Title: **Effective Lateral Resistance of Combined Timber Joints with nails and bolts**

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Keywords: **Combined joint, Allowable slip, Allowable resistance, Maximum resistance, Energy capacity**

Footnote: **None**

Abstract

An experimental study on combined steel-to-timber joints with nails and bolts is conducted in this study. Principal results are as follows: The initial stiffness and effective allowable resistance of combined joints depend obviously on clearances in predrilled bolt-holes. The combined joints with nails and bolts have high potential of energy capacity to resist strong earthquake forces. There are upper limits of clearances in predrilled bolt-holes that allow advantages of considering the synthetic resistance of combined joints in practical structural design. Combining the joint components with appropriate design will give higher performance against strong earthquakes increasing the safety margin and energy capacity until the failure. The combined joints should be designed under the restrictions of particular specifications in closed design systems because the advantages of combining the joint components are influenced obviously by various actual conditions, which is too difficult to consider in detail in open design systems.

Keywords

Combined joint, allowable slip, allowable resistance, maximum resistance, energy capacity

Introduction

Various mechanical fasteners are used in timber constructions alone or combined with other fasteners to resist loads and external forces. Timber joints with fasteners of each kind have their unique load-displacement characteristics, which makes it difficult to evaluate the design resistance of combined joints with different kinds of fasteners by a common standard method. Considering this difficulty, the current Japanese standard for timber structures[1] does not allow summation of the allowable resistance of timber joints with different fasteners in common with most of the other codes or standards.

Some effective combination of different fasteners, however, may be a choice to improve the actual safety of timber constructions. The difficulty in determination of design allowable resistance by a standard method comes from inevitable initial large displacements of some fasteners due to loose contacts or clearances in predrilled holes and/or variation in ultimate displacement or ductility among various specifications of the joints with different fasteners. The design resistance, however, may be able to be evaluated when the combined joints are designed under the restriction of specifications in closed design and construction systems, which may give an advantage for designing the timber joints with high structural performance. Based on this background, the authors conducted an experimental study on combined steel-to-timber joints with ordinary nails and bolts in this study.

Material and methods

Lateral resistance tests were carried out on joints assembled with glulams of todomatsu (*Abies sachalinensis*) as a main member, fastened to two steel side plates by either a bolt or nails, or a combination of them. Thicknesses of main member (t), which were equal to effective bolt lengths, were 60, 90 and 120mm respectively. Bolts were of diameter (d_b) 10mm. The steel side plates and all adopted bolts of steel grade SS400[2], and common nails (CN-50)[3] were utilized in making the test specimens. The SS400 steel

products with thick less than 16 mm are provided yield stress of not less than 245 N/mm^2 and tensile strength of 400-510 N/mm^2. The CN-50 nail was 2.87 mm in diameter and 50.8 mm in length, and the standard strength of its materials is 690 N/mm^2. Table 1 shows the basic properties of the specimens fabricated with moisture contents of between 10.6-11.5% (Average of 11.1%).

Figure 1 shows the geometry of the specimen and its nomenclature. One bolt was adopted per a bolted joint and 16 nails, 8 nails in each side, were adopted per a nailed joint. The bolt and the nails were positioned according to the standard margins and spacing[1]. We prepared 18 joints only with nails (N), 18 joints only with bolts (B) and 18 combined joints (BN) with both nails and bolts. The nails were hammered moderately ensuring a slight gap and the bolts were only 'hand-tightened' to avoid initial friction between the steel plates and timber. The bolted joints had clearances in predrilled bolt-holes of 2mm in the steel plates and 2mm in the timber. The details of the combined joints were the same as the nailed or bolted joints. The joint specimens were fixed onto the testing machine as shown in Fig. 2 and thrust up and down by a hydraulic cylinder, capable of taking outputs up to 113kN. A load cell, capable of taking measurements up to 100kN, and two displacement transducers fixed on both sides of the specimens, capable of taking slip readings up to 50mm, were used to measure load and displacements respectively. The joint specimens were loaded under the displacement control system. Twenty-seven specimens were tested monotonically until the joint completely failed and the other specimens were tested cyclically. Under the cyclic mode, loads were applied repetitively to the joints at 3 common slip levels (1, 2 and 3mm) from overview of the monotonic load-slip curves of nailed, bolted and combined joints (see Fig. 3 shown later) and each level consisted of 2 cycles. At the end of the 2nd cycle of the 3rd slip level, the joints were loaded monotonically until complete failure.

Numerical simulation of design initial slips of bolted joints

A Monte-Carlo simulation was conducted to estimate the design initial slips of the bolted joints with

clearances in predrilled bolt-holes. Assuming a 5.0% single-tailed normal distribution probability[4, 5], 1000 random combinations of initial locations of bolts in their predrilled holes of steel plates and wood-members in the loading direction, which corresponded to initial slips, were generated with a standard deviation that made 95% of the random location distributed within the clearance 2mm in the steel plate and the same clearance in the wood-member[6-9]. The random numbers due to the normal distribution are often generated by the Box-Muller method and the method using central limit theorem[10]. In this, the central limit theorem was adopted to approximate the normal distribution and the random ratios of initial slips to the total clearances in predrilled bolt-holes were generated by the random function of Visual Basic, which distributed from 0 to 1[11].

From the obtained distribution of random initial locations of the bolts, 5th percentile upper limit ratio of initial slips to the clearance was determined non-parametrically. The experimental load-slip curves of bolted joints were shifted to have the initial slips corresponded to this ratio.

Results and discussion

Figure 3 shows the monotonic load-slip curves of three specimens of each joint configuration. The envelope load-slip curves extracted from the data of the cyclic tests are discussed collectively with them hereafter, because the envelope load-slip curves in the cyclic tests were similar to those in the monotonic tests except slight increases of the slips in inelastic ranges and the maximum loads in the cyclic tests were rather a little higher than those in the monotonic tests in this study[12]. At all main member thickness, the nailed joints had similar load-slip curves with gradual nail-pull-off and failed finally in nail-head-tear-off[13] (Fig. 4). The maximum loads of the bolted joints increased as the main member thickness increased from 60mm to 120mm, which corresponded to main member thickness/bolt diameter ratio from 6 to 12, though the increase became smaller within the range from 9 to 12 in main member thickness/bolt diameter ratio. The ductility of the bolted joints kept on increasing above 90mm, on the other hand[14]. This increase in

ductility, which is directly related to energy capacity up to the final failure, gives an advantage against strong earthquake forces, though it is little considered in allowable stress design for any loads or forces.

The load-slip curves of the combined joints (Fig. 3(c)) had characteristic drops-in-grooves (DIG), which showed transition phases of load bearing from only by nails to both by nails and bolts. These transitions are the results of inevitable initial slips of the bolts located in predrilled bolt-holes of greater diameter, which bring about a difficulty of evaluating the lateral resistance of combined joints. The load-slip behavior of the combined joints after reaching the maximum loads depends on the ductility of the joint components as can be seen in Fig. 3(b) and (c). The ductility of timber joints is the result of detailed specifications of the joints and loading conditions, and then it cannot be determined uniquely to a kind of joint.

The general experimental results of the nailed, bolted and combined joints are shown in Table 2[15]. An essential problem for designing combined joints is how to evaluate allowable upper limits of working resistance (allowable resistance) for practical use in open and/or closed structural design systems. Many criteria have been suggested to determine the allowable resistance of timber joints, some of which are adopted to the standard allowable resistance available for open use in current design codes, standards or recommendations[1, 15-18]. The principal criteria are; (1) apparent yield loads determined in various ways, (2) loads at some allowable displacements to ensure serviceability or tolerable slight damage of structures, (3) loads derived from design maximum loads and the safety factor, and (4) loads determined to ensure the recommended ductility to conform to the basic assumption of earthquake-resistant design of timber constructions. These criteria are partially or entirely applied to timber joints considering actual conditions of loads and forces and expected structural performance in the regions where the structures are built.

Currently in Japan, the loads calculated by the criteria (1), (3) and (4) are mostly adopted to determine the standard allowable resistance of structural timber joints[1, 15] to ensure the required serviceability or tolerable slight damage for loads and forces assumed in allowable resistance design and the prevention of collapse against strong seismic forces assumed in ultimate resistance design. Table 2

shows the average experimental results and the standard short term allowable resistance of the nailed, bolted and combined joints, which includes the characteristic values shown in Fig. 5(a) determined by the criteria (1), (3) and (4). Although the bolted joints were assembled with clearances in predrilled bolt-holes, the steel side plates connected with hand-tightened bolts slipped downwards due to their own weight during specimen set-up. Consequently, the loading of the bolted joints started with the bolts located at the bases of the main member predrilled bolt-holes and at the tops of the side member predrilled bolt-holes. This explains why the bolted joints tested here had no initial slips (Fig. 3(b)). To obtain the most conservative load-slip curves of the bolted joints, therefore, the experimental results of the bolted joints were modified with an initial slip of 4mm, which corresponded to the total clearance in predrilled bolt-holes. Then, the load-slip curves of the combined joints were modified using the load-slip curves of the bolted joints with initial slips 0mm and 4mm, which were the lower and upper bounds of initial slips possible in actual joints. The characteristic values in Fig. 5(a) were recalculated for the modified load-slip curves and were listed in Table 3[15].

Tables 2 and 3 indicate, however, that the combination of the criteria (1), (3) and (4) does not give adequate design short term allowable resistance of the combined joints.

As can be seen in the tables, the calculated yield loads of some combined joints are too low, even dropping into negatives (see [a] in Tables 2 and 3), or some other values were greater than P_{max} (see [b] in Tables 2 and 3). A principal reason for this error is the presence of DIG. Although the load-slip curves of the combined joints are continuous, they do not follow evenly crossing DIG, which renders suitable bilinear mapping difficult. One of the practical criteria to determine the design allowable resistance of combined joints is some allowable displacement (criterion (2)), which ensures serviceability or tolerable slight damage in actual conditions. This universal criterion in structural design allows mechanically reasonable summation of the loads beard by different fasteners of a combined joint at a displacement common to every fastener. The other essential elements that should be considered to ensure the ultimate resistance against strong earthquake forces are the safety factor (criterion (3)) and the recommended ductility (criterion (4))[16].

These criteria are illustrated in Fig. 5(b). The design allowable resistance of a combined joint is given as the lowest value among the loads determined by the criteria (2), (3) and (4).

To discuss the design allowable resistance of the combined joints quantitatively, we should first estimate the design initial slips for given clearances in predrilled bolt-holes. The simulated 5th percentile upper limit initial slips resulted in about 75% of the clearances in predrilled bolt-holes, which corresponded to 1.5mm for the joints with 2.0mm total clearances and 3.0mm for the joints with 4.0mm total clearances. From this simulated result, the load-slip curves of the bolted joints were re-modified assuming the initial slips 0, 1.5 and 3.0mm. Thereafter, the average load-slip curves of the nailed joints (Fig. 6(a)) and those of the bolted joints with the initial slips above (Fig. 6(b)) were synthesized into the load-slip curves of the combined joints (Fig. 6(c)).

Next, we have to determine the allowable joint slips. Some definite allowable slips have been considered as one of the principal criteria for determining the standard allowable resistance of various timber joints in the past. The allowable slips for various fasteners, however, are not specified in the design standards and are different from each other, which makes the simple summation of the standard allowable resistance very difficult even though the fasteners are installed with no initial clearances. The joint slips at the standard allowable resistance of single joints, moreover, are often incompatible with the joint slips correspondent to the deformations of structural elements at the standard allowable resistance. For example, the slips of corner nails of shear walls at the standard allowable resistance vary approximately from 1 to 3 mm due to sizes or configurations of walls[19, 20], while the slips at the standard allowable resistance of single nailed joints are roughly 1.5 mm[21]. This incompatibility seems unavoidable for determining the standard allowable resistance of timber joints separately from actual load-slip curves of them in open design systems. Because we can hardly evaluate the joint slips at the practical allowable resistance of various structural elements under various loading conditions on a common basis. These discrepancies indicate the difficulty of determining the reasonable design allowable resistance of any combined joint in an open design system.

When we design combined joints in a closed design system, on the other hand, we can determine

the allowable joint slips in a more reasonable way for particular joint arrangements under particular loading conditions. That is, the allowable slips can be determined to satisfy particular requirements in actual service conditions to avoid excessive deformation or unrecoverable damage of the structures. Though the major timber constructions are designed following the recognized design codes or standards for open use, reasonable closed design will also be helpful to make the structural design and development of timber constructions more flexible. If we focus on a braced wooden frame as a simple example, for example, the total brace elongation, the sum of the pure brace elongation and the slips of both end joints, never exceed the elongation corresponding to the allowable shear strain of the frame[16], which is determined to ensure the serviceability of the structures against wind or seismic forces in allowable resistance design. Because the pure elongation of the brace is usually much less than the joint slips, the slip of an end joint may be allowed to be around 40 or 45 % (one half of 80 or 90 %) to the allowable total elongation of the brace assembled with ordinary structural lumber and joints. If we consider an example of braced wooden frame of 2730mm high and 1820mm wide and assume the allowable pure shear strain 1/300 rad or 1/150 rad[16], the allowable total elongation of the brace results in 5.1 or 10.1mm. The allowable slip of an end joint can be estimated as 2.0mm (roundly 40% of 5.1mm) or 4.0mm (roundly 40% of 10.1mm).

Table 4 shows the loads at the smaller allowable slips 2.0mm (criterion (2)), the loads of 2/3 of the maximum loads (criterion (3)), and the loads that ensure the recommended ductility (criterion (4)) calculated from the experimental results of nailed, bolted and combined joints according to the definition shown in Fig. 5(b), and Table 5 shows those loads calculated from the modified results of combined joints. The whole view of Tables 2, 3, 4 and 5 gives the following discussion:

1. The initial stiffness of the combined joints varies obviously depending on the clearances in predrilled bolt-holes.
2. The reduction of the maximum resistance due to the clearances in predrilled bolt-holes depends on the ductility of the joint component that bears the loads from the beginning.
3. The effective design short term allowable resistance of the combined joints varies obviously depending

on the clearances in predrilled bolt-holes. The effective ratios of the design short term allowable resistance of the joints with 4.0mm clearances in predrilled bolt-holes varied from 0.52 to 0.75 (0.62 in average) for the combination of criteria (2), (3) and (4) (Fig. 5(b)).

4. The elasto-plastic energy capacity or work until the failure depends on the ductility of the joint components of each kind. The effective ratios of the energy capacity or work of the combined joints to the simple summation of those of the nailed and bolted joints tested in this study varied from 0.90 to 1.17 under little influence of the clearances in predrilled bolt-holes. This result, however, is restricted to the joints having far greater ultimate slips in comparison with initial clearances.

The modified design short term allowable resistance of the combined joints with clearances in predrilled bolt-holes in Table 5 was determined by the criterion (2) (allowable slip) for the joints with main member thickness/bolt diameter ratio of 9 or 12, which had relatively higher ductility, and it was reduced by the criterion (4) (recommended ductility) for the joints with main member thickness/bolt diameter ratio of 6, which had relatively lower ductility. The principal criterion determining the design allowable resistance is naturally varied by the allowable slip, clearance in predrilled bolt-holes and ductility of constituent joints.

The actual design short term allowable resistance of the combined joints with main member thickness/bolt diameter ratio of 9 or 12 in Table 4 was determined by the criterion (2) and was smaller than that of the nailed joints. This contradiction comes from large standard deviation of the design short term allowable resistance determined by the criterion (2). The criterion (2) gives the design short term allowable resistance of combined joints in wide variation because of its natural dependency on random initial slips of bolted joints. Particularly if the initial slips vary crossing over the allowable slip, the lower limit evaluation calculated from all data including some specimens with smaller initial slips that give higher loads at the same allowable slip may result in lower design allowable resistance. It is because the existence of higher loads increases the standard deviation for the same minimum load and higher average load than the evaluation from the data excluding the higher values, which sometimes results in unreasonably low design

allowable resistance. In these cases, the design allowable resistance of the combined joints should be determined to be equivalent to that of the nailed joints for the serviceability limit design.

The evaluated design short term allowable resistance of the combined joints with main member thickness/bolt diameter ratio of 9 was less than that of the bolted joints in Table 4, which were determined from the test results without any consideration to the reduction due to clearances in predrilled bolt-holes. For these clearances in predrilled bolt-holes, consideration for the synthetic resistance has no advantage in the current design procedure that obligates only conceptual but no quantitative consideration to the reduction in effective resistance due to inevitable clearances in predrilled bolt-holes. The relationship between the total clearance in predrilled bolt-holes and the resultant design short term allowable resistance of nailed, bolted and combined joints is shown in Fig. 7 for each main member thickness/bolt diameter ratio. Figure 7 indicates probable upper limits of clearances in predrilled bolt-holes for some joint arrangements or configurations allowing the advantage of considering the synthetic resistance of combined joints in the current design procedure. The discussion above only concerns with the evaluation of design allowable resistance or serviceability limit resistance following the current design procedure regardless of actual initial slips of bolted joints, which does not deny the following actual advantages of combined joints.

1. Initial stiffness of bolted joints with clearances in predrilled bolt-holes used alone can be improved by combining with additional nailed or screwed joints that have no initial slips, or with glued joints.
2. On the contrary, maximum resistance of nailed or screwed joints used alone can be improved by combining with additional bolted joints. Even if the clearances in predrilled bolt-holes of bolted joints hinder the obvious increase of the allowable resistance estimated following the current design standard, the actual maximum resistance or safety factors of them will increase if the nailed or screwed joints are designed appropriately to have far greater ultimate slips than probable initial slips of the bolted joints.
3. The principal advantage of combined joints is the improvement of energy capacity or work until the failure in comparison with single-use of the joint component that precedes bearing applied loads. The energy capacity of the combined joints designed effectively can be more than 90% to the simple

summation of the energy capacity of both joint components loaded alone as the test result of this study shows.

The second and third advantages indicate that the combined joints designed effectively will have higher performance to survive under strong earthquakes, even though these advantages are considered less or almost nothing in evaluating allowable or serviceability limit resistance following the current design standard. The effective allowable resistance of combined joints with different kinds of fasteners is principally dependent on two components; ductility of joint components and characteristic initial slips of joint components.

This study only shows a kind of case study of the combined joints of particular configuration and the test results cannot be applied quantitatively to other configurations. The entire load-slip curves of the joint components, which characterize the resultant mechanical performance of the combined joints, vary in wide range due to many actual conditions; *i.e.* end and side margins, spacing, loading direction to the grain direction, length/diameter ratios of the fasteners, boundary conditions of the fastener heads and tips, and possible brittle behavior of a cluster of fasteners or an eccentric load distribution among the fasteners. Considering these elements, it is very difficult to propose a general design procedure of combined joints for open use. This fact confirms the validity of the current codes or standards that do not allow the summation of the allowable resistance of timber joints with different fasteners. It also indicates that careful considerations on the elements above must be required even when designing the combined joints of particular specifications for closed use.

Conclusions

The experimental study on combined steel-to-timber joints with nails and bolts together with a Monte-Carlo simulation of design initial slips of bolted joints gave the following conclusions.

1. The simulated 5th percentile upper limit initial slips of bolted joints are about 75% of the clearances in

predrilled bolt-holes.

2. The initial stiffness of the combined joints depends obviously on the clearances in predrilled bolt-holes of the bolted joints.
3. The effective maximum resistance of the combined joints depends on both the clearances in bolt-holes and the ductility of the joint component that bears the loads from the beginning.
4. The principal advantage of combining the nailed and bolted joints is the high potential of energy capacity to resist strong earthquake forces.
5. There are upper limits of clearances in bolt-holes that allow practical advantages of considering the synthetic resistance of combined joints. Combining the joint components even with larger clearances will still have the advantages in the increase of additional resistance beyond the design short term resistance and energy capacity until the failure.
6. The advantages of combining the joint components, however, are influenced obviously by various actual conditions; *i.e.* end and side margins, spacing, loading direction to the grain direction, length/diameter ratios of the fasteners, boundary conditions of the fastener heads and tips, and possible brittle behavior of a cluster of fasteners or an eccentric load distribution among the fasteners. Practically, it is too difficult to consider the variation of load-slip characteristics of the joint components depending on these conditions in detail in open design systems. The combined joints, therefore, should be designed under the restrictions of particular specifications based on the experimental load-slip data or substitutive analyses in closed design systems. Or, they should be used as a fail-safe joint-system against strong earthquakes expecting no advantage in general allowable resistance design.

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Title of figures

Fig. 1. Specimen geometry and nomenclature. GL, glulam; SP, steel plate; d_b, bolt diameter; d_n, nail diameter; t, main member thickness

Fig. 2. Configuration of the specimen set-up. a, monotonic loading mode; b, cyclic modes

Fig. 3. Load-slip curves of (a) nailed joints, (b) bolted joints and (c) combined joints with nails and bolt obtained from the monotonic loading tests. t, main member thickness; d_b bolt diameter; DIG, drop in groove

Fig. 4. Typical failure in the nailed joints specimen.

Fig. 5. Nomenclature, definition of the variables and illustration of determination of allowable lateral resistance in relation to the load-slip curves of the joints. (a), typical load-slip curve of nailed and bolted joints; (b), load-slip curve of combined joints

Fig. 6. Typical load-slip curves of (a) nailed joints obtained from experiment and simulated load-slip curves of (b) bolted joints and (c) combined joints with clearance in predrilled bolt-holes. t, main member thickness; d_b bolt diameter; C, total clearance between bolt and predrilled bolt-holes of steel plate and main member; δ_i, simulated initial slip

Fig. 7. Relationships between short term allowable resistance of joints and the clearance in predrilled bolt-holes. t/d_b, main member thickness/bolt diameter ratio

Fig. 1

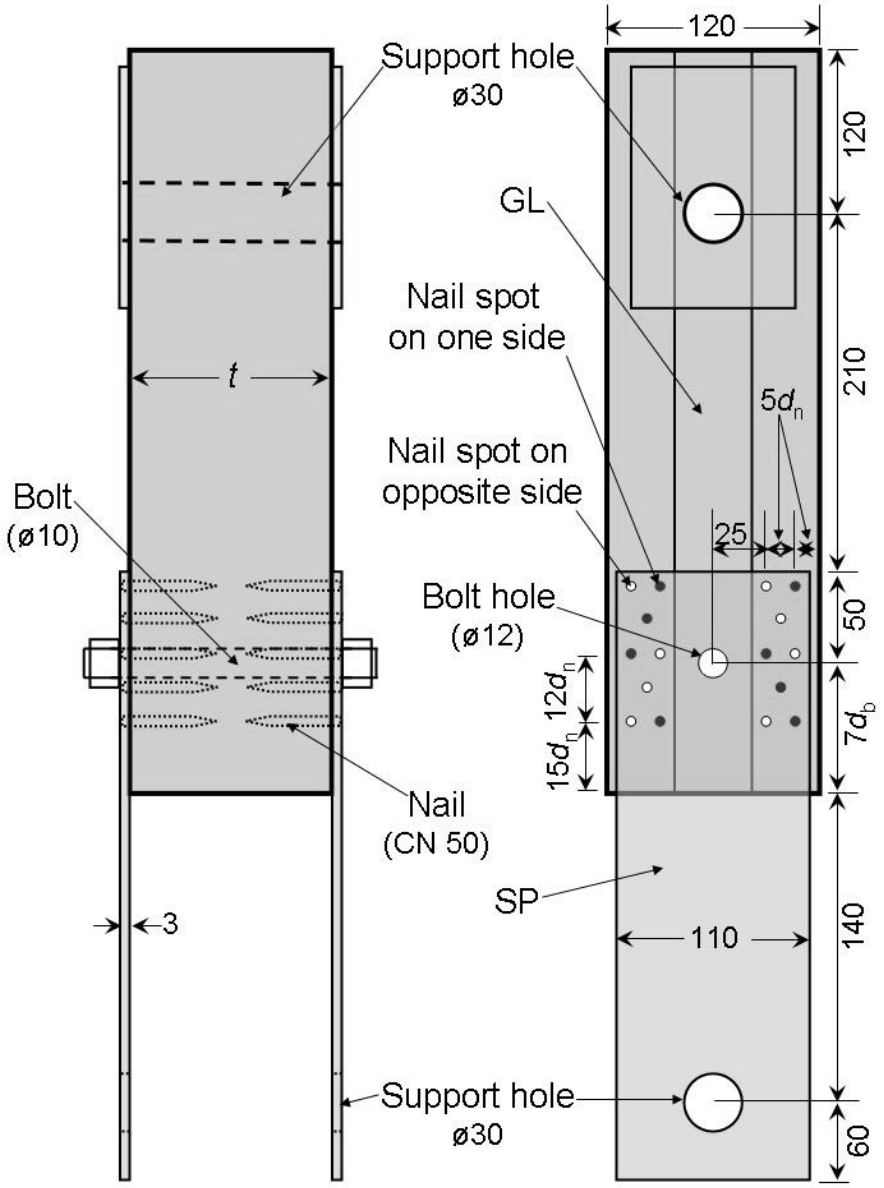

Support hole
ø30
GL
Nail spot
on one side
Nail spot on
opposite side
Bolt hole
(ø12)
Bolt
(ø10)
Nail
(CN 50)
SP
Support hole
ø30
t
3
120
120
210
$5d_n$
25
50
$12d_n$
$15d_n$
$7d_b$
140
110
60

Fig. 2

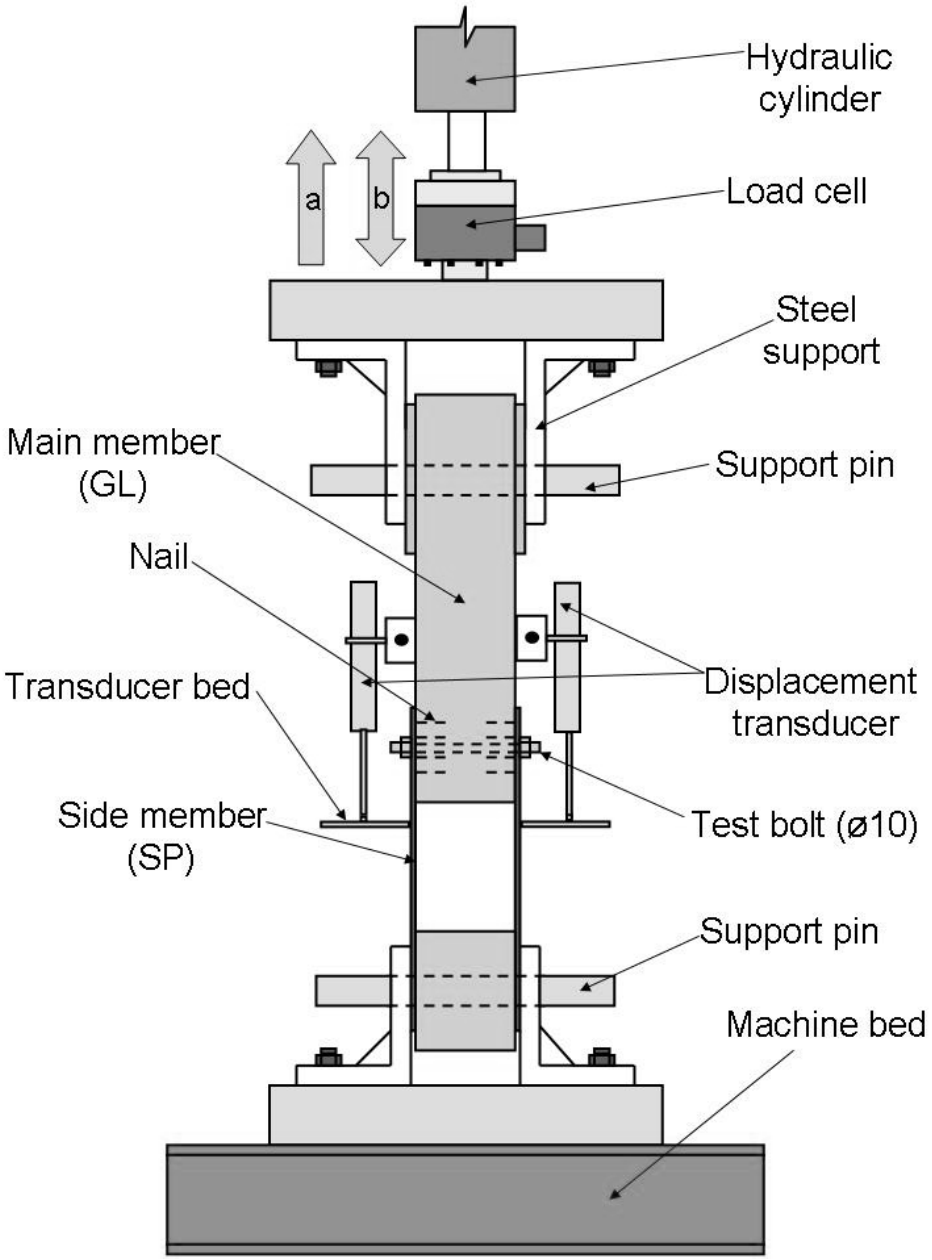

Hydraulic cylinder
Load cell
a
b
Steel support
Main member (GL)
Support pin
Nail
Transducer bed
Displacement transducer
Side member (SP)
Test bolt (ø10)
Support pin
Machine bed

Fig. 3

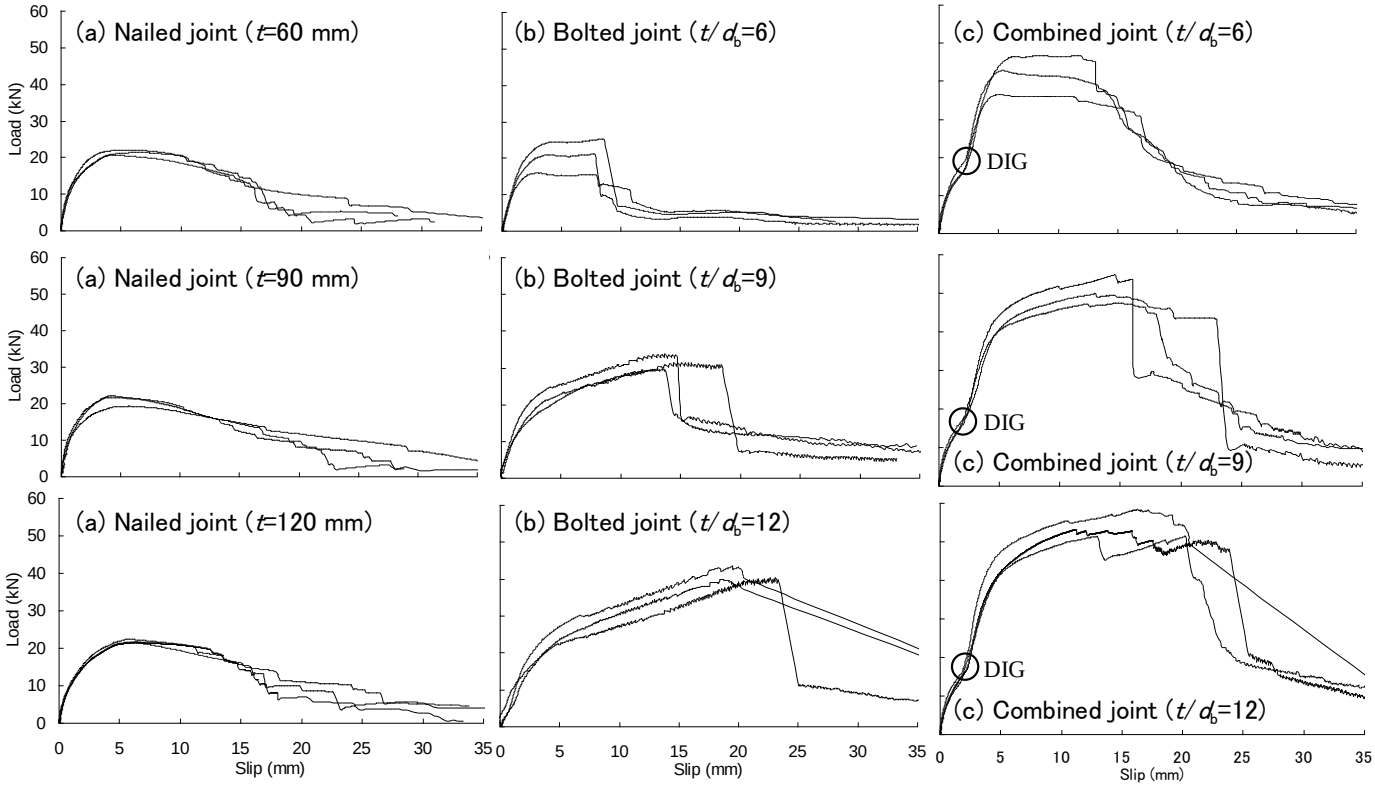

(a) Nailed joint (t=60 mm)
(b) Bolted joint (t/d_b=6)
(c) Combined joint (t/d_b=6)
DIG
(a) Nailed joint (t=90 mm)
(b) Bolted joint (t/d_b=9)
DIG
(c) Combined joint (t/d_b=9)
(a) Nailed joint (t=120 mm)
(b) Bolted joint (t/d_b=12)
DIG
(c) Combined joint (t/d_b=12)
Load (kN)
Slip (mm)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35

Fig. 4

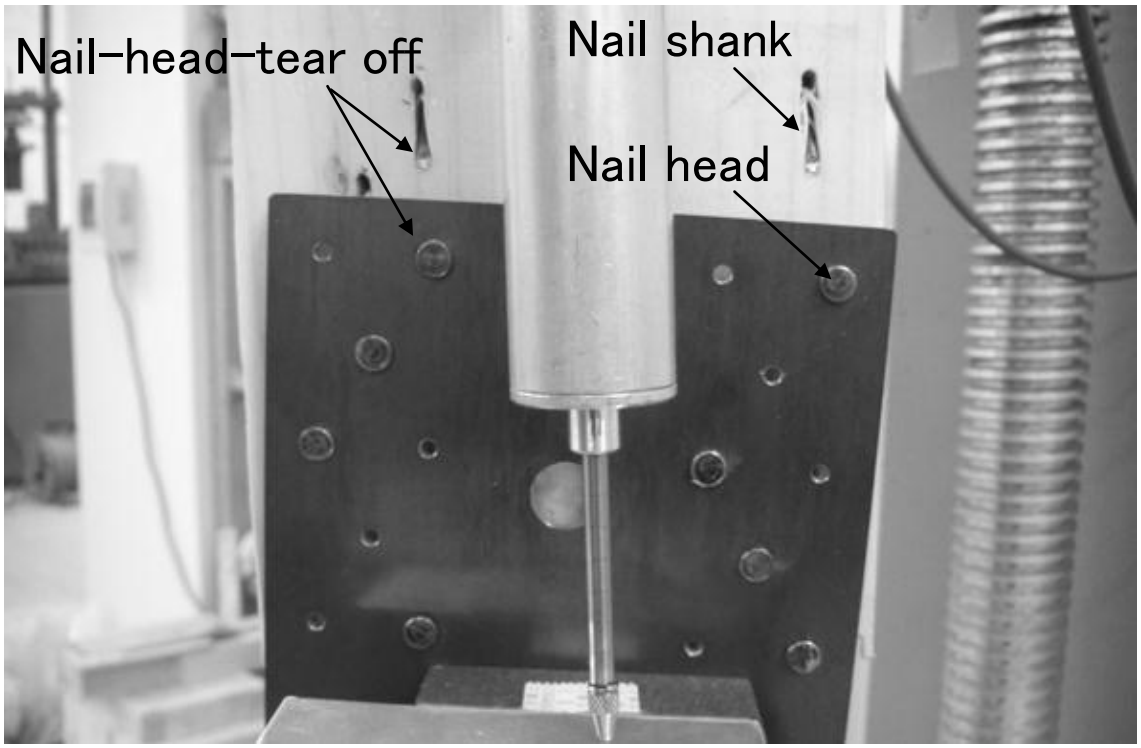
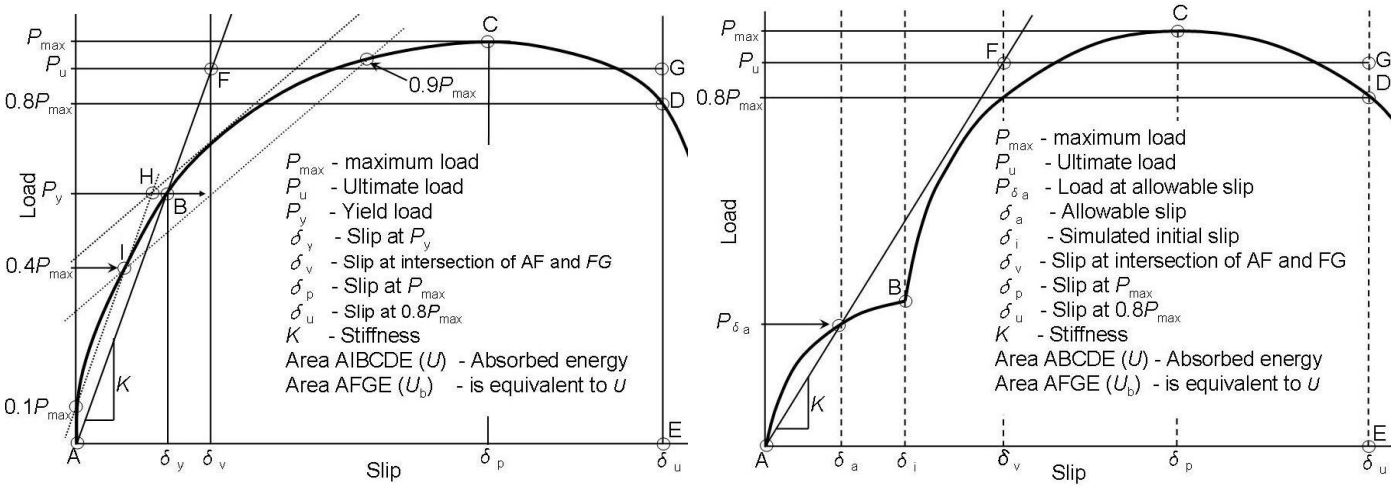


Fig. 5


P_{max}
P_u
$0.8P_{max}$
P_y
$0.4P_{max}$
$0.1P_{max}$
Load
Slip
A
B
C
D
E
F
G
H
I
K
$0.9P_{max}$
δ_y
δ_v
δ_p
δ_u
P_{max} - maximum load
P_u - Ultimate load
P_y - Yield load
δ_y - Slip at P_y
δ_v - Slip at intersection of AF and *FG*
δ_p - Slip at P_{max}
δ_u - Slip at $0.8P_{max}$
K - Stiffness
Area AIBCDE (*U*) - Absorbed energy
Area AFGE (U_b) - is equivalent to *U*
$P_{\delta a}$
δ_a
δ_i

(a) (b)

Fig. 6

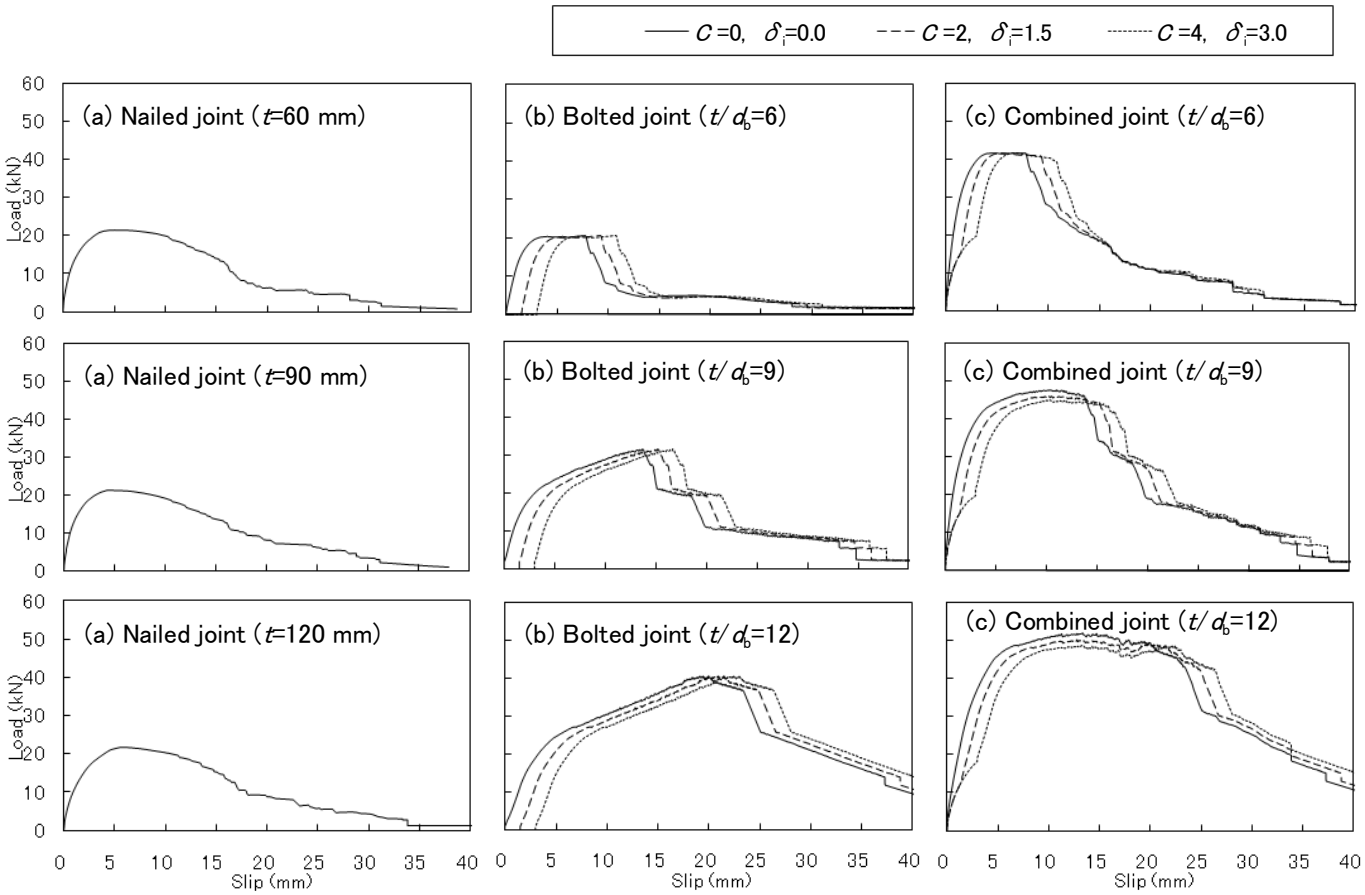

C =0, δi=0.0
C =2, δi=1.5
C =4, δi=3.0
(a) Nailed joint (t=60 mm)
(b) Bolted joint (t/db=6)
(c) Combined joint (t/db=6)
(a) Nailed joint (t=90 mm)
(b) Bolted joint (t/db=9)
(c) Combined joint (t/db=9)
(a) Nailed joint (t=120 mm)
(b) Bolted joint (t/db=12)
(c) Combined joint (t/db=12)
Load (kN)
Slip (mm)
0
10
20
30
40
50
60
5
15
25
35

Fig. 7

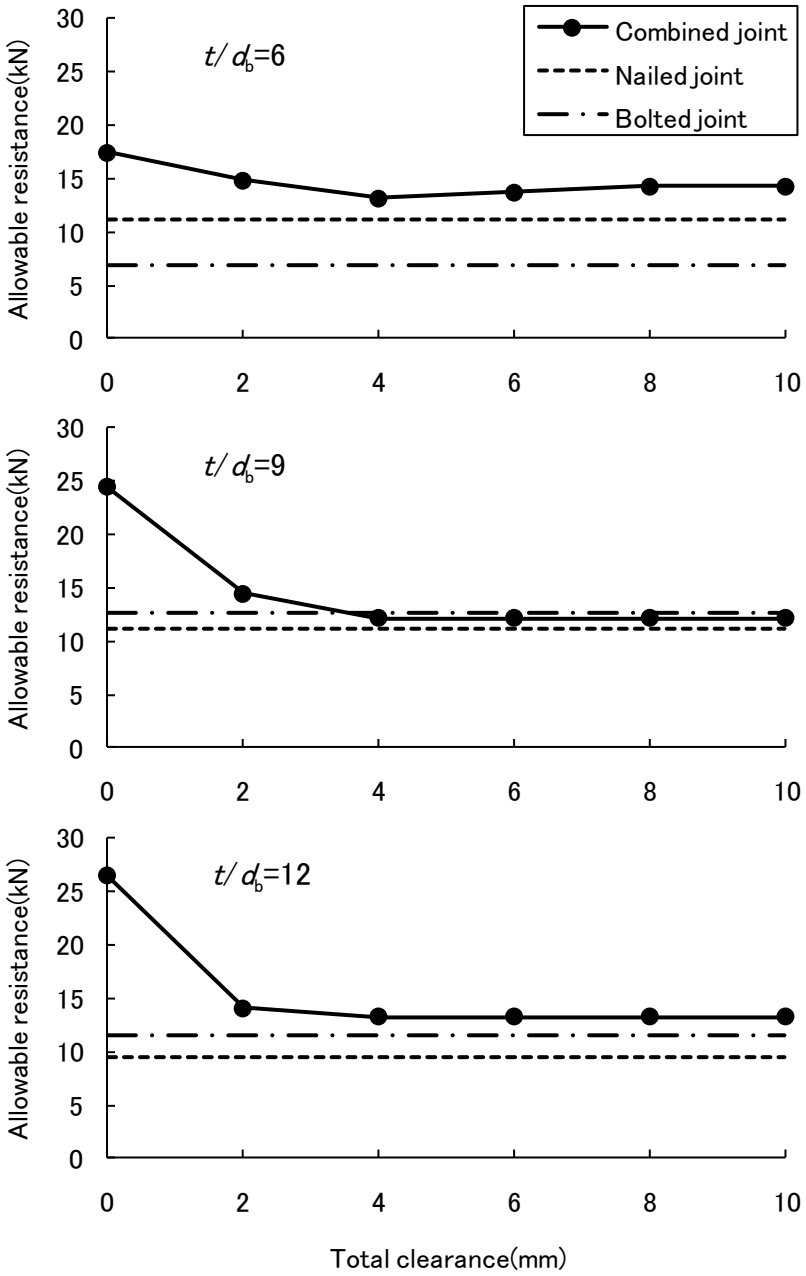

Combined joint
Nailed joint
Bolted joint
t/ db=6
t/ db=9
t/ db=12
Allowable resistance(kN)
Total clearance(mm)
0
5
10
15
20
25
30
0
2
4
6
8
10

Table 1. Properties of laminated timber udes to assemble the specimens

t (mm)	Joint type	Middle lamina				Peripheral lamina			
		ρ (kg/m^3)		E_{fr} (GPa)		ρ (kg/m^3)		E_{fr} (GPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Monotonic loading specimen									
60	N, B, BN	392	51.5	11.0	0.73	407	17.6	11.0	0.91
90	N, B, BN	388	56.2	10.0	0.58	405	24.3	10.0	1.02
120	N, B, BN	413	40.7	11.0	1.99	412	36.2	12.0	0.94
Cyclic loading specimen									
60	N, B, BN	390	45.0	11.0	2.16	390	35.4	11.0	1.55
90	N, B, BN	438	11.8	11.0	1.78	372	23.2	10.0	1.23
120	N, B, BN	399	45.4	11.0	0.72	382	16.5	11.0	0.55

t, main member thickness; ρ, density; E_{fr}, dynamic modulus of elasticity; SD, standard deviation; N, B and BN, nailed, bolted and cobined joints, respectively

Table 2. Experimental results of nailed, bolted and the combined joints

t (mm)	K (kN/mm)	U (kN·mm)	P_{max} (kN)	δ_P (mm)	P_y (kN)	δ_y (mm)	P_u (kN)	μ	$0.2P_u \cdot (2\mu-1)^{0.5}$ (kN)	$2/3P_{max}$ (kN)	P_a (kN)
Nailed joints											
60	13.3	260	22.0	5.4	12.5 (9.0)	0.96	20.5	8.64	16.5 (14.2)	14.7 (13.2)	9.0
90	13.1	231	21.0	4.7	11.0 (9.4)	0.85	19.2	8.78	15.5 (13.7)	14.0 (12.1)	9.4
120	9.5	256	21.6	6.9	11.8 (8.7)	1.25	20.0	6.56	13.9 (11.1)	14.4 (12.1)	8.7
Bolted joints											
60	12.5	185	21.8	7.4	13.0 (7.2)	1.05	20.7	6.13	13.4 (9.0)	14.5 (7.2)	7.2
90	7.4	397	34.8	13.8	19.0 (13.6)	2.60	30.4	3.71	15.2 (12.1)	23.2 (14.3)	12.1
120	6.0	586	40.7	19.4	22.1 (18.7)	3.74	33.7	3.55	16.6 (13.8)	27.1 (24.6)	13.8
Combined joints											
60	8.9	518	43.0	8.8	0.2[a] (-7.8[a])	1.96	42.8	3.13	19.1 (15.9)	28.7 (21.3)	-7.8[a]
90	7.8	799	53.6	14.8	64.0[b] (-5.0[a])	5.96	53.3	2.71	22.1 (13.3)	35.7 (27.9)	-5.0[a]
120	7.1	982	55.2	16.1	89.5[b] (-133[a])	6.76	54.8	2.86	23.5 (18.7)	36.8 (33.0)	-133[a]

t, main member thickness; K, initial stiffness; U, energy capacity; P_{max}, maximum load; δ_P, slip at P_{max}; P_y, yield load; δ_y, slip at P_y; P_u, ultimate load; μ, ratio of δ_u to δ_v as shown in Fig. 4; P_a, short term allwable resistance; [a], value too low or negative value; [b], value higher than P_{max}; *parentheses* denotes 95% lower limit value

Table 3. Results obtained from modified load-slip curves of the bolted joint and the combined joint

t (mm)	K (kN/mm)	U (kN·mm)	P_{max} (kN)	δ_P (mm)	P_y (kN)	δ_y (mm)	P_u (kN)	μ	$0.2P_u \cdot (2\mu-1)^{0.5}$ (kN)	$2/3P_{max}$ (kN)	P_a (kN)
Bolted joints (C=4 mm)											
60	3.0	187	21.8	11.5	47.4[b] (14.3)	6.48	16.7	2.53	6.7 (4.2)	14.5 (7.2)	4.2
90	2.9	409	34.8	17.8	19.0 (13.6)	6.60	28.0	2.03	9.7 (7.4)	23.2 (14.3)	7.4
120	2.9	644	40.7	23.4	22.1 (18.7)	7.74	31.6	2.32	12.1 (9.3)	27.1 (24.6)	9.3
Combined joints (C=0 mm)											
60	25.6	392	43.4	6.8	25.3 (18.5)	1.00	41.3	6.61	28.2 (21.4)	28.9 (21.0)	18.5
90	18.8	674	51.7	11.6	30.0 (19.9)	1.66	48.0	6.12	31.6 (25.1)	34.5 (24.7)	19.9
120	14.6	962	54.3	14.8	33.1 (23.2)	2.30	49.9	6.23	33.4 (25.3)	36.2 (30.5)	23.2
Combined joints (C=4 mm)											
60	8.9	442	42.9	8.3	5.5[a] (-24.2[a])	2.12	41.0	3.20	17.5 (10.8)	28.6 (21.3)	-24.2[a]
90	5.3	710	48.5	14.4	172[b] (-769[a])	6.45	50.6[b]	2.07	17.4 (15.2)	32.3 (23.0)	-769[a]
120	4.9	990	50.9	18.9	-177[a] (-1231[a])	6.94	49.9	2.72	20.5 (16.9)	33.9 (28.5)	-1231[a]

C, total clearance between lead-hole and bolt; t, main member thickness; K, initial stiffness; U, energy capacity; P_{max}, maximum load; δ_P, slip at P_{max}; P_y, yield load; δ_y, slip at P_y; P_u, ultimate load; μ, ratio of δ_u to δ_v as shown in Fig. 4; P_a, short term allwable resistance; [a], value too low or negative value; [b], value higher than P_{max}; *parentheses* denotes 95% lower limit value

Table 4. Experimental results evaluated by the method shown in Fig. 4(b)

t (mm)	K (kN/mm)	U (kN·mm)	P_{max} (kN)	δ_P (mm)	P_{δ_a} (kN)	δ_a (mm)	P_u (kN)	μ	$0.2P_u \cdot (2\mu-1)^{0.5}$ (kN)	$2/3P_{max}$ (kN)	P_a (kN)
Nailed joints											
60	8.5	260	22.0	5.5	16.9 (14.3)	2.00	21.3	5.35	13.3 (11.1)	14.7 (13.2)	11.1
90	8.1	231	21.0	4.8	16.1 (12.1)	2.00	20.2	5.18	12.3 (11.2)	14.0 (12.1)	11.2
120	7.4	256	21.6	7.0	14.8 (13.2)	2.00	20.5	4.98	12.3 (9.6)	14.4 (12.1)	9.6
Bolted joints											
60	8.9	185	21.8	7.5	17.8 (12.5)	2.00	21.6	4.10	11.4 (6.9)	14.5 (7.2)	6.9
90	8.2	397	34.8	13.8	16.5 (12.8)	2.00	29.7	4.34	16.3 (12.6)	23.2 (14.3)	12.6
120	7.6	586	40.7	19.4	15.3 (11.4)	2.00	32.6	5.04	19.6 (15.1)	27.1 (24.6)	11.4
Combined joints											
60	8.5	518	43.0	8.9	17.0 (10.8)	2.00	43.1	2.93	18.7 (15.4)	28.7 (21.3)	10.8
90	8.9	799	53.6	14.8	17.9 (9.9)	2.00	51.0	3.25	23.7 (16.7)	35.7 (27.9)	9.9
120	8.2	982	55.2	16.1	16.4 (13.5)	2.00	52.3	3.46	25.4 (21.4)	36.8 (33.0)	13.5

t, main member thickness; K, initial stiffness; U, energy capacity; P_{max}, maximum load; δ_p, slip at P_{max}; P_{δ_a}, load at δ_a; δ_a, allowable slip; P_u, ultimate load; μ, ratio of δ_u to δ_v as shown in Fig. 4; P_a, short term allowable resistance; *parentheses* denotes 95% lower limit value

Table 5. Shear resistance of combined joints with clearance between bolt and bolt lead-hole

t (mm)	K (kN/mm)	U (kN·mm)	P_{max} (kN)	δ_p (mm)	P_{δ_a} (kN)	δ_a (mm)	P_u (kN)	μ	$0.2P_u \cdot (2\mu-1)^{0.5}$ (kN)	$2/3P_{max}$ (kN)	P_a (kN)
C=0 mm, δ_i=0 mm											
60	17.3	392	43.4	6.8	34.7 (30.0)	2.00	43.3	4.20	23.2 (17.4)	28.9 (21.0)	17.4
90	16.3	674	51.7	11.6	32.6 (27.0)	2.00	48.6	5.12	29.4 (24.5)	34.5 (24.7)	24.5
120	15.0	962	54.3	14.8	30.0 (26.5)	2.00	49.5	6.43	33.8 (27.7)	36.2 (30.5)	26.5
C=2 mm, δ_i=1.5 mm											
60	11.9	416	43.3	6.5	23.8 (22.3)	2.00	42.2	3.36	19.8 (14.9)	28.9 (21.4)	14.9
90	10.7	685	50.5	12.8	21.4 (14.5)	2.00	47.7	3.81	24.1 (20.2)	33.6 (24.2)	14.5
120	9.6	970	53.0	16.9	19.1 (14.1)	2.00	48.8	4.45	27.1 (22.1)	35.4 (30.2)	14.1
C=4 mm, δ_i=3 mm											
60	8.5	432	43.2	7.5	16.9 (14.3)	2.00	42.0	2.65	17.0 (13.2)	28.8 (21.4)	13.2
90	8.1	696	49.5	13.9	16.1 (12.1)	2.00	46.2	3.18	21.1 (17.9)	33.0 (23.4)	12.1
120	7.4	981	51.8	18.0	14.8 (13.2)	2.00	47.5	3.79	24.0 (19.5)	34.5 (29.4)	13.2

C, total clearance; δ_i, simulated initial slip; t, main member thickness; K, initial stiffness; U, energy capacity; P_{max}, maximum load; δ_p, slip at P_{max}; P_{δ_a}, load at δ_a; δ_a, allowable slip; P_u, ultimate load; μ, ratio of δ_u to δ_v as shown in Fig. 4; P_a, short term allowable resistance; *parentheses* denotes 95% lower limit value