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ORIGINAL ARTICLE

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Lateral resistance of anchor-bolt joints between timber sills and foundations II. Effective lateral resistance of multiple anchor-bolt joints

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Abstract Monte Carlo simulations were conducted to estimate the effective lateral resistance of multiple anchor-bolt joints with ordinary specifications of Japanese post and beam constructions. Basic lateral load–slip curves of single anchor-bolt joints required in the simulations were determined from the test results of our earlier report. The effective lateral resistance of multiple anchor-bolt joints was estimated for some combinations of loading direction, length/diameter ratio of anchor bolts, lead-hole clearance, and number of anchor bolts. The principal results of the simulations are: (1) anchor-bolt joints loaded perpendicular to lateral forces are not recommended to be counted as supplementary resisting elements because their supplementary shares are far less than those expected from their allowable lateral resistance; (2) multiple anchor-bolt joints with small length/diameter ratios have comparatively lower effective resistance ratios than multiple anchor-bolt joints with large length/diameter ratios; (3) the effective resistance of multiple anchor-bolt joints is affected not only by lead-hole clearance or number of bolts but also variance of load–slip characteristics of single anchor-bolt joints.

Key words Multiple anchor-bolt joints · Lead-hole clearance · Effective lateral resistance · Monte Carlo simulation

Introduction

Wind or earthquake forces applied to wooden structures must be transmitted to foundations through files of anchor-bolt joints arranged along shear wall lines of ground floors. The lateral resistance of them, however, has not been discussed in detail in contrast to strict consideration of the resistance of wooden shear walls, floor diaphragms, other structural elements, or structural joints between them.[1–4] In our earlier report,[5] we presented the results of an experimental study on single anchor-bolt joints with ordinary specifications of Japanese post and beam constructions. Lead holes for anchor bolts in timber sills, however, are usually bored loosely for fixing the sills easily onto foundations. Then anchor-bolt joints arranged in a file do not share even lateral forces, which may result in a lower effective lateral resistance than the ideal resistance expected from the resistance of a single anchor-bolt joint and number of anchor bolts.

Experimental estimation of the effective lateral resistance of multiple anchor-bolt joints, however, needs heavy testing facilities and much labor. A useful way of estimating the lateral resistance without such requirements is via the Monte Carlo method.[6,7] In this study, we conducted some numerical simulations by this method on the effective lateral resistance of multiple anchor-bolt joints with lead-hole clearances.

Numerical simulations

Supplementary load sharing by anchor-bolt joints arranged perpendicular to lateral forces

In a wooden shear wall construction, lateral force is mainly transmitted through files of multiple anchor-bolt joints arranged along the shear wall lines parallel to the lateral force, as shown in Fig. 1. The most conservative design for transmitting the lateral force shared by a shear wall line is to install a sufficient number of anchor-bolt joints along the

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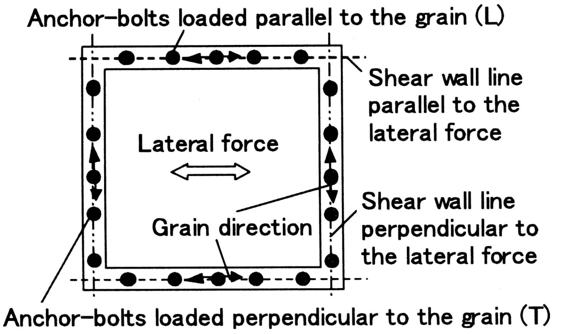


Fig. 1. Arrangement of anchor bolts

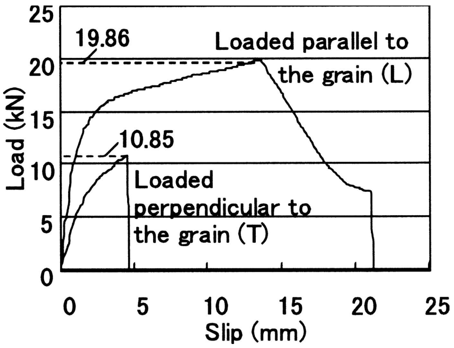


Fig. 2. Moderate load–slip curves used in the simulations

wall line so that they can satisfactorily cover the lateral resistance of the shear wall line. In practical design, anchor-bolt joints in a construction are usually designed less strictly so that the lateral resistance of files of anchor-bolt joints along the shear wall lines parallel to the lateral force satisfy the required resistance in total, although it does not guarantee safety apart from the floor diaphragm reaching ideal stiffness.

Furthermore, design lateral resistance of anchor-bolt joints is occasionally supplemented with the lateral resistance of some of the anchor-bolt joints arranged along the shear wall lines perpendicular to the lateral force, as shown in Fig. 1, if the total allowable lateral resistance of the shear wall lines parallel to the lateral force exceeds the total allowable resistance of the anchor-bolt joints arranged along them. Rows of anchor-bolt joints arranged perpendicular to lateral forces, however, are loaded perpendicular to the grains of timber sills, which have the risk of brittle splitting of timber. This may result in low effective lateral resistance when the anchor bolts are installed with lead-hole clearances.[6,7] To estimate the supplementary effects of the joints arranged perpendicular to lateral forces to the total resistance, Monte Carlo simulations were made for some combinations of anchor-bolt joints arranged parallel and/or perpendicular to lateral forces. Anchor bolts that were 12 mm in diameter and 95 mm in effective length were used in the following combinations:

1. Ten anchor bolts were arranged parallel to the lateral force or the grain of the timber, and no anchor bolts were arranged perpendicular to the lateral force or the grain of timber (L10T0).
2. Five anchor bolts were arranged parallel to the lateral force or the grain of the timber and five anchor bolts were placed in a perpendicular arrangement (L5T5).
3. Ten anchor bolts were placed perpendicular to the lateral force or the grain of the timber (L0T10).

In the simulations, moderate experimental load–slip curves shown in Fig. 2 that were obtained from our earlier report[5] were selected as the definite load–slip curves for both loading directions. The initial gap of each anchor bolt was determined as follows. The random initial gap between each anchor bolt and its lead hole was determined using two quasi-random variables r and θ in polar coordinates as shown in Fig. 3 in the same way shown in previous studies.[6,7] In the simulations, two lead-hole clearances of 3 and 6 mm were taken into consideration. The floor diaphragm was assumed to be of ideal stiffness for transmission of the lateral force to each anchor bolt. The calculation was repeated 100 times, which corresponded to 1000 anchor bolts, for each combination.

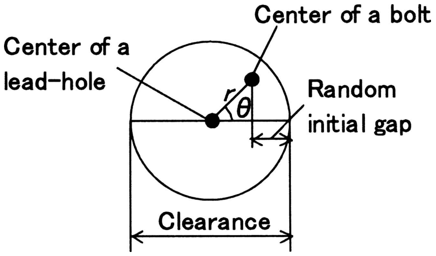


Fig. 3. Determination of random initial gaps

Lateral resistance of anchor-bolt joints along shear wall lines parallel to lateral force

Effective lateral resistance of files of anchor-bolt joints along the shear wall lines parallel to lateral forces was simulated more strictly. The load–slip properties of single anchor-bolt joints loaded parallel to the grain obtained in our previous study,[5] particularly the maximum slips of the bolts of 16 mm diameter, were varied over a wide range that seemed difficult to represent by definite moderate or averaged load–slip curves. Then, the following procedures of numerical simulations were adopted:

1. Each experimental load(P)–slip(s) curve up to the maximum load P_m was approximated by the exponential expression Eq. 1 and by two linear segments from P_m to $0.8P_m$ and from $0.8P_m$ to $0.5P_m$ after the maximum load as shown in Fig. 4.[8,9]

$$P = (p_0 + k_1 s)\left\{1 - \exp\left(-\frac{k_0}{p_0}s\right)\right\} \tag{1}$$

2. Parameters k_0 and p_0 in Eq. 1 and Fig. 4 were fitted to the normal distributions. Parameter k_1, on the other hand,

was fitted to the lognormal distribution. This was because k_1 had a wide variance and preliminary fitting to the normal distribution, which distributed from minus infinity, occasionally gave unreal quasi-random values. The slip S_{pm} at the maximum load was divided into two components, elastic slip $S_1 = P_m/k_0$ and plastic slip $S_2 = S_{pm} - P_m/k_0$. The latter slip component S_2 and the other two slip components S_3 and S_4, which gave the linear segments after P_m, were also fitted to the lognormal distributions.

3. Quasi-random load–slip curves of single anchor-bolt joints were calculated by substituting quasi-random variables given by Eq. 2 assuming a normal distribution[10] into the parameters above.

$$\lambda = \sigma\left(\sum_{i=1}^{12} r_i - 6\right) + \mu \qquad (2)$$

where λ is the quasi-random variable, σ is the standard deviation, μ is the average, and r_i is the i-th uniform random variable distributed from 0 to 1. Average σ and standard deviation μ used for generating quasi-random variables λ are shown in Table 1. The parameters fitted to the lognormal distributions were transformed from the quasi-random variables given by Eq. 2. Each parameter was assumed to be independent of the other, although there might have been some interdependence among some of the parameters.[9]

4. Random initial gap between each anchor bolt and its lead hole was determined using two random variables r and θ in polar coordinates in the same way as mentioned above (Fig. 3).

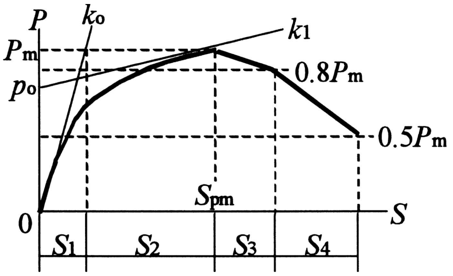


Fig. 4. Approximation of load–slip curves

5. Load–slip curves of files of anchor-bolt joints were simulated from random load–slip curves of single anchor-bolt joints with random initial gaps.

Simulations were performed for combinations of two bolt diameters, 12 and 16 mm, and three lead-hole clearances, 0, 3, and 6 mm. The length/diameter ratios of the anchor bolts above were about 8 and 6, which corresponded to 16 and 12 for bolted joints with single insert plates arranged symmetrically. A file of anchor-bolt joints was assumed to consist of 5, 10, or 15 anchor bolts. The calculation was repeated 1000 times for each configuration.

Results and discussion

Supplementary load sharing by anchor-bolt joints arranged perpendicular to lateral forces

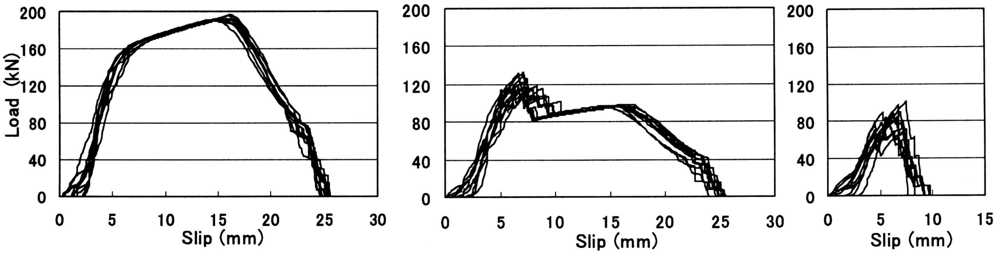
Figure 5 shows examples of the simulated load–slip curves of three combinations of anchor-bolt joints loaded parallel and/or perpendicular to the grain, where 10 curves randomly extracted from 100 simulated curves for lead-hole clearance of 6 mm are shown for each combination. Table 2 shows the simulated effective ratios of average or fifth percentile lower limit resistance of the combinations of anchor-bolt joints to the ideal resistance calculated as the products of the maximum resistance of single anchor-bolt joints shown in Fig. 2 and the number of anchor bolts. The effective resistance ratios of the combinations of ten anchor bolts loaded parallel to the grain dropped only slightly, even for the larger lead-hole clearance of 6 mm.

For the combinations including anchor bolts loaded perpendicular to the grain, on the other hand, the simulations showed obvious reductions of the effective resistance ratios. A notable fact was that the effective resistance ratio of the combination of five anchor bolts loaded parallel to the grain and five anchor bolts loaded perpendicular to the grain with lead-hole clearance of 3 mm was less than that of the combination of ten anchor bolts loaded perpendicular to the grain. This result came from the difference in slips at maximum loads of single anchor-bolt joints between two loading directions making effective load sharing with each other very difficult. When lead-hole clearance became larger, 6 mm in this case, the effective resistance ratio of the combination of ten anchor bolts loaded perpendicular to the grain

Table 1. Averages and standard deviations used for generating quasi-random variables

Bolt diameter (mm)		K_0 (kN/mm)	K_1[a] (kN/mm)	p_0 (kN)	S_2[a] (mm)	S_3[a] (mm)	S_4[a] (mm)
12							
	μ	13.40	0.27	15.80	10.18	2.71	1.47
	σ	3.52	1.85	1.35	1.45	2.19	2.26
16							
	μ	23.70	0.25	26.70	8.67	2.44	6.49
	σ	3.91	2.09	2.42	2.36	2.92	3.32

μ, Average; σ, standard deviation
[a] Equivalent values transformed from the lognormal distributions



(a) L10T0 (b) L5T5 (c) L0T10

Fig. 5a–c. Examples of the simulated load–slip curves of combinations of anchor-bolt joints with clearance of 6 mm loaded parallel and/or perpendicular to the grain. **a** Ten anchor bolts loaded parallel to the grain. **b** Five anchor bolts loaded parallel and five anchor bolts loaded perpendicular to the grain. **c** Ten anchor bolts loaded perpendicular to the grain

Table 2. Simulated effective ratios of average or fifth percentile lower limit resistance of combinations of ten anchor-bolt joints to the ideal resistance

Combination of anchor bolts	Lead-hole clearance (mm)	Effective resistance ratio	
		Average	LL5
L10T0	0	1.00	1.00
	3	0.98	0.97
	6	0.97	0.96
L5T5	0	1.00	1.00
	3	0.86	0.81
	6	0.80	0.72
L0T10	0	1.00	1.00
	3	0.90	0.86
	6	0.78	0.63

LL5, fifth percentile lower limit effective resistance ratio; L10T0, ten anchor bolts loaded parallel to the grain; L5T5, five anchor bolts loaded parallel and five anchor bolts loaded perpendicular to the grain; L0T10, ten anchor bolts loaded perpendicular to the grain

became less than that of the combination of five anchor bolts loaded parallel to the grain and five anchor bolts loaded perpendicular to the grain. This was because the effective load sharing of each anchor bolt became more variable due to wider distribution of its initial gap, which resulted in low possibility of effective load sharing among anchor bolts common in either case of loading direction.

The effective share R_{T5} of the anchor bolts loaded perpendicular to the grain supplementary to the anchor bolts loaded parallel to the grain arranged directly beneath the shear wall lines and its effective ratio r_{TE} to the ideal resistance R_{TI} can be expressed as follows:

$$R_{T5} = R_5 + R_{L5} \tag{3}$$

where R_5 is the total fifth percentile lower limit resistance, and R_{L5} is the fifth percentile lower limit resistance of anchor-bolt joints loaded parallel to the grain.

$$r_{TE} = R_{T5}/T_{TI} \tag{4}$$

where R_{TI} is the ideal resistance of anchor-bolt joints loaded perpendicular to the grain.

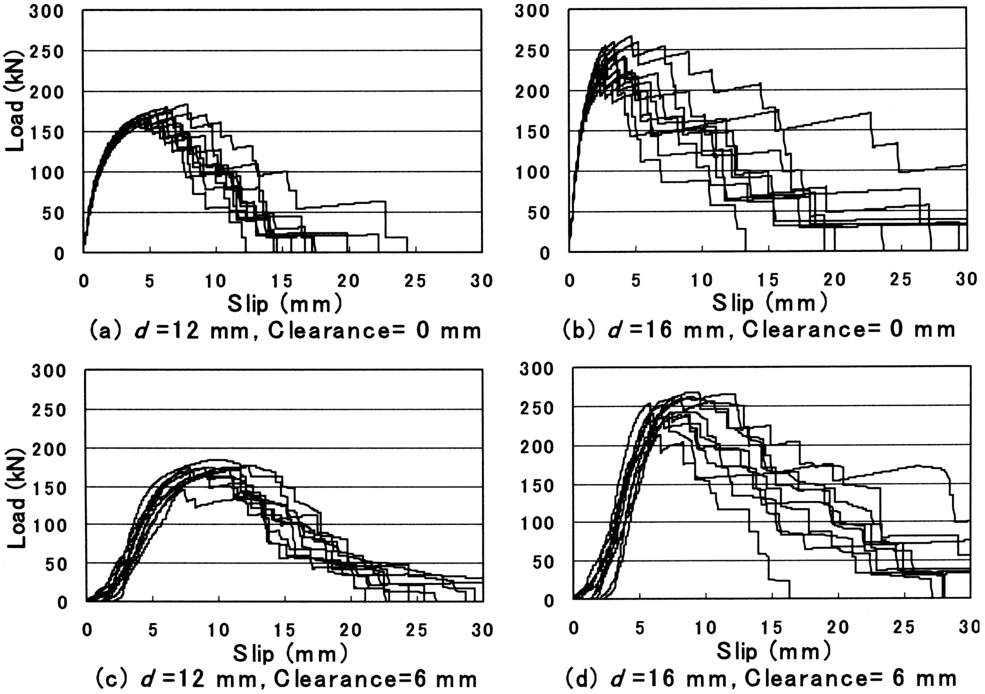
The resultant effective ratios r_{TE} were 0.52 for lead-hole clearance of 3 mm and 0.28 for lead-hole clearance of 6 mm. The actual effective ratios may be less than these values, because they were calculated assuming an ideally stiff floor diaphragm. This means that the supplementary shares of the anchor bolts loaded perpendicular to the grain are far less than those expected from their allowable lateral resistance. Therefore, structural designers should not count the effective lateral resistance of anchor-bolt joints arranged in a row perpendicular to lateral forces or should evaluate it very conservatively.

Lateral resistance of anchor-bolt joints along shear wall lines parallel to lateral force

Figure 6 shows examples of the simulated load–slip curves of files of anchor-bolt joints loaded parallel to the grain, where 10 curves randomly extracted from 1000 simulated curves are shown for each assumption. The stricter simulations with random load–slip curves of single anchor-bolt joints gave more variable load–slip behavior of files of anchor-bolt joints than that simulated with definite load–slip curves as shown in Fig. 5a and Fig. 6c.

Table 3 shows the effective ratios of fifth percentile lower limit maximum resistance of files of anchor-bolt joints to the control resistance calculated from fifth percentile lower limit resistance of single anchor-bolt joints. The reason why some of the ratios exceeded unity is that the multiple member effect completely offset the reduction of effective resistance. As shown in Table 3, the effective resistance ratios were not clearly affected by lead-hole clearance, which was against expectation.[6,7] This was because the probable combinations of random load–slip curves and random initial gaps did not always cause brittle failures more easily but sometimes offset them in the way that ductile anchor-bolt joints with smaller initial gaps preceded brittle anchor-bolt joints with larger initial gaps to bear lateral forces.

The effective ratios of files of 12-mm anchor bolts were stable regardless of lead-hole clearances or number of bolts. The effective resistance of files of 16-mm anchor bolts, on the other hand, was reduced to between 80% and 90% of



(a) *d* =12 mm, Clearance= 0 mm

(b) *d* =16 mm, Clearance= 0 mm

(c) *d* =12 mm, Clearance=6 mm

(d) *d* =16 mm, Clearance= 6 mm

Fig. 6a–d. Examples of the simulated load–slip curves of files of anchor-bolt joints with 12- (**a**, **c**) or 16-mm (**b**, **d**) anchor-bolts loaded parallel to the grain with clearances of zero (**a**, **b**) or 6mm (**c**, **d**)

Table 3. Simulated effective ratios of fifth percentile lower limit resistance of files of anchor-bolt joints to the control resistance calculated from fifth percentile lower limit resistance of single anchor-bolt joints

Number of bolts	Lead-hole clearance (mm)	Effective resistance ratio	
		12-mm diameter	16-mm diameter
5	0	1.03	0.82
	3	1.03	0.86
	6	0.99	0.84
10	0	1.03	0.84
	3	1.03	0.88
	6	0.99	0.83
15	0	1.03	0.85
	3	1.04	0.89
	6	1.01	0.86

the control resistance. These reductions mainly arose from wider variance of the load–slip characteristics of single anchor-bolt joints with 16-mm bolts randomly given with the larger standard deviations of slip components S_2, S_3, and S_4 in Table 1, which resulted in higher probability of brittle failure.

From the simulated results, it is concluded that the effective lateral resistance of files of anchor-bolt joints with 12-mm bolts can be practically estimated by summing up the resistance of all anchor bolts loaded parallel to lateral forces. For the files of anchor-bolt joints with 16-mm bolts, however, some conservative consideration must be required. The simulations in this study can cover only the sills and anchor bolts normally used in Japanese post and beam construction. If thinner sills are used, the effective resistance may be affected more clearly by load–slip characteristics and lead-hole clearance.

An important fact indicated in Fig. 6 is that the maximum resistance of the files of anchor-bolt joints with no lead-hole clearance had variances as wide as those of the files with lead-hole clearance of 6mm, in spite of evident difference between load–slip characteristics, particularly in the initial slips. This fact is more clearly understood in Table 3. This means that structural designers should properly consider the reduction in effective resistance of multiple fastener joints resulting from variance of the load–slip characteristics of single fastener joints even if they are installed with no lead-hole clearance. This is particularly important when they use multiple fasteners of different kinds. The variance of load–slip characteristics of mechanical timber joints is closely related to their failure modes and it becomes wider when the joints have high probability of brittle splitting of their timber members. Risk of brittle splitting is clearly affected by margins, loading direction, or moisture condition. When the risk of brittle failures increases, ultimate slips of mechanical joints become not only smaller but also more variable, which results in lower effective lateral resistance as shown by the numerical simulations above.

Conclusions

We performed Monte Carlo simulations of the effective lateral resistance of multiple anchor-bolt joints and reached the following conclusions:

1. The supplementary shares of anchor bolts arranged in a row perpendicular to lateral forces are far less than those expected from their allowable lateral resistance.

Structural designers should not count the effective lateral resistance of them or should evaluate it very conservatively.

2. The effective resistance is not obviously affected by lead-hole clearance or number of bolts if the anchor-bolt joints are loaded parallel to lateral forces in the case of ordinary sills of Japanese post and beam construction.
3. The effective lateral resistance of files of 12-mm anchor bolts parallel to lateral forces can reasonably be calculated from the allowable lateral resistance of single anchor-bolt joints. The effective lateral resistance of files of 16-mm anchor bolts should be properly reduced.
4. The effective lateral resistance of files of anchor-bolt joints is affected not only by lead-hole clearance but also by variance of load–slip characteristics of single anchor-bolt joints.

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