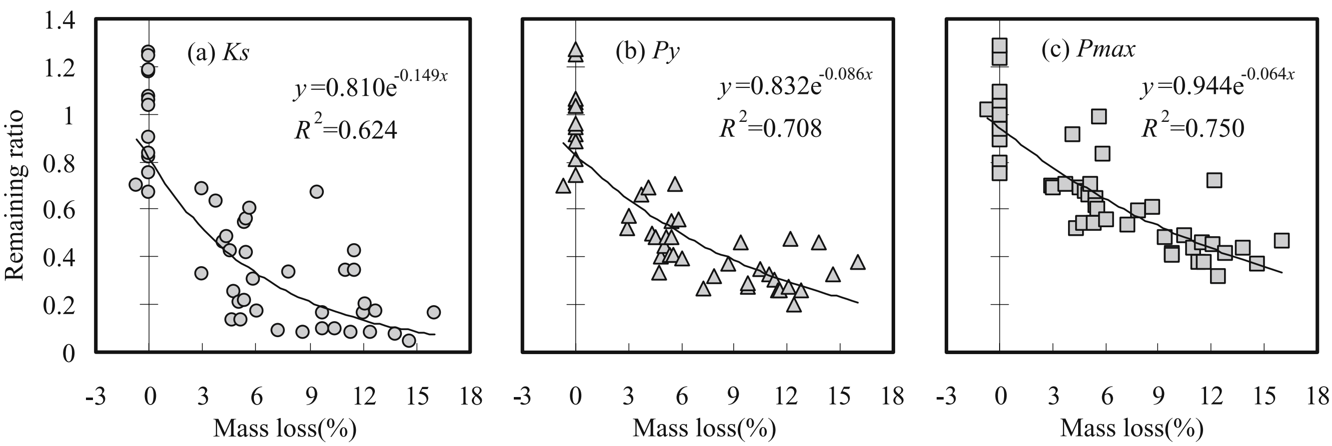

Fig. 6a–c. Relationship between remaining ratio of shear performance of dowel-type joints and mass loss. **a** K_s, **b** P_y, **c** P_{max}

Table 2. Results of shear tests of dowel-type joints using control samples

Loading type	Density (kg/m^3)	MC (%)	K_s (kN/mm)	P_y (kN)	D_y (mm)	P_{max} (kN)	D_{max} (mm)	Energy (kNmm)
Air-dry condition								
Monotonic	472 (24.6)	13.6 (0.25)	14.1 (3.16)	11.1 (0.53)	2.33 (0.45)	11.3 (0.57)	3.68 (1.95)	47.1 (21.3)
Cyclic (+)	468 (21.6)	12.9 (0.25)	16.0 (2.45)	11.3 (0.27)	2.41 (0.06)	12.5 (0.75)	2.94 (0.40)	27.3 (6.11)
Cyclic (–)	468 (21.6)	12.9 (0.25)	20.0 (6.20)	12.1 (0.04)	1.84 (0.09)	12.8 (0.73)	1.99 (0.09)	25.8 (9.86)
Wet condition								
Monotonic	478 (32.4)	64.5 (11.1)	7.41 (1.90)	6.38 (1.47)	2.90 (0.31)	6.92 (1.59)	6.92 (1.16)	48.8 (12.4)
Cyclic (+)	470 (24.1)	73.7 (8.69)	6.64 (0.98)	6.94 (0.27)	2.88 (0.18)	7.29 (0.40)	6.33 (0.28)	37.8 (7.50)
Cyclic (–)	470 (24.1)	73.7 (8.69)	9.49 (1.64)	6.34 (0.50)	1.80 (0.20)	7.05 (0.36)	4.78 (1.66)	34.5 (14.6)

Numbers in parentheses show standard deviations. Cyclic (+) and (–) show results in tensile loading and compressive loading, respectively
MC, Moisture content; K_s, initial stiffness; P_y, yield load; D_y, yield displacement; P_{max}, maximum load; D_{max}, displacement corresponding to maximum load

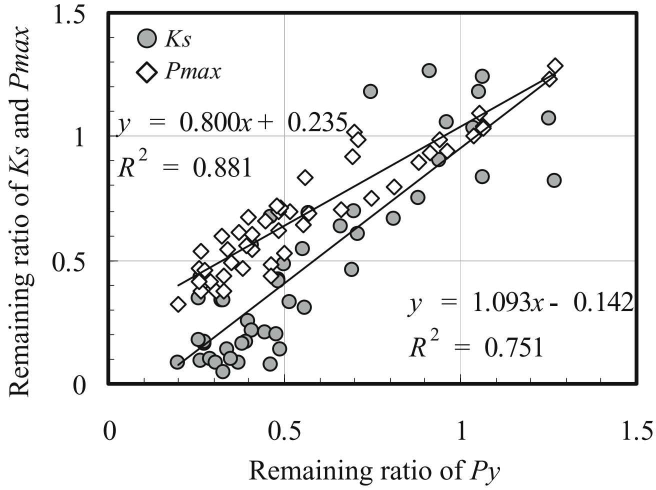

Fig. 7. Comparison of remaining ratio of initial stiffness and maximum load with remaining ratio of yield load

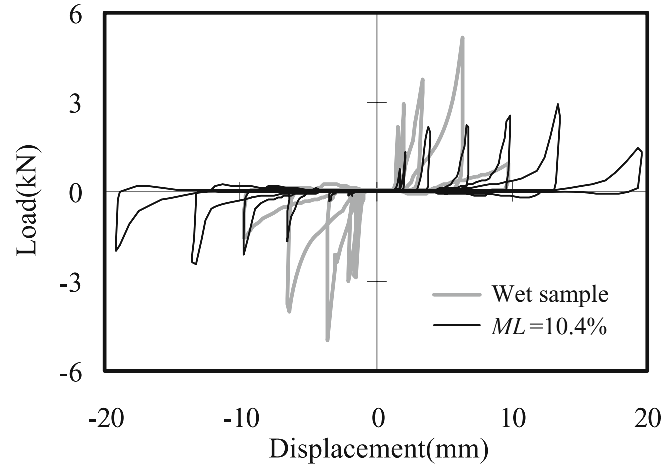

Fig. 8. Third-cycle hysteresis loops of dowel-type joint. *ML*, Mass loss

joints, subsamples taken to include the dowel lead hole (168 mm long, 105 mm wide, and 30 mm thick) were cut from shear test samples, as shown in Fig. 1. Subsamples were oven-dried at 105°C for 24 h, and then were air-dried at room temperature. The percent mass loss (ML) was estimated from the difference in the air-dried weight of the subsample and the weight calculated from the air-dried density before the decay test. It is well known that the strength of wood against brown rot fungi is significantly decreased, even with a small mass loss of wood.[1,2] This study also revealed the same tendency; initial stiffness, yield load, and maximum load of dowel-type joints were significantly decreased with a small mass loss. The reduction of shear performance was the largest for initial stiffness, followed by yield load and maximum load, in that order.

The relationship of the reduction of yield load with the reduction of initial stiffness and that with maximum load are shown in Fig. 7. The initial stiffness and the maximum load were linearly decreased with decreasing yield load, and were 1.15% and 0.77% decreased for a 1% reduction of the yield load, respectively. Results described above showed that the effect of decay differed depending on the sort of shear performance of dowel-type joints.

Hysteresis property

The hysteresis loop at the third cycle is shown in Fig. 8. Wet control samples showed pinched hysteresis loops and inoculated samples showed low peak load and thinner hysteresis loops. When a dowel-type timber joint with a small thickness/dowel diameter ratio is cyclically loaded to the same displacement level, the dowel-type joint exhibits pinched hysteretic behavior by irrecoverable crushing of wood. The irrecoverable crushing of inoculated sample became significant for decay degradation, and, as a consequence, the deformation without wood support was increased and the hysteresis loop was thinner. To investigate the effect of decay on those hysteresis properties, the displacement due

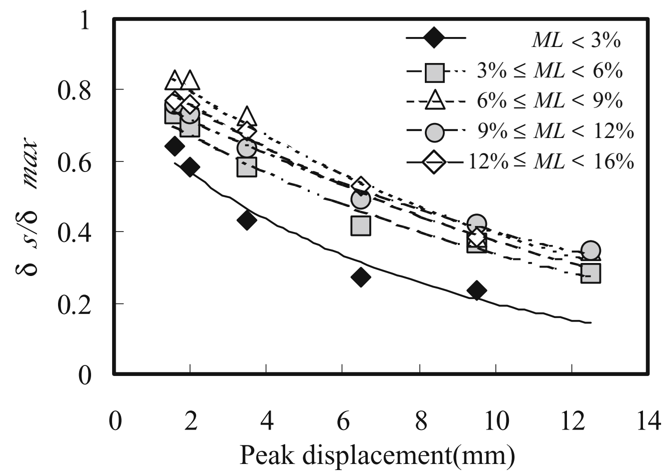

Fig. 9. Relationship between the value of (δ_s/δ_{max}) and peak displacement for different mass loss ranges

to the gap between the dowel and the dowel lead hole and the equivalent viscous damping were calculated for second and third loops obtained from reversed cyclic loading tests. Hysteresis properties were obtained from wet control and inoculated samples.

Displacement due to the gap between the dowel and the lead hole (δ_s) was defined by displacement until the load reached 0.05 kN, as shown in Fig. 4. The ratio of displacement due to the gap to peak displacement on the loop (δ_s/δ_{max}) is shown in Fig. 9. The values of (δ_s/δ_{max}) for inoculated sample were 1.20 to 2.29 times as large as that for the wet control sample. The irrecoverable deformation of wood was significantly caused by the fungus, and accordingly, the gap between the dowel and the lead hole under cyclic loading was expanded and the values of (δ_s/δ_{max}) were increased.

Equivalent viscous damping (heq) was obtained from the ratio of the cyclic dissipated energy to the potential energy, as shown in Fig. 4. The relationship between the equivalent viscous damping and the absolute value of the

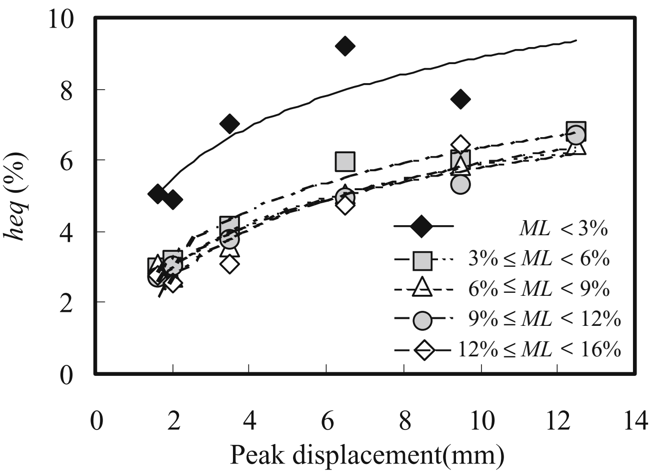

Fig. 10. Relationship between equivalent viscous damping and peak displacement for different mass loss ranges

peak displacement on the loop is shown in Fig. 10. Inoculated samples showing mass loss in the range of 3% to 16% showed almost the same equivalent viscous damping, a decrease of about 35% on average, as sound samples.

The increase of gap between dowel and dowel lead hole and pinched hysteretic behavior in dowel-type joints is attributed to loosening of the joints. The dowel-type joints exposed to the fungus showed very low resistance under cyclic loading conditions because of increased deformation without wood support and thinner hysteresis loop in dowel-type joints.

Conclusions

Monotonic and reversed cyclic loading tests were conducted on dowel-type joints that were exposed to a brown rot fungus, *Fomitopsis palustris*. 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 reduction of shear performance caused by the fungus had the largest effect on the initial stiffness, followed by yield load and maximum load, in that order. For a 1% reduction of the yield load, the initial stiffness was decreased 1.15% and the maximum load was decreased 0.77%. When the dowel-type joint exposed to the fungus was subjected to reversed cyclic loading, the gap between the dowel and the lead hole was increased and equivalent viscous damping was decreased.

Therefore, decay around the dowel lead hole especially affects the load–displacement behavior at small displacement levels and dowel-type joints under cyclic loading conditions can be expected to show very low resistance to forces acting on the wooden structure.

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