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ORIGINAL ARTICLE

Relationship between clamp force and pull-out strength in lag screw timber joints

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Abstract This study empirically examines the relationship between clamp force and pull-out strength in lag screw joints of timber members, using data obtained in tightening tests and pull-out tests. Maximum clamp force per unit screw length as determined from the tightening tests was lower than the lower bound for the 95% tolerance range for pull-out strength per unit screw length as determined from the pull-out tests. Moreover, X-ray CT (computed tomography) observations of anchor members from both tests revealed that failure behavior clearly differed between the tightening test and the pull-out test: tightening caused damage to the wooden, female thread in addition to major splitting damage in the wood perpendicular to the grain near the tip of the lag screw.

Keywords Lag screw joints · Clamp force · Pull-out strength · Tightening test

Introduction

Lag screws which have benefits of minimal loosening and slippage during the initial application of loads are increasingly used to join timber members [1]. Construction management is an important component of ensuring lag screw joints are sufficiently strong, which require managers to exercise more caution than with bolt joints. For example, lag screws often cause wood cracking if screwed in without drilling a pilot hole, or driven in using a hammer [1]. These concerns are not limited to wood cracking: over-tightening lag screws may cause such joints to no longer perform at their true strength. Take for example the case of using a wrench to join a steel plate (or washer) to a timber member with a lag screw. Some of the force generated acts as a compressive force on the timber member, which generates an equivalent pull-out force on the lag screw. Tightening the lag screw until the pull-out force exceeds the wood's pull-out strength causes the axial force on the joint ("clamp force" below) to weaken, leading to poor adhesion between the two members. Among other construction management-related considerations, builders should ensure that lag screw joints are fastened with the proper amount of torque to prevent this from happening. To determine what constitutes "proper" torque, it is imperative to determine first the degree of clamp force caused by tightening a lag screw, and second how that clamp force relates to the pull-out strength of that screw. While many studies have been conducted on screw joints' pull-out strength, shear strength, and other mechanical properties [2–9], we can find none that regard the relationship between clamp force and pull-out force for lag screws. We are currently developing a high damping shear wall, in which the clamp force of lag screws in wood acts as a frictional resistance force between two timber members or between a timber member

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and a steel plate [10]. Controlling the clamp force is an important part of generating the frictional resistance in this project. We thus became interested in clarifying the relationship between clamp force and pull-out strength in lag screws, to investigate techniques for controlling the clamp force of lag screws.

In the present study, we empirically studied the relationship between clamp force and pull-out strength using experimental data collected from tightening tests and pull-out tests. Our study also covers clamp force-related settings and considerations for preventing defects due to lag screw tightening.

Materials and methods

Tightening tests of lag screw timber joints

Lag screw joints were subjected to tightening tests according to the protocol in Matsubara et al. [11] using a bolt force tester (NST-500NM: Japan Instrumentation System Co., Ltd., Nara, Japan). Test specimens were composed of four parts: an attaching member, an anchor member, a round washer, and a lag screw (Fig. 1). Attaching and anchor members were created from three conifers: *Cryptomeria japonica*, *Chamaecyparis obtusa*, and *Pseudotsuga menziesii*. Figure 2 contains their dimensions: attaching members were 30 × 45 × 200 mm while anchor members were 60 × 45 × 60 mm. Specimens were tested after sitting in the laboratory for approx. one month at 20 ± 2 °C. A bolt hole of φ13 mm was drilled in the attaching member; a pilot hole of φ7.5 mm and 55 mm deep was drilled in the anchor member. The curing room ranged from 32 to 43% humidity during the curing period (humidity was not strictly controlled). The density and moisture content of each specimen are shown in Table 1. To estimate the effect of washer sizes on clamp force and tightening angle, round washers of three dimensions were tested: φ30 × 2.3 mm (diameter–thickness ratio = 13.0), φ32 × 3.2 mm (10.0), and φ35 × 4.5 mm (7.8). M12 lag screws were used, having a length of 180 mm and pitch diameter of 4.4 mm. One is pictured in Fig. 3 along with detailed dimensions. During the tests, specimens were first set up in the testing device, and clamp force was measured by means of a load cell wedged between the attaching and anchor members. The tightening angle of the screw head was also measured. The screw was inserted along the wood perpendicular to the grain. The anchor member was held by a rotation-stopping component to limit any rotation due to tightening torque. Lag screws were tightened using a torque wrench until the screw head pressed against the round washer, i.e., until the axial force reached 10–30 N. Screws were tightened at a speed of 20 rpm until a reduction in clamp force was observed, according to the protocol in [11]. Screws were fastened for an effective screw length (i.e., the distance the screw embeds in the anchor member; see Fig. 1) determined prior to testing: 42.7 mm for specimens with φ30 × 2.3 mm washers, 41.8 mm for specimens with φ32 × 3.2 mm washers, and 40.5 mm for specimens with φ35 × 4.5 mm washers. Six specimens were tested in each condition.

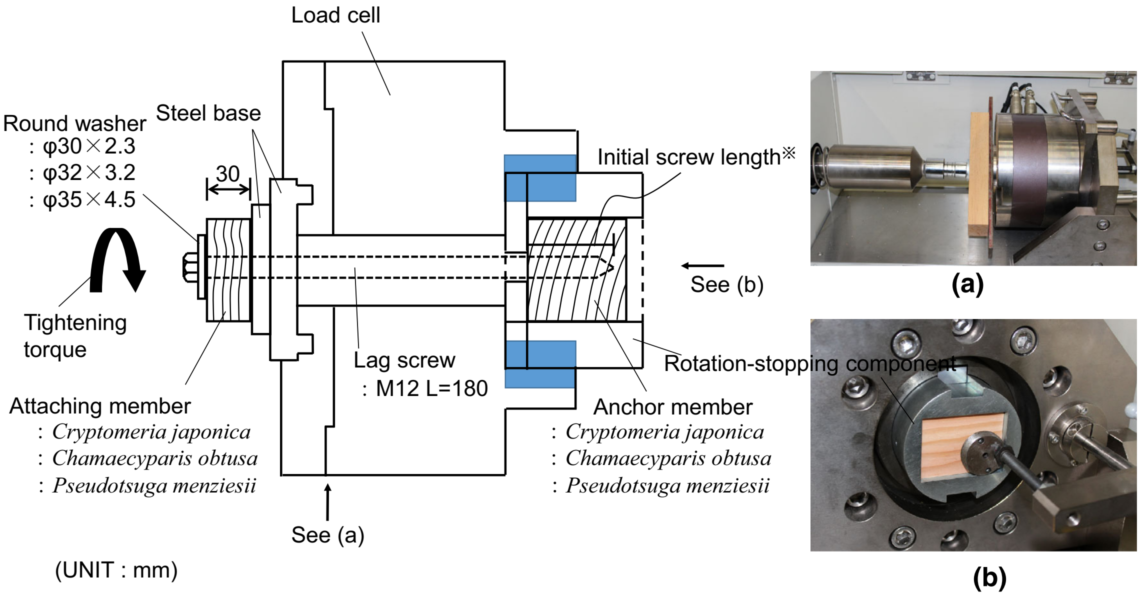


Fig. 1 Tightening test method for lag screw timber joints. *Reference mark* the initial screw length = 42.7 mm for φ30 × 2.3 mm washers; 41.8 mm for φ32 × 3.2 mm washers; 40.5 mm for φ35 × 4.5 mm washers

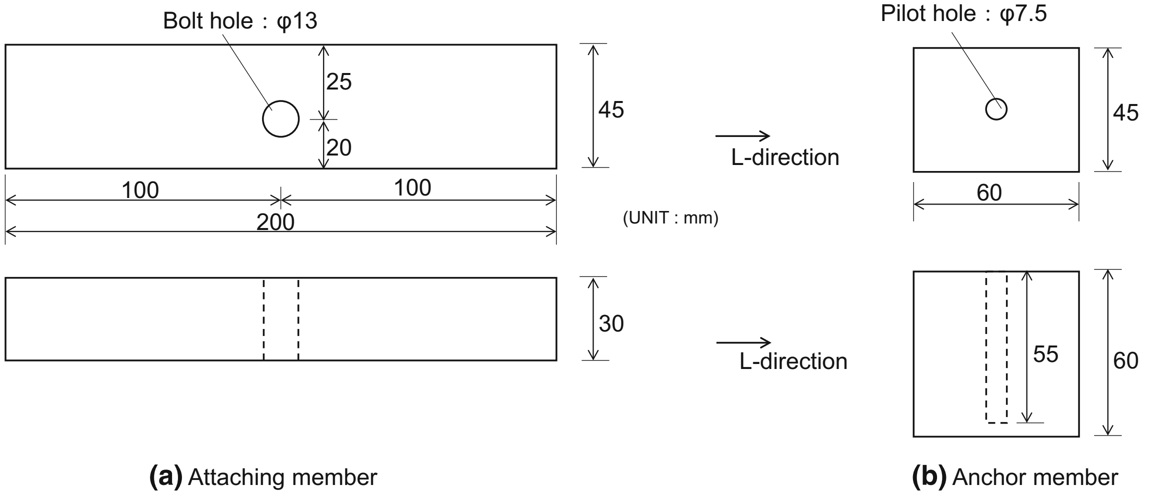


Fig. 2 Dimensions of attaching member and anchor member

Table 1 Basic properties of test materials

Conifer species	Member	Density (kg/m^3)	Moisture content (%)
Cryptomeria japonica	Attaching member		
	Ave.	312	9.8
	SD	15.4	0.7
	Anchor member		
	Ave.	353	9.0
	SD	7.3	0.4
Chamaecyparis obtusa	Attaching member		
	Ave.	423	9.3
	SD	20.6	1.2
	Anchor member		
	Ave.	429	8.7
	SD	8.2	0.6
Pseudotsuga menziesii	Attaching member		
	Ave.	572	8.5
	SD	70.2	1.0
	Anchor member		
	Ave.	661	8.7
	SD	11.5	0.7

Ave. average, *SD* standard deviation

Pull-out tests of lag screw timber joints

Lag screw pull-out tests were performed using leftover anchor member from the tightening tests. The anchor members tested were made from the same three tree species. Figure 4 shows the experimental method. Specimen dimensions, pilot hole diameter, and screw-insertion direction were identical to the tightening tests. Wood density and moisture content were within the ranges indicated in Table 1. First, a screw was inserted into an anchor member fixed by the rotation-stopping component to a target screw length of 46 mm [here, 45.0–49.0 mm (measured screw length)] using a torque wrench. Pull-out tests were conducted at a test speed of 88 mm/min (=tightening speed 20 rpm × pitch diameter of 4.4 mm) using a universal tester (AG-100kNX Plus: Shimadzu Corp., Kyoto, Japan). Load was measured over a single stroke. Six specimens were tested in each condition.

X-ray CT (computed tomography) scanning

Failure behavior following the tightening test and pull-out test was observed in each anchor member using an X-ray CT scanner (SkyScan2211, Bruker, Kontich, Belgium).

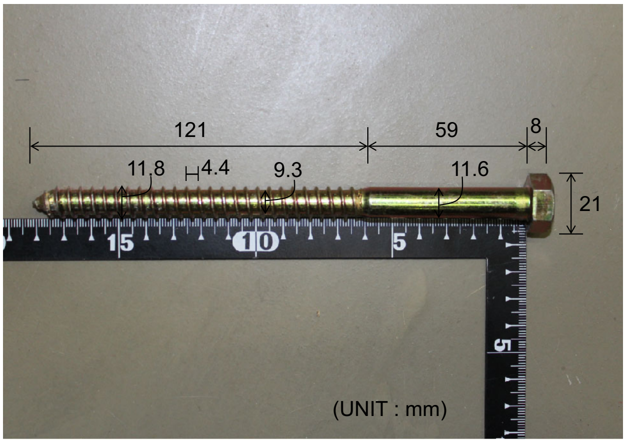


Fig. 3 Detailed dimensions of lag screw

Specimens were imaged using a flat-panel X-ray detector at a tube voltage of 50 kV and tube current of 320 µA.

Results and discussion

Relationship between clamp force and tightening angle

Figure 5 shows the relationship between clamp force and tightening angle obtained in the tightening tests for a representative specimen of each tree species. As tightening angle increases, clamp force continues to rise even after some initial yielding, but decreases after reaching a maximum value. Figure 6 shows the relationship between washer diameter–thickness ratio and maximum clamp force. Significant variation in clamp force due to diameter–thickness ratio is not visible for *C. japonica* members. However, *C. obtusa* and *P. menziesii* members exhibit higher maximum clamp force at larger diameter–thickness ratios. In addition, Fig. 5 shows that larger diameter–thickness ratios result in the maximum clamp force being reached at larger tightening angles. We next investigated the relationship between maximum tightening angle in the maximum clamp force and the initial elasticity gradient (kN/°) based on the relationship between clamp force and tightening angle. Initial elasticity gradient was determined separately for each specimen by calculating the slope of the elasticity gradient using the method of least squares over the interval it appeared linear. Maximum tightening angle was determined by subtracting the *x*-intersect of the elasticity gradient from tightening angle. Figure 7 shows the relationship between washer diameter–thickness ratio and maximum tightening angle. Maximum tightening angle seems to increase with increasing diameter–thickness ratio for *C. japonica*, *C. obtusa*, and *P. menziesii* specimens. Figure 8 shows the relationship between initial elasticity gradient and maximum tightening angle. Although there is a rather large dispersion, maximum tightening angle tends to decrease with increasing initial elasticity gradient. Where embedment traces of round washer on attaching member were confirmed visually in all specimens, this finding can be attributed to the washer exhibiting higher embedment stiffness at smaller diameter–thickness ratios [12].

Comparison of pull-out strength and maximum clamp force

Figure 9 shows the representative load–displacement profiles obtained in the pull-out tests for a single test stroke, while Table 2 shows an overview of pull-out strength. Pull-out strength is defined in this study as the maximum load

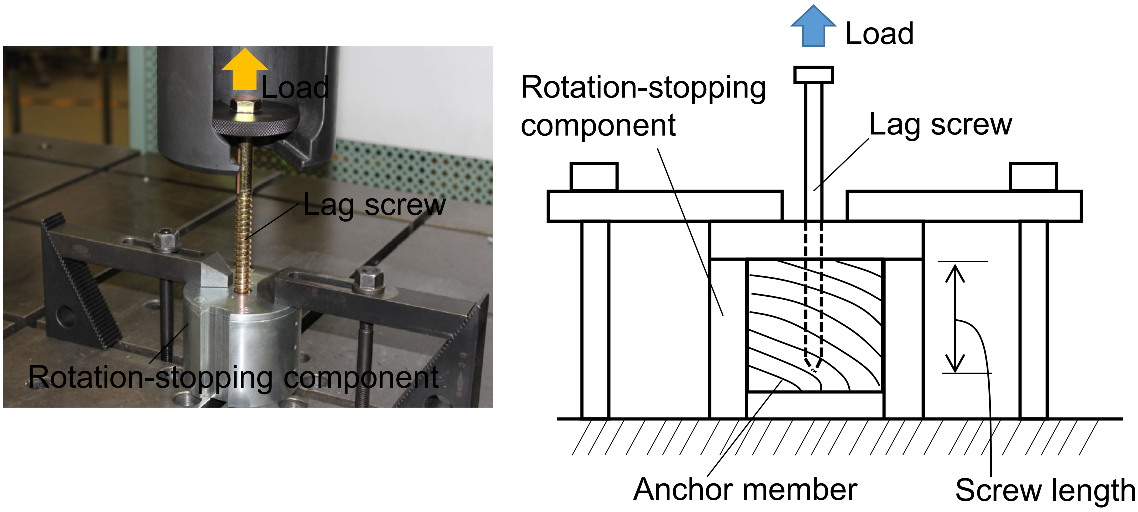


Fig. 4 Pull-out test method for lag screw timber joints

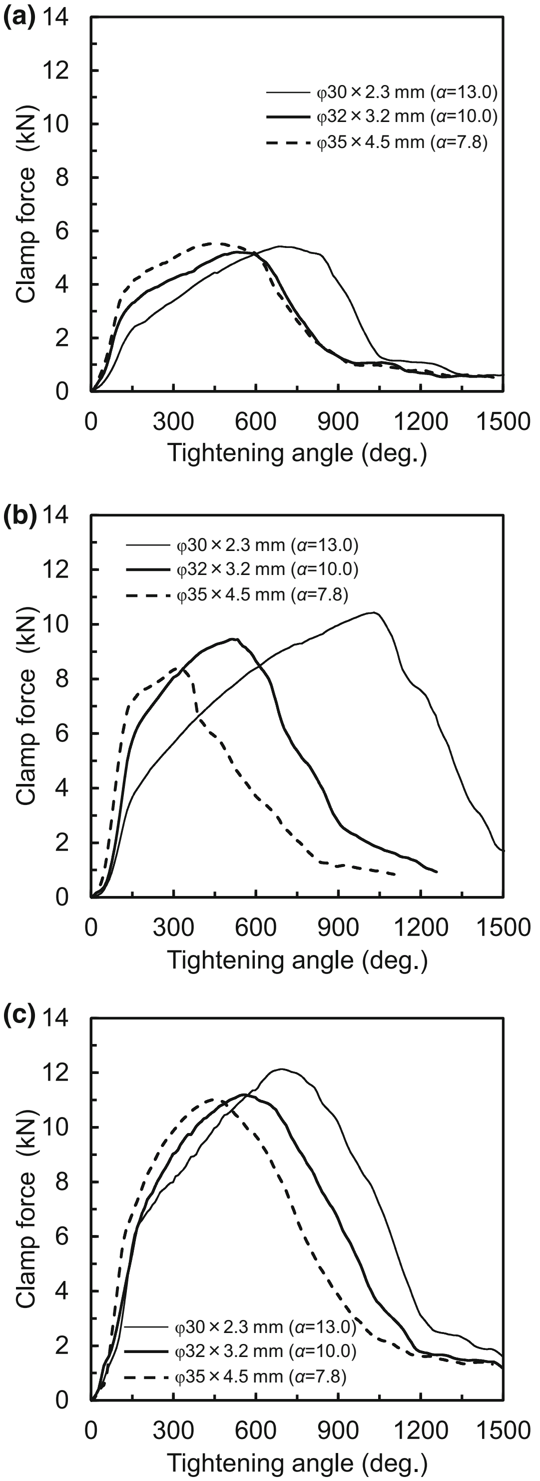


Fig. 5 Relationship between clamp force and tightening angle. **a** *Cryptomeria japonica*, **b** *Chamaecyparis obtusa*, **c** *Pseudotsuga menziesii* and α diameter–thickness ratio of round washer

observed in the pull-out test. The table contains values for $P_{\text{max-L}}$ (kN/mm) and $P_{5\%\text{-pull}}$ (kN/mm): these measures, respectively, indicate pull-out strength per unit screw

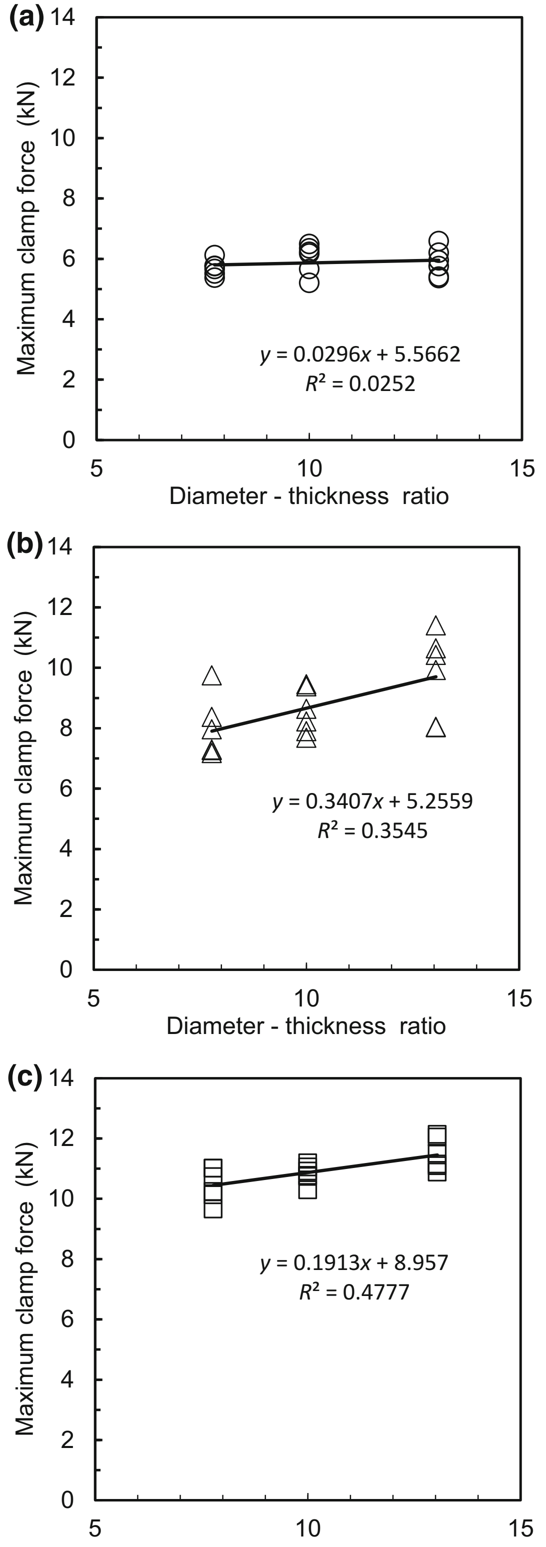


Fig. 6 Relationship between maximum clamp force and diameter–thickness ratio of round washer. **a** *Cryptomeria japonica*, **b** *Chamaecyparis obtusa*, and **c** *Pseudotsuga menziesii*

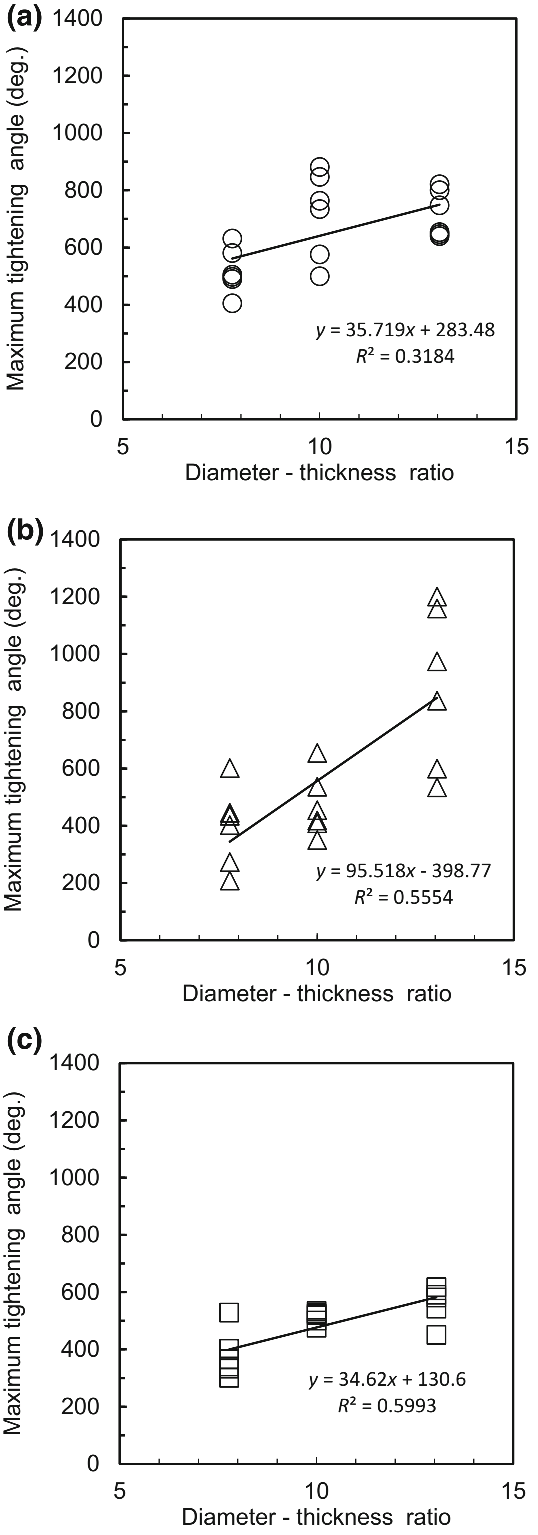


Fig. 7 Relationship between maximum tightening angle and diameter–thickness ratio of round washer. **a** *Cryptomeria japonica*, **b** *Chamaecyparis obtusa*, and **c** *Pseudotsuga menziesii*

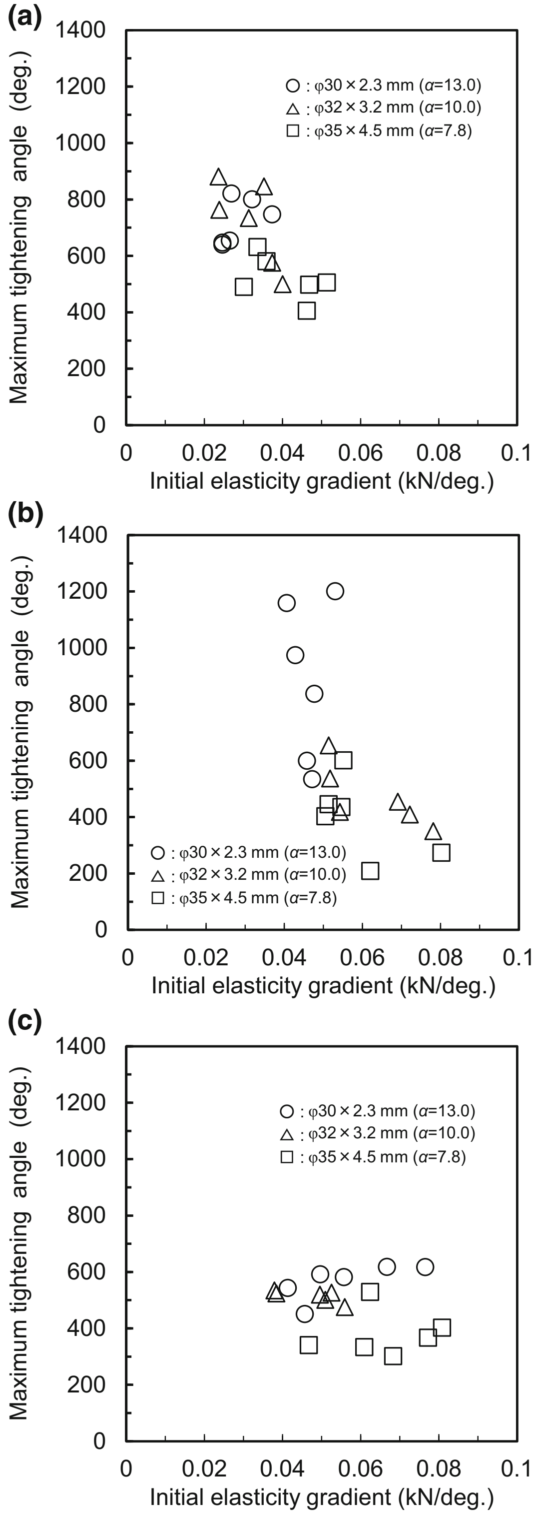


Fig. 8 Relationship between maximum tightening angle and initial elasticity gradient. **a** *Cryptomeria japonica*, **b** *Chamaecyparis obtusa*, **c** *Pseudotsuga menziesii*, and α diameter–thickness ratio of round washer

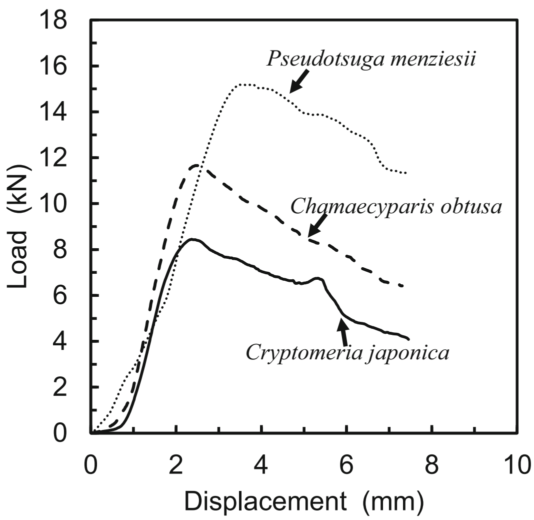


Fig. 9 Load–displacement relationship obtained in pull-out tests

Table 2 Results of pull-out tests

Conifer species	$P_{\max}$ (kN)	$P_{\max\text{-L}}$ (kN/mm)	$P_{5\%\text{-pull}}$ (kN/mm)
Cryptomeria japonica			
Max.	9.12	0.198	0.142
Min.	7.52	0.159	
Ave.	8.32	0.179	
SD	0.67	0.016	
Chamaecyparis obtusa			
Max.	11.83	0.252	0.204
Min.	9.92	0.216	
Ave.	11.13	0.239	
SD	0.81	0.015	
Pseudotsuga menziesii			
Max.	16.53	0.329	0.272
Min.	13.37	0.294	
Ave.	14.93	0.312	
SD	1.03	0.017	

P_{max} pull-out strength, $P_{max\text{-}L}$ pull-out strength per unit screw length, $P_{5\%\text{-}pull}$ 5% lower limit value of pull-out strength per unit screw length, *Max.* maximum, *Min* minimum, *Ave.* average, *SD* standard deviation

length and the lower bound for the 95% tolerance range for pull-out strength per unit screw length (confidence level = 75%) [13]. Figure 9 and Table 2 both indicate that $P_{\max}$, $P_{\max\text{-L}}$, and $P_{5\%\text{-pull}}$ were highest in *P. menzeisii*, followed by *C. obtusa* and *C. japonica*. Next, the maximum clamp force obtained in the tightening tests was converted into maximum clamp force per unit screw length (F_{L}: kN/mm). The relationship between F_{L} and $P_{5\%\text{-pull}}$ was then examined. Figure 10 shows the relationship between washer diameter–thickness ratio and $F_{\mathrm{L}}/P_{5\%\text{-pull}}$.

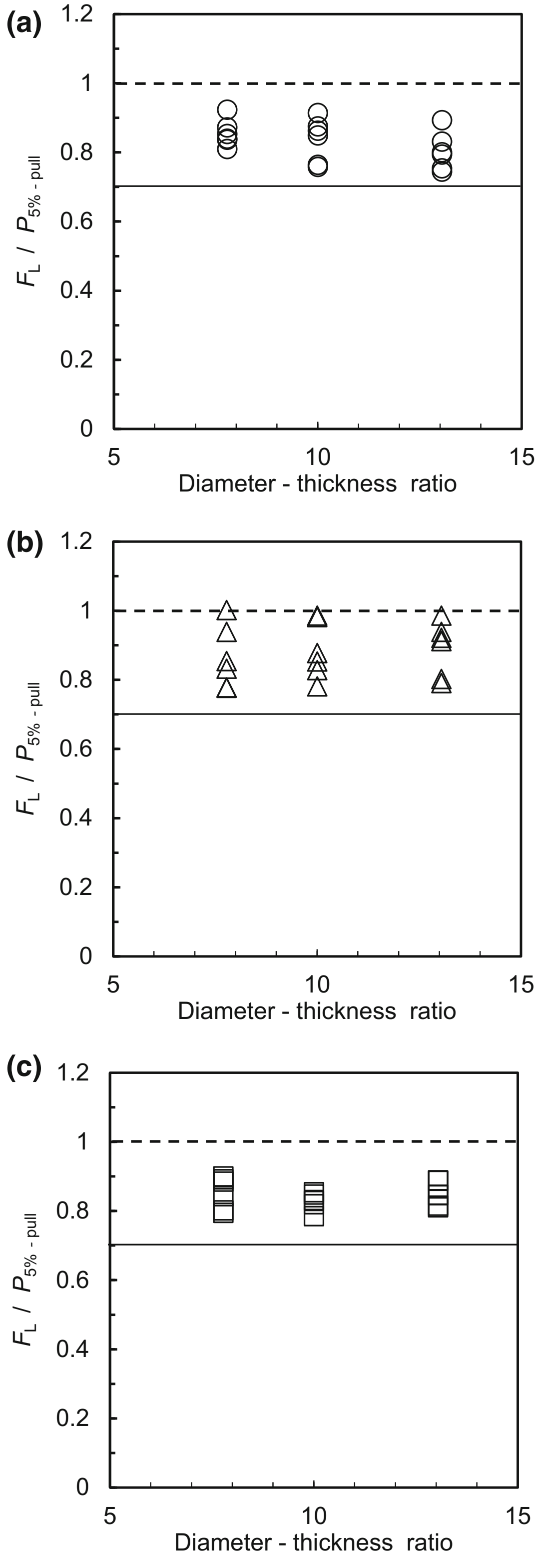
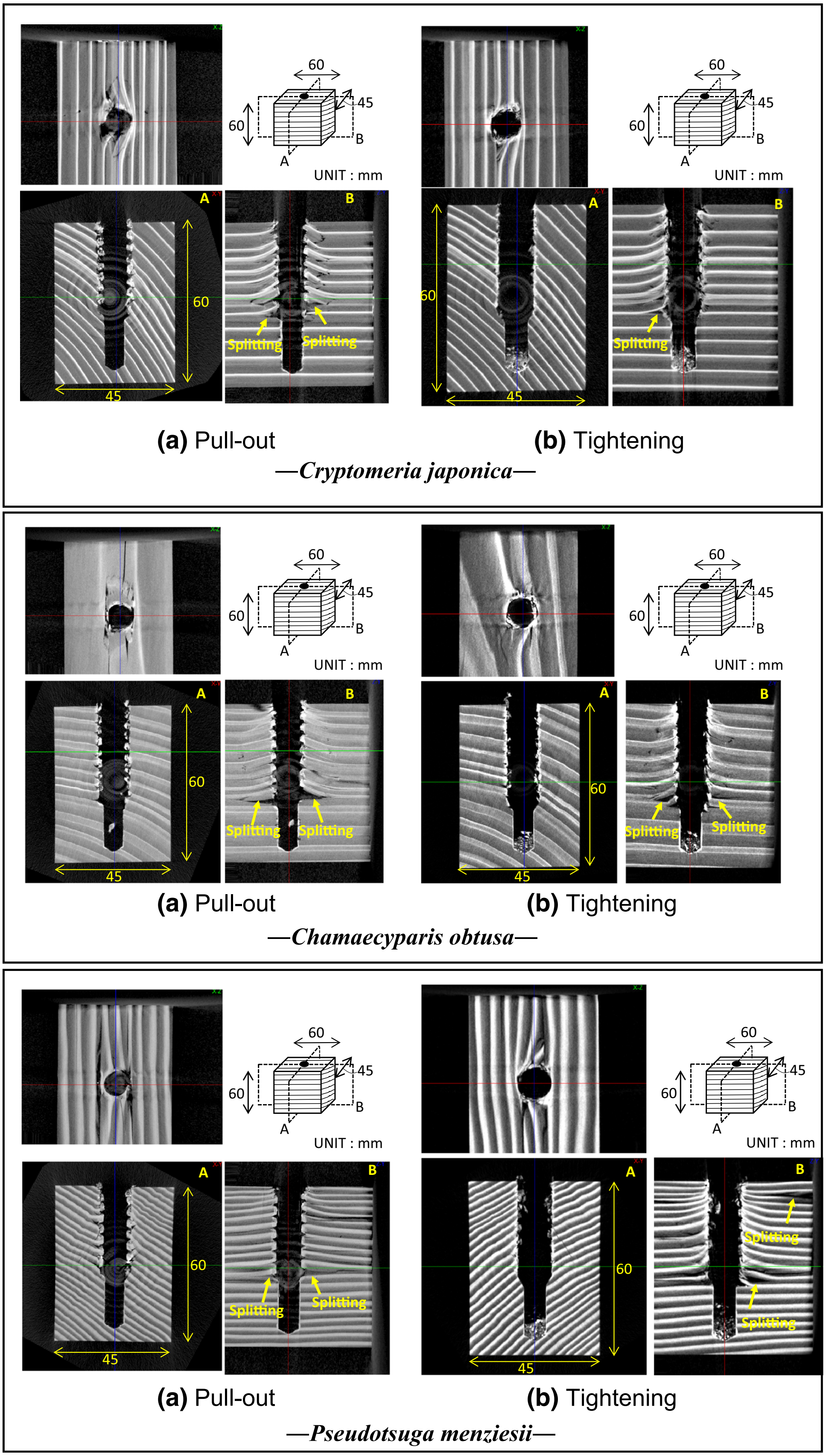


Fig. 10 Relationship between $F_{\mathrm{L}}/P_{5\%\text{-pull}}$ and diameter–thickness ratio of round washer. **a** *Cryptomeria japonica*, **b** *Chamaecyparis obtusa*, **c** *Pseudotsuga menziesii*, F_{L}: maximum clamp force per unit screw length, and $P_{5\%\text{-pull}}$: 5% lower limit value of pull-out strength per unit screw length



(a) Pull-out (b) Tightening

—*Cryptomeria japonica*—

(a) Pull-out (b) Tightening

—*Chamaecyparis obtusa*—

(a) Pull-out (b) Tightening

—*Pseudotsuga menziesii*—

Fig. 11 X-ray CT-scan images of typical failures of anchor members observed after the tightening and pull-out tests

Here, the screw length in tightening for F_L was calculated according to the following equation:

$$L_{screw} = L_{init.} + \frac{P\theta_{max}}{360}, \qquad (1)$$

where L_{screw} is screw length in tightening, $L_{init.}$ is initial screw length prior to tightening test (as described in Fig. 1), P is screw pitch (4.4 mm), and θ_{max} is maximum tightening angle calculated as described above. Strictly speaking, a lag screw expands when tightened, altering its pitch. We estimated the maximum expansion factors for the lag screw having the highest recorded maximum clamp force among all 54 specimens ($\sim$12 kN) based on screw length, cross-sectional area, and elastic Young's modulus. As the value measured was only in the order of 0.09%, Eq. (1) simplifies this consideration by assuming a constant screw pitch. In addition, Eq. (1) is simplified by neglecting the deformation between the thread of the lag screw and the wood. No obvious trends were observed in the relationship between washer diameter–thickness ratio and $F_L/P_{5\%\text{-pull}}$ for any of the tree species. Generally speaking, however, F_L shrunk more than $P_{5\%\text{-pull}}$, with *C. japonica*, *C. obtusa*, and *P. menzeisii* having respective average and minimum $F_L/P_{5\%\text{-pull}}$ ratios of 0.83 and 0.74, 0.88 and 0.78, and 0.84 and 0.78. Figure 11 shows X-ray CT images of anchor members after the tightening (in φ35 × 4.5 mm) and pull-out tests. The images depict the damage sustained by anchor members in the tightening and pull-out tests. Major splitting damage was observed in the wood perpendicular to the grain near the tip of the lag screw in *C. japonica*, *C. obtusa*, and *P. menzeisii* specimens. The female grooves that formed in the wood are relatively distinct, but some deformation behavior is visible in wooden ridges between the grooves, which have warped upward in the direction of the pull-out force. In comparison, significant splitting damage, similar to that sustained in the pull-out tests, was observed in each tree species following the tightening tests. However, the wooden grooves were lost in all tree species, failure behavior that clearly differed from that seen after the pull-out tests. We can consider these differences in failure behavior in combination with F_L being smaller than $P_{5\%\text{-pull}}$. Mechanical resistance on a lag screw is attributable to the compressive resistance placed on the screw thread along a joint's axis by the surrounding wood [14]. When the lag screw is tightened, however, shear resistance generated from tightening torque are generated in addition to this compressive resistance. We can thus suppose that these composite mechanical elements result in the destruction of the wooden internal thread, and accordingly a smaller F_L than $P_{5\%\text{-pull}}$.

In summary, tightening resulted in a smaller maximum clamp force than the pull-out force observed in the pull-out test, and failure behavior in anchor members clearly differed between the pull-out tests and the tightening tests. When assessing maximum clamp force, it appears necessary to multiply $P_{5\%\text{-pull}}$ by a reduction coefficient of some magnitude to prevent damage to anchor members due to tightening. We propose a value of 0.7 for this coefficient, as F_L is approximately 70% of $P_{5\%\text{-pull}}$ when calculated for all specimens tested in this study (see Fig. 10).

Conclusions

We performed tightening tests and pull-out tests on lag screw joints, and investigated the relationship between clamp force and pull-out strength data obtained in the experiments. Joints consisted of two timber members of three tree species (*C. japonica*, *C. obtusa*, and *P. menzeisii*), M12 lag screws, and round washers of three sizes (φ30 × 2.3, φ32 × 3.2, and φ35 × 4.5 mm). Our findings are as follows:

1) In the tightening tests, maximum tightening angle increased with increasing washer diameter–thickness ratio, and maximum tightening angle decreased with increasing initial elasticity gradient.
2) In the pull-out tests, *P. menzeisii* had the highest pull-out strength, followed by *C. obtusa* and *C. japonica*.
3) Maximum clamp force per unit screw length (F_L) was lower than the lower bound for the 95% tolerance range for pull-out strength per unit screw length ($P_{5\%\text{-pull}}$). Their ratio ($F_L/P_{5\%\text{-pull}}$) had respective average and minimum values of 0.83 and 0.74 for *C. japonica* specimens, 0.88 and 0.78 for *C. obtusa*, and 0.84 and 0.78 for *P. menzeisii* specimens.
4) X-ray CT observations of anchor members following the tightening and pull-out tests revealed that failure behavior clearly differed between the two tests: tightening caused damage to the wooden, female thread in addition to major splitting damage in the wood perpendicular to the grain near the tip of the lag screw.

The findings above reveal that tightening the lag screw in a lag screw joint between timber members results in a smaller maximum clamp force than the pull-out strength for the same joint. They suggest the necessity of taking their relationship into account when deciding on a clamp force for tightening steps to prevent damage to the anchor member.

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