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ORIGINAL ARTICLE

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Estimation of shear strength of dowel-type timber connections with multiple slotted-in steel plates by European yield theory

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Abstract The shear strength of dowel-type timber connections with multiple slotted-in steel plates was estimated based on European yield theory. The values calculated based on the yield theory were compared with experimentally obtained results. An experiment was performed on dowel-type timber connections with two and three slotted-in steel plates under lateral loads parallel to the grain. The yield mode of the dowel-type connection assumed in this study corresponds approximately to the failure mode of the connection obtained from the experiment. The shear strength of the dowel-type connections calculated based on the yield theory showed good agreement with the results for shear strength obtained in the experiment. The yield theory was useful for estimating the shear strength of the dowel-type connection with multiple slotted-in steel plates. The shear strength of the dowel-type connection was greatly affected by the spacing of the steel plates, the number of steel plates, and the timber thickness. The values of these parameters that showed the proper shear strength of the dowel-type connection could be estimated based on the yield theory.

Key words Multiple shear connection · Dowel · European yield theory · Shear strength · Yield mode

Introduction

Timber is widely used in large-scale structures, e.g., bridges, gyms, and schools, in Japan. These structures often make use of mechanical fasteners, and dowels are a very commonly used type of fastener. The strength of dowel-type connections frequently dominates the design of timber structures. Therefore, proper evaluation of the strength of dowel-type connections is important to develop national design procedures for use in timber structures.

The shear strength of dowel-type timber connections subjected to lateral force can be estimated well using European yield theory.[1,2] European yield theory has been applied to single and double shear timber connections, but not to multiple shear connections, which are often present in large-scale structures. In the National Design Specification,[3] the design value for a single or double shear connection is calculated from the yield theory, and that for a multiple shear bolted connection is calculated from the value obtained for a single shear plane multiplied by the number of shear planes. However, the calculated value of a multiple shear bolted connection estimated by this method may not always agree with the actual shear strength of the connection. The reason for this is that the shear strength of bolted connections as obtained by the yield theory corresponds to the yield mode, and multiple shear bolted connections have characteristic yield modes.[4,5] Therefore, an equation based on European yield theory was obtained for estimating the shear strength of dowel-type timber connections with multiple slotted-in steel plates, which are one of the most general connections with multiple shear planes. The values calculated using the proposed equation were compared with the experimental results obtained for dowel-type timber connections with two and three slotted-in steel plates, and the accuracy of the proposed equation was examined. Furthermore, the relationship between the shear strength of multiple shear connections and the arrangement of steel plates was examined using this equation based on the yield theory.

Modeling

The design equation for the shear strength of dowel-type timber connections is based on a theory originally proposed by Johansen.[6] Several yield modes of the dowel-type timber

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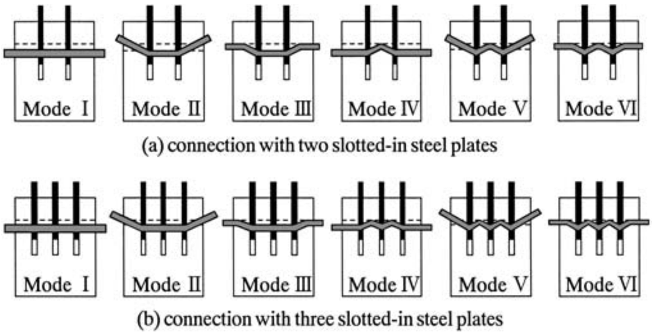

Fig. 1a,b. Yield modes for dowel-type connection with multiple slotted-in steel plates. **a** Two slotted-in plates; **b** three slotted-in plates

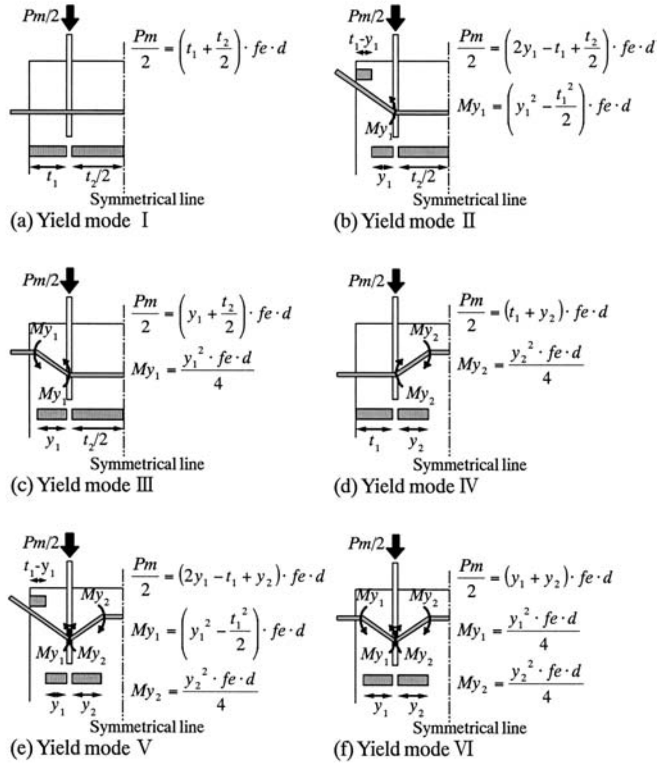

Fig. 2a–f. Yield conditions of timber and dowel in dowel-type connection with two slotted-in steel plates. **a** Yield mode I; **b** yield mode II; **c** yield mode III; **d** yield mode IV; **e** yield mode V; **f** yield mode VI. P_m, yield strength of dowel-type connection; f_e, embedding strength of timber; d, dowel diameter; M_{y1} and M_{y2}, yield moment of dowel

connection are assumed in this theory. The yield mode depends on the hypothesis that the dowel remains straight during yielding, and the yield moment of the dowel is reached at several points. The shear strength of the dowel-type connection differs according to the yield mode.

If the dowel-type connection with two slotted-in steel plates is symmetric, then the connection has six yield modes, as shown in Fig. 1a. If the dowel-type connection with three slotted-in steel plates is symmetric and the steel plates are placed equidistantly, then the connection also has six yield modes, as shown in Fig. 1b. These yield modes are similar to those for connections with two slotted-in steel plates. The yield theory is based on the assumption that embedding of timber and bending of dowel have stiff-plastic behavior. In this article, the symmetrical connection in the dowel-type connection with two slotted-in steel plates is considered. The stress distribution of timber and the moment of the dowel are expressed in Fig. 2, and the estimating equations of shear strength of the dowel-type connection were derived from the equilibrium equations of forces and moments in Fig. 2. The shear strength of the dowel-type connection with three slotted-in steel plates could also be calculated according to the same procedure. Therefore, when the dowel-type connection with multiple slotted-in steel plates is symmetric and has equidistantly placed steel plates, the shear strength of the connection is expressed as follows:

$$P_m = C \cdot f_e \cdot d \tag{1}$$

$$C = \min\begin{cases} 2t_1 + (\mathrm{ns}-1)\cdot t_2 \\ 2t_1\left\{\sqrt{2+\dfrac{2}{3}\cdot\dfrac{F}{f_e}\cdot\left(\dfrac{d}{t_1}\right)^2}-1\right\}+(\mathrm{ns}-1)\cdot t_2 \\ d\sqrt{\dfrac{8}{3}\cdot\dfrac{F}{f_e}}+(\mathrm{ns}-1)\cdot t_2 \\ 2t_1+(\mathrm{ns}-1)\cdot d\sqrt{\dfrac{8}{3}\cdot\dfrac{F}{f_e}} \\ 2t_1\left\{\sqrt{2+\dfrac{2}{3}\cdot\dfrac{F}{f_e}\cdot\left(\dfrac{d}{t_1}\right)^2}-1\right\}+(\mathrm{ns}-1)\cdot d\sqrt{\dfrac{8}{3}\cdot\dfrac{F}{f_e}} \\ \mathrm{ns}\cdot d\sqrt{\dfrac{8}{3}\cdot\dfrac{F}{f_e}} \end{cases}$$

where P_m is the shear strength of the dowel-type connection (N), f_e is the embedding strength of the timber (MPa), F is the strength of the dowel (MPa), d is the dowel diameter (mm), t_1 is the distance (mm) between the outer steel plate and the edge of the timber, t_2 is the distance (mm) between the steel plates, and ns is the number of steel plates. The yield moments ($M_{y1} = M_{y2}$) of dowel in Fig. 2 replaced the strength (F) of dowel using a plastic section modulus.

Materials and methods

Shear tests of dowel-type connections with two or three slotted-in steel plates were conducted on sugi (*Cryptomeria japonica*) and karamatsu (*Larix kaempferi*) glued laminated timbers. The configurations of the specimens and their outlines are shown in Fig. 3 and Table 1, respectively. The grades of sugi and karamatsu glued laminated timbers were E75-F240 and E150-F435, respectively, according to the Japanese Agricultural Standard.[7] The grade of the steel plates and dowels were SS400 according to the Japanese Industrial Standard.[8] Two or three steel plates having a thickness of 12 mm were inserted into the timber, and the steel plates and timber were connected with a dowel having a diameter (d) of 20 mm. The clearance between the steel plate and the timber was 2 mm. The predrilled hole in the

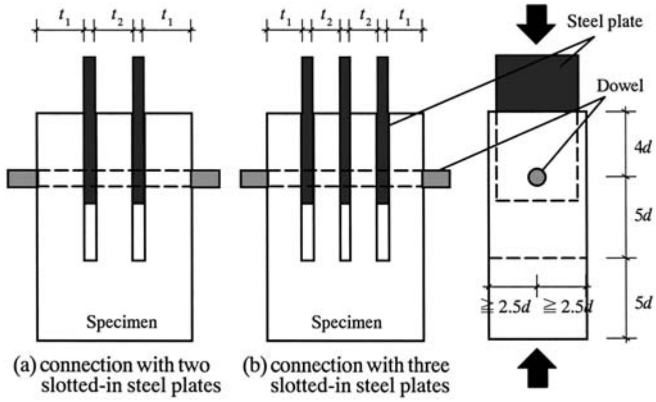

Fig. 3a,b. Configuration of dowel-type connection test. **a** Two slotted-in plates; **b** three slotted-in plates

Table 1. Summary of dowel-type connection test

Specimen	*T/d*	t_2/t_1
ns = 2		
Sugi	4, 8, 12, 20	0.5, 1.0, 2.0
Sugi	4, 8, 12	5.0
Karamatsu	4, 8, 12, 20	2.0
ns = 3		
Sugi	8, 12, 23	0.5, 1.0, 2.0

T/d, ratio of thickness to dowel diameter; t_2/t_1, ratio of distance between steel plates to distance between edge of timber and steel plate; *ns*, number of slotted-in steel plate

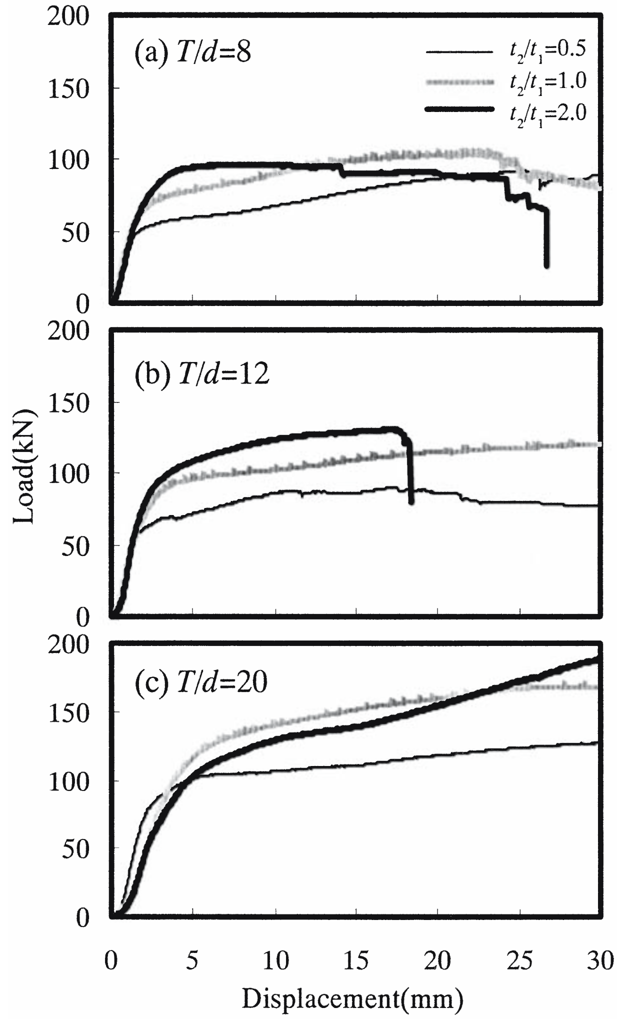

Fig. 4a–c. Load–displacement diagrams for dowel-type connection with two slotted-in steel plates. **a** *T/d* = 8; **b** *T/d* = 12; **c** *T/d* = 20. t_2/t_1, ratio of distance between steel plates to distance between edge of timber and steel plate; *T/d*, ratio of thickness to dowel diameter

timber was 21–24mm in diameter. The dowels were arranged perpendicular to the interface of the lamina. The timber thickness/dowel diameter ratios (*T/d*) were 4, 8, 12, 20, and 23. The ratios of the distance between the steel plates to the distance between the edge of the timber and the steel plate (t_2/t_1) were 0.5, 1.0, 2.0, and 5.0. Dowel-type connections under lateral loads parallel to the grain were tested in compression, as shown in Fig. 3. The tests were carried out at a constant rate of 1.5mm/min[9] and were terminated when the slip exceeded 30mm or when the load decreased to 50% of the maximum load.

Results and discussion

Evaluation methods

Figure 4 shows the typical load–displacement curves of the dowel-type connection with two slotted-in steel plates. When the *T/d* ratio was 8 or 12, the load after yielding increased as the t_2/t_1 ratios increased. For the *T/d* ratio of 20, the loads of the dowel-type connection with a t_2/t_1 ratio of 1.0 were larger than those with t_2/t_1 ratios of 0.5 and 2.0.

The yield strength and the ultimate strength were obtained experimentally from the load–slip relationships. The yield strength was evaluated by the 5% offset method according to ASTM D5652.[10] In this method, the line that passes through the points on the curves corresponding to 10% and 40% of the maximum load is shifted 5% of the dowel diameter toward the positive *x*-direction, and yield strength is defined as the intersection of this line and the load–displacement curve. The ultimate strength was obtained from the maximum load up to a displacement of 15mm, according to EN26891.[11]

Shear strength of the dowel-type connection

Table 2 shows the experimentally obtained results. Failure mode classification was performed based on Fig. 1. The dowel-type connection showed all failure modes (I to VI). For failure modes II to VI, the ultimate strength of the dowel-type connection was 1.1–1.5 times the yield strength.

The experimentally obtained yield strength of the dowel-type connection was compared with the shear strength of connection calculated using Eq. 1. In this equation, the

Table 2. Results of shear tests of dowel-type connection

Specimen	*T/d*	t_2/t_1	Dy (mm)	Pmy (kN)	Du (mm)	Pmu (kN)	Pmu/Pmy	Failure mode[a]
ns = 2								
Sugi								
	4	0.5	2.4	42.6	6.1	46.0	1.08	I
	4	1.0	2.5	42.2	4.4	44.7	1.06	I
	4	2.0	3.0	42.9	8.0	45.3	1.06	I
	4	5.0	2.7	55.7	3.6	57.3	1.03	I
	8	0.5	2.6	55.0	14.9	80.7	1.47	II
	8	1.0	2.7	71.1	14.4	98.1	1.38	II
	8	2.0	3.1	83.8	6.4	92.0	1.10	II
	8	5.0	2.4	88.9	9.3	97.8	1.10	IV
	12	0.5	2.6	66.1	13.8	94.2	1.43	II
	12	1.0	3.6	89.6	11.2	102.5	1.14	II
	12	2.0	2.5	94.0	12.6	123.7	1.32	V
	12	5.0	2.7	114.0	10.5	127.8	1.12	IV
	20	0.5	3.1	84.8	14.9	107.4	1.27	III
	20	1.0	5.3	106.5	15.0	147.0	1.38	VI
	20	2.0	4.0	99.8	14.9	139.0	1.39	V
Karamatsu								
	4	2.0	3.2	62.4	4.8	69.5	1.11	I
	8	2.0	2.7	106.2	5.5	124.1	1.17	II
	12	2.0	4.3	108.4	15.0	161.1	1.49	V
	20	2.0	3.7	117.9	15.0	177.7	1.51	V
ns = 3								
Sugi								
	8	0.5	2.7	65.9	14.9	94.4	1.43	II
	8	1.0	2.6	81.2	7.8	91.4	1.13	II
	8	2.0	2.4	80.5	5.6	86.1	1.07	I
	12	0.5	2.7	83.2	15.0	101.0	1.21	II
	12	1.0	2.4	108.0	9.1	120.5	1.12	II
	12	2.0	1.7	123.1	4.3	133.9	1.09	II
	23	0.5	5.2	122.5	10.9	153.0	1.25	III
	23	1.0	4.0	171.0	12.3	212.2	1.24	V
	23	2.0	4.5	160.6	14.9	218.6	1.36	V

Dy, yield displacement; Pmy, yield strength; Du, ultimate displacement; Pmu, ultimate strength; ns, number of slotted-in steel plates
[a] Failure modes illustrated in Fig. 1

embedding strength of wood and the yield moment of the dowel govern the properties for determining the shear strength of the dowel-type connection. The embedding yield strength of timber parallel to the grain was obtained from embedding tests, according to ASTM D5764,[12] and was evaluated using the 5% offset method.[10] The embedding strength of *sugi* glued laminated timber that was used in the shear tests of dowel-type connection with the t_2/t_1 ratio of 0.5, 1.0, and 2.0 was 25.8 MPa, and that used in the shear tests of connection with the t_2/t_1 ratio of 5.0 was 40.8 MPa. The embedding strength of karamatsu glued laminated timber was 36.2 MPa. The yield strength of the dowel was based on the yield point (235 MPa) of grade SS400 steel.[8] In the present study, the shear strength of the dowel-type connection calculated from Eq. 1 using the embedding yield strength of timber and the yield strength of the dowel was assumed to be the yield strength of the dowel-type connection.[1]

Figures 5 and 6 show the yield strength of the dowel-type connection with two and three slotted-in steel plates using sugi glued laminated timber, respectively. Regardless of the t_2/t_1 ratio, the results calculated using Eq. 1 agreed well with the yield strengths obtained in the experiments. The yield mode assumed by Eq. 1 corresponded to the experimentally obtained failure mode, as shown in Table 2 and Figs. 5 and 6. Figure 7 shows the relationship between the yield strengths of the dowel-type connection obtained in the experiments and those calculated using Eq. 1. The yield strengths of the dowel-type connection with multiple slotted-in steel plates calculated using Eq. 1 showed good agreement with those obtained in the experiments.

These results indicate that Eq. 1, which is based on the yield theory, is useful for estimating the shear strength of the dowel-type connection with multiple slotted-in steel plates.

Effect of steel plate spacing

The shear strength of the dowel-type connection with multiple slotted-in steel plates differed with the arrangement of the slotted-in steel plates, as shown in Fig. 4. The relationship between the shear strength of the dowel-type connection and the steel plate spacing was examined using Eq. 1. Figure 8 shows the relationship between the yield strengths of the dowel-type connections as calculated from Eq. 1 and the t_2/t_1 ratios. The embedding strength (25.8 MPa) of sugi was used for this calculation. For dowel-type connections with either two or three slotted-in steel plates, the yield strengths of the dowel-type connections with *T/d* ratios of 4

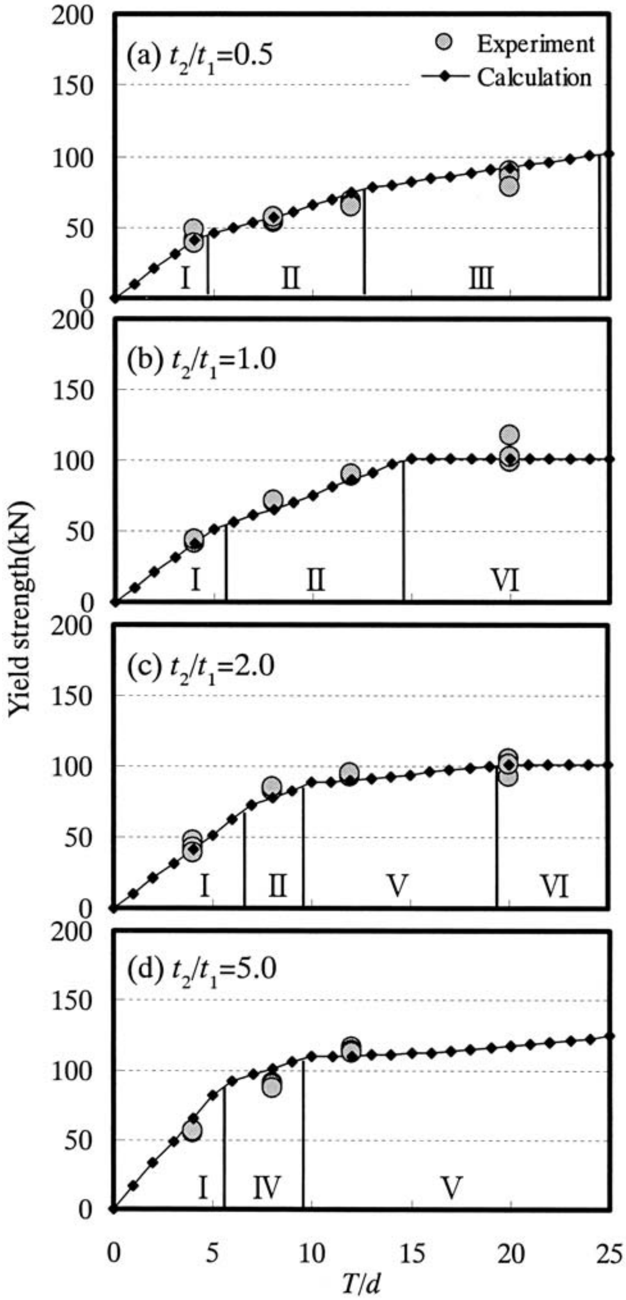

Fig. 5a–d. Relations between yield strength of dowel-type connection with two slotted-in steel plates and ratio of thickness to dowel diameter. **a** $t_2/t_1 = 0.5$; **b** $t_2/t_1 = 1.0$; **c** $t_2/t_1 = 2.0$; **d** $t_2/t_1 = 5.0$. *Roman numerals* indicate yield mode according to Fig. 1

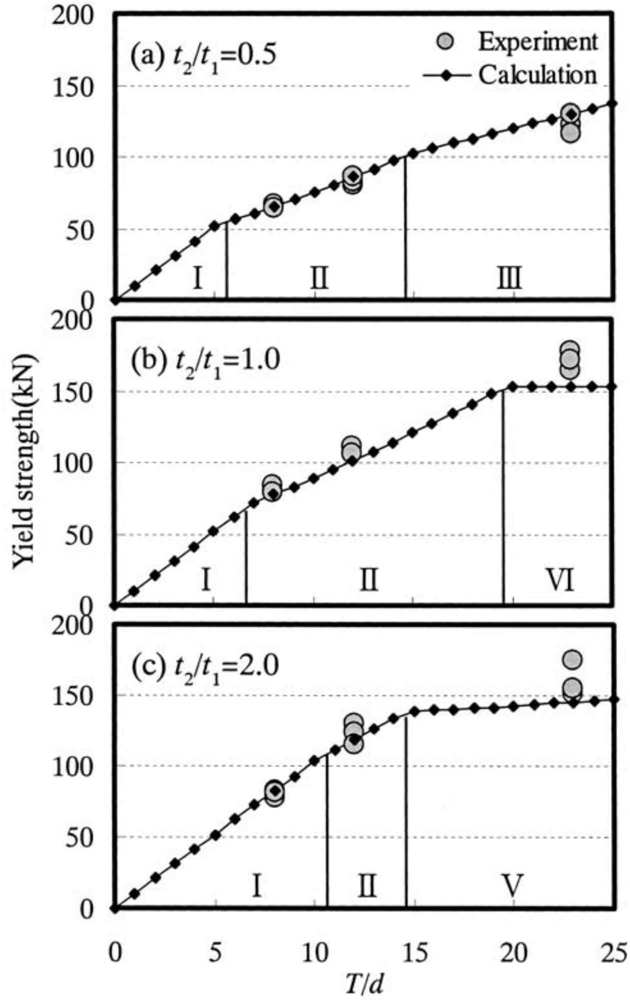

Fig. 6a–c. Relations between yield strength of dowel-type connection with three slotted-in steel plates and ratio of thickness to dowel diameter. **a** $t_2/t_1 = 0.5$; **b** $t_2/t_1 = 1.0$; **c** $t_2/t_1 = 2.0$

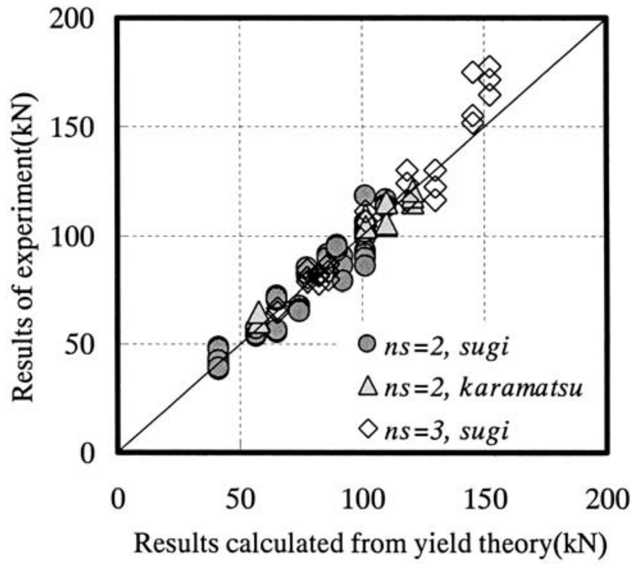

Fig. 7. Comparison of results of the experiment with results calculated based on the yield theory. *ns*, number of slotted-in steel plates

were constant regardless of the t_2/t_1 ratio. For *T/d* ratios larger than 8, the yield strength of dowel-type connection was affected by the steel plate spacing. For the case of two slotted-in steel plates, the yield strengths of dowel-type connections having a *T/d* ratio of 8 increased as the t_2/t_1 ratio increased. In addition, the t_2/t_1 ratios that resulted in the highest yield strengths were close to 1.0 as the *T/d* ratios increased. These results indicate that the yield strength of the dowel-type connection was affected by not only the *T/d* ratio but also the t_2/t_1 ratio.

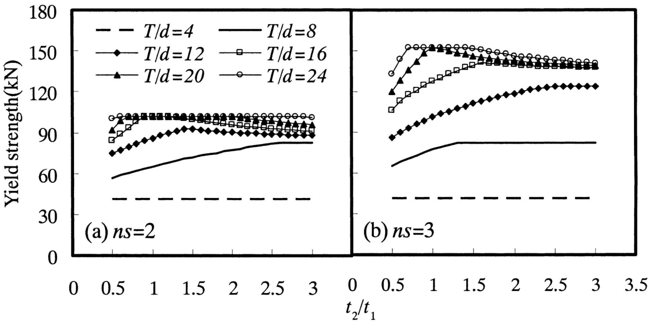

Fig. 8a,b. Relations between yield strength of dowel-type connection and ratio of distance between steel plates to distance between edge of timber and steel plate. **a** *ns* = 2; **b** *ns* = 3

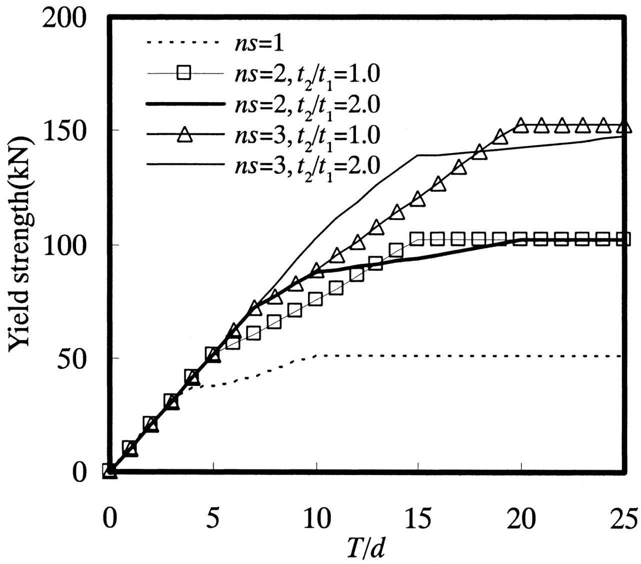

Fig. 9. Relations between yield strength of dowel-type connection calculated based on yield theory and number of slotted-in steel plates

The yield strength of the dowel-type connection with three slotted-in steel plates also showed the same tendency. For example, when the *T/d* ratio was 12, the yield strengths of the dowel-type connections with a t_2/t_1 ratio of 1.0 were 15% smaller than those with a t_2/t_1 ratio of 2.0. However, when the *T/d* ratio was 20, the yield strengths of the dowel-type connections with a t_2/t_1 ratio of 1.0 were 7% larger than those with a t_2/t_1 ratio of 2.0. These results indicate that the shear strength of dowel-type connections is adequate when appropriate t_2/t_1 and *T/d* ratios are applied. Depending on the thickness of the timber, the shear strength of the dowel-type connection would be greatly affected by the number of slotted-in steel plates. Figure 9 shows the yield strengths of dowel-type connections with one, two, and three slotted-in steel plates, as calculated by Eq. 1, with respect to the *T/d* ratio. The embedding strength (25.8 MPa) of sugi was used for this calculation. When the *T/d* ratio was 5, 10, 15, and 20, the yield strength of the dowel-type connection with two slotted-in steel plates was, respectively, 1.4, 1.6, 1.9, and 2.0 times as large as those with one slotted-in steel plate, and the yield strength of the dowel-type connection with three slotted-in steel plates was, respectively, 1.4, 1.9, 2.5, and 2.9 times as large as those with one slotted-in steel plate. When the *T/d* ratio was larger than 14 or 18, respectively, for the dowel-type connections with two or three slotted-in steel plates, the yield strengths approached the yield strength values obtained for the dowel-type connection with one slotted-in steel plate multiplied by the number of steel plates.

Conclusions

The shear strength of the dowel-type timber connection with multiple slotted-in steel plates as calculated based on the yield theory agreed well with the results obtained experimentally using the 5% offset method from the load–displacement relations. This result indicates that the yield theory can estimate the shear strength of dowel-type connections not only with a single slotted-in steel plate but also with multiple slotted-in steel plates.

When the dowel-type connection with multiple slotted-in steel plates has known timber thickness/dowel diameter ratios, the shear strength of connection is affected by the number of slotted-in steel plates, the distance between steel plates, and the distance between the edge of the timber and the steel plate. If the relationships between the shear strength of the connection and these parameters were investigated based on the yield theory, the values of these parameters would show the adequate shear strength of the dowel-type connection.

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