Original

Static Tensile Strength of Wood Butt Joints with Metal Plate Connectors

Effects of Plate Geometry and Specific Gravity of Wood

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Abstract——In order to obtain basic design data of wood butt joints with metal plate connectors, static tensile tests were made on the joints connected with sixteen types of plate.

Two types of failure mode of joints were observed. In the case when joints failed in withdrawal of the teeth, a linear relationship between ultimate load of joints and specific gravity of wood existed, and strength per tooth increased by about 12 kg with increasing specific gravity by 0.1. In the case when joints failed in tension at the middle of the plate, ultimate load of joints did not depend on the specific gravity of wood but on tensile strength of the plate connector, and strength per tooth decreased with increasing the number of row of the teeth. Transition of these two types of failure mode was found on six rows type of the plate; withdrawal of teeth was observed when the number of row was less than six.

Introduction

Wood trusses jointed with metal plate connectors have been widely used in residental construction of the world. In Japan, they have been introduced recently in construction of prefabricated wooden houses and light framed (2×4's) wooden houses. None of industrial standard and structural code of joints with metal plate connectors is, however, prepared so far in Japan, but those suitable for own meteorological condition of Japan are needed.

Mechanical properties of this type of joint has been studied with respect to factors affecting joint performance, for example, effective teeth and area of the plate[1], duration of load[2], moisture cycling[3] and repeatea loading[4,5]. But studies concerning the relationship between specific gravity of wood and mechanical performance of the joints are scarce.

The purpose of this study is to clarify the effects of specific gravity of wood and plate geometry on static tensile strength, relative displacement and failure mode of the joints.

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1. Experimental

1-1 Wood

Wood used in this study were 40 mm thick, 90 mm wide, clear and straight-grained Western Hemlock *(Tsuga heteterophylla)*, which was conditioned to 12 percent moisture content. So as to be able to find the effect of specific gravity of wood on tensile strength of joints, stocks of a range of specific gravities from 0.34 to 0.53 (air-dried) were selected.

Relation between specific gravity of wood and compressive strength obtained in the preliminary test were $\sigma = 1478\rho - 191$, where σ was the compressive strength in kg/cm^2, and ρ the specific gravity of wood. The correlation coefficient was 0.898.

1-2 Metal plate connector

Metal plate connectors used were Gang-Nail (Punched-out tooth plate connector produced by ABC Corp., U.S.A.) of 18 gage mild steel with galvanized finish. Sixteen different sizes and types of plates were cut from large original size of plate connectors (20 rows $\times$ 15 columns of teeth). Geometry of the plates and the teeth are shown in Fig. 1 and Table 1, respectively. There are two types of plates when number of

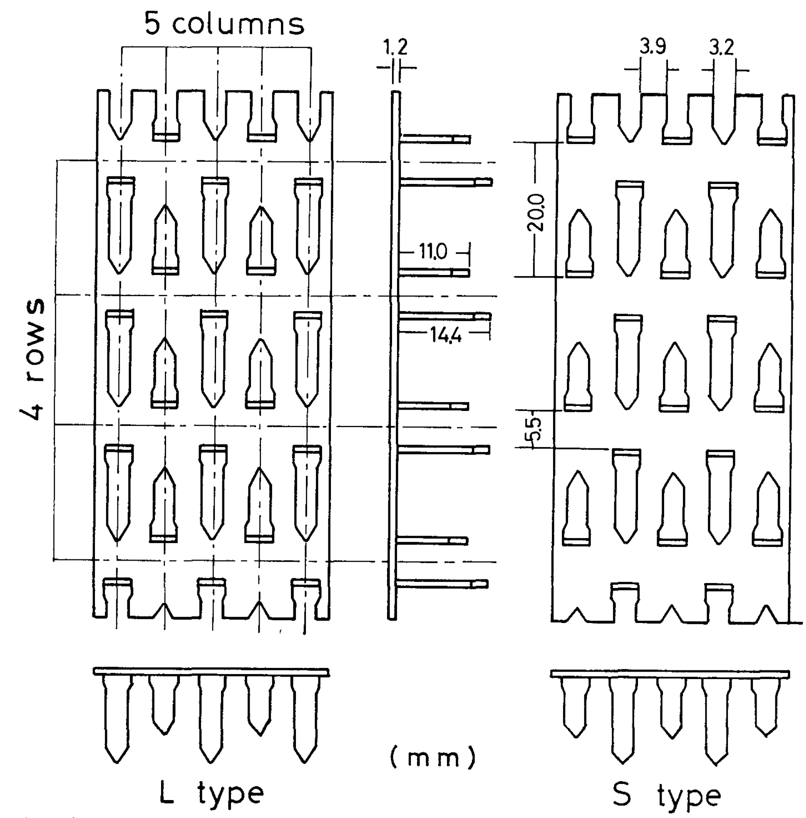

Fig. 1. An example of geometry and arrangement of teeth of a metal plate connector. (In case of 4 rows and 5 columns)

Table 1. Classification of plate types and number of teeth. (Number of short teeth) +(Number of long teeth)=(Total number of teeth)

Column	Type	Row			
		2	4	6	8
3	S	4+ 2= 6*1	8+ 4=12	12+ 6=18	not tested
	L	2+ 4= 6	4+ 8=12	6+12=18	not tested
5	S	6+ 4=10	12+ 8=20	18+12=30	24+16=40
	L	4+ 6=10	8+12=20	12+18=30*2	16+24=40
10		10+10=20	not tested	30+30=60*3	not tested

*1: 2-3-S type, *2: 6-5-L type, *3: 6-10 type.

teeth columns is odd, which are:

(1) L-type; the middle column consisted of long tooth, and

(2) S-type; the middle column consisted of short tooth.

Definition of the rows and columns of a plate connector is illustrated in the figure which shows a plate of connector with four rows and five columns of teeth, and for short symbol 4–5 is used hereafter. If the number is odd, "S" or "L" is added to the above symbol so as to identify which type of plate is used. For example, 8-5-L means L-type plate with eight rows and five columns of teeth.

1-3 Specimen

All of the joints consisted of two wood members butt-jointed with two metal plate connectors. An example of geometry of a joint specimen is shown in Fig. 2 (4-5-S type). The length of one wood member ranges from 120 mm (2–3 type) to 300 mm (6–10 type). Each of those connectors was pressed into both sides of tightly fitted wood members using an hydraulic press. The pressure was applied until the teeth penetrated the lumber but the plate did not crush the wood members.

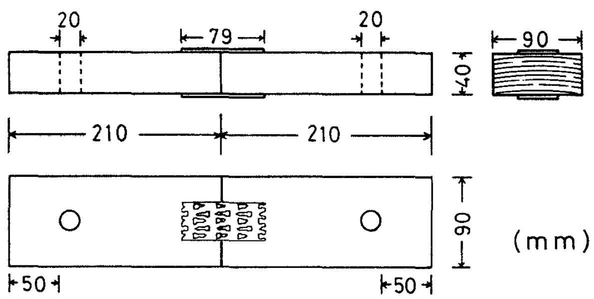

Fig. 2. An example of geometry of a joint specimen for static tensile test.

1-4 Testing procedure

A universal testing machine was used to measure the ultimate tensile load and the relative displacement of the joints during loading. Except for 6–10 type, the specimens were held in the testing machine by 20 mm diameter bolts through 5 mm thick steel plates on each side of the specimen. 6–10 type specimen was held with tension grips of the machine.

Load was applied until the specimen failed, and the relative displacement was measured by two electric exsotensiometers set at both sides of the specimen. From the beginning of loading to the failure of the specimen, it took about 3 or 4 minutes for each specimen.

2. Results and Discussion

2-1 Case of 2 rows type

2-1-1 Relation between ultimate load and specific gravity of wood

Relations between ultimate load and specific gravity of wood are plotted in Fig. 3. These relations appear to be linear, namely ultimate load increases linearly with increasing specific gravity of wood. This is because the bearing resistance of wood depends on specific gravity of wood. The similar inclination is observed on

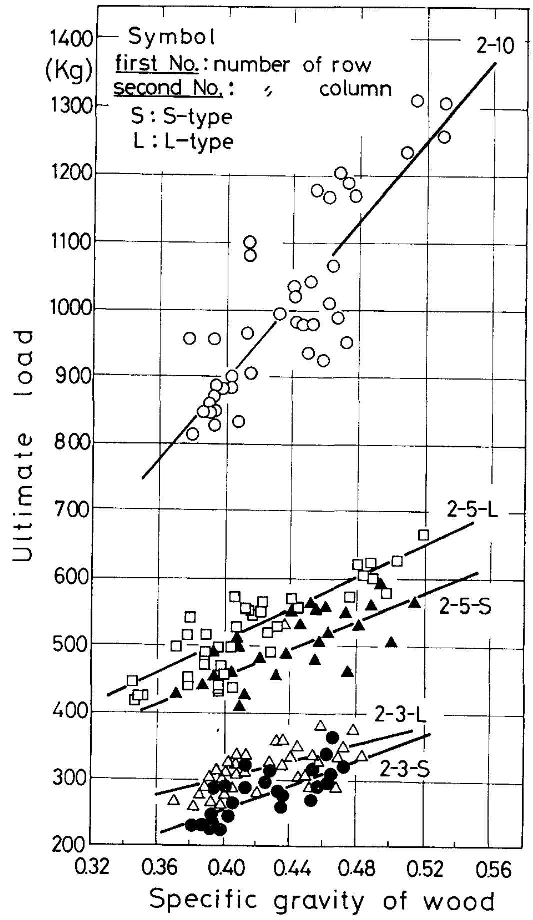

Fig. 3. Ultimate load of joints with two rows type plate connectors as a function of specific gravity of wood.

Table 2. Coefficients of linear regression line and correlation coefficients between ultimate load of joints and specific gravity of wood. (In case of two rows type of plate connectors)
(Ultimate load) $=A\times$ (Specific gravity of wood) $+B$

Type	A (kg)	B (kg)	Correlation coefficient
2-3-S	862	−85.8	0.740
2-3-L	690	23.2	0.649
2-5-S	931	91.3	0.724
2-5-L	1179	34.5	0.951
2-10	2896	−260	0.853

the common nail-joints subjected to a load perpendicular to grain.

Table 2 shows the correlation coefficients and the coefficients of linear regression calculated from these data.

As for the failure of this (two rows) type of joint, all the teeth were pulled from one of the wood blocks and wood tissue around the tooth holes was crushed.

Ultimate load of joints with plate connectors of L-type is slightly higher than that of S-type at the same level of specific gravity, which indicates that the longer tooth has more bearing capacity than the shorter.

Though the ultimate load of joints with greater number of teeth column is higher than that with smaller number, there are not so much differences in the ultimate load per tooth among them. Coefficients of linear regression and correlation coefficients between ultimate load per tooth and specific gravity of wood are calculated (Table 3), and the regression lines are compared in Fig. 4.

Table 3. Coefficients of linear regression line between ultimate load per tooth and specific gravity of wood. (In case of two rows type of plate connectors)
(Ultimate load per tooth) $=a\times$ (Specific gravity of wood) $+b$

Type	a (kg)	b (kg)
2-3-S	144	−14.3
2-3-L	115	3.86
2-5-S	93.1	9.13
2-5-L	118	3.45
2-10	145	−13.0

From the figure, average bearing capacity per tooth in S-type plate is slightly lower than that in L-type. This difference may decrease when the column number becomes greater, because it depends on the fraction in total teeth number of numbers of short and long teeth.

Mean value of "a" in Table 3 is 123. This means that ultimate load per tooth

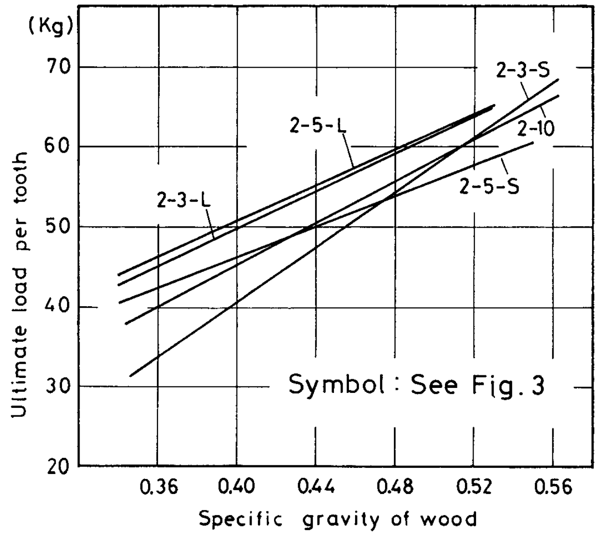

Fig. 4. Ultimate load per tooth as a function of specific gravity of wood. (In case of two rows type plate connectors)

increases by approximately 12.3 kg with increasing specific gravity of wood by 0.1.

2-1-2 Relative displacement

Figure 5 shows the relation of static tensile load to relative displacement of the joints made with wood blocks of specific gravity ranged 0.39–0.41. Individual point in the figure indicates a mean of the measurements made on ten specimens. As known in general, all of these curves are nonlinear and the distinct proportional limit does not exist on them. It is clear that the stiffness of the joint becomes higher

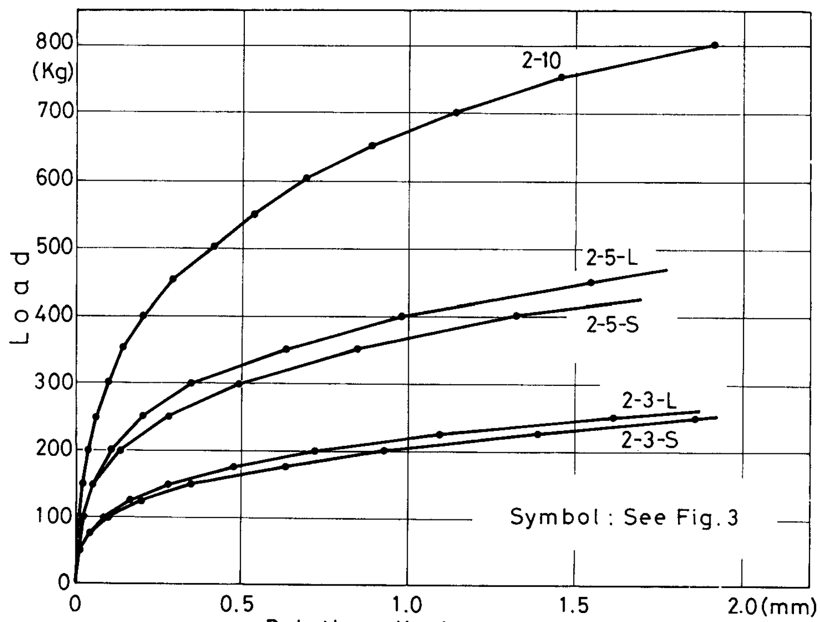

Fig. 5. Load-displacement curves of joints with two rows type plate connectors.

with increasing the total number of teeth of the plate connector.

Joints with L-type plate connector show higher stiffness than that with S-type of the same number of columns. This is because a long tooth has higher resistance against deformation of the joint than a short tooth, as well as in the bearing capacity.

Relations between load level (fraction of the individual ultimate load) and relative displacement of the joints are shown in Fig. 6. Though there is a little difference among joints with different types of plate connector, those curves can be approximately expressed into a representative curve, which would be useful to predict the ultimate load from deformation of the joint.

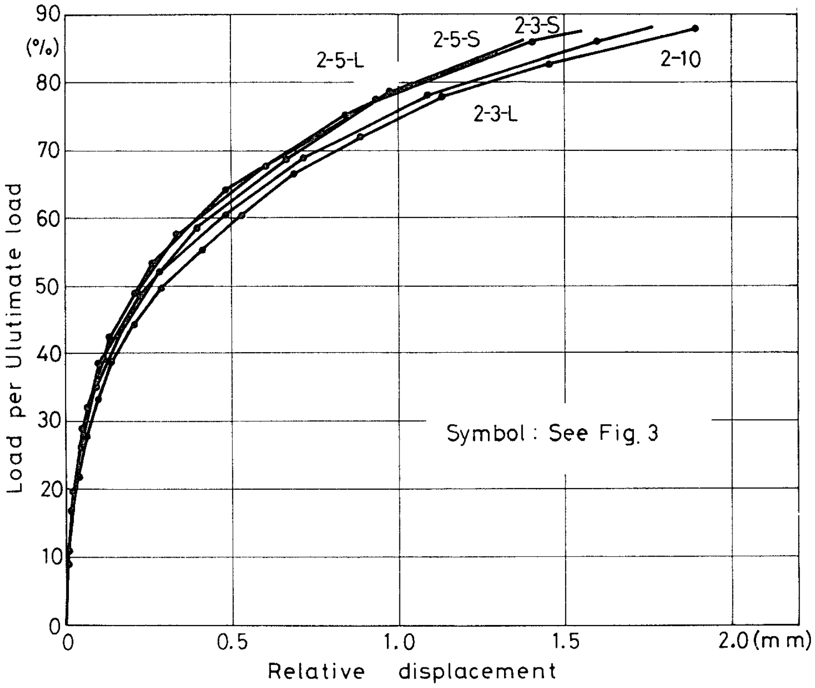

Fig. 6. Relation between fraction of individual ultimate load (load/ultimate load) and relative displacement of joints with two rows type plate connectors.

2-2 Case of 4 rows

2-2-1 Relation between ultimate load and specific gravity of wood

Relation between ultimate load and specific gravity of wood in case of joints with 4 rows type plate connector is shown in Fig. 7, and coefficients of linear regression on those data and the correlation coefficients are summarized in Table 4. As similar to the case of 2 rows type plate connectors, a linear relationship between ultimate load and specific gravity of wood was observed and the ultimate load of joints with L-type plate was higher than that with S-type plate at the same level of specific gravity, and failure mode of all this type (four rows) of joints was also withdrawal of the teeth. In this figure, the ultimate loads increase with increasing column number of teeth.

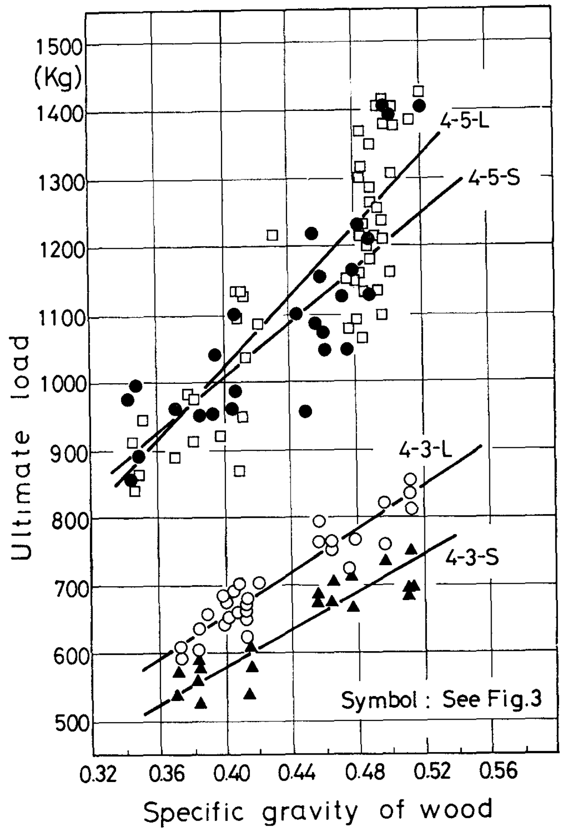

Fig. 7. Ultimate load of joints with four rows type of connectors as a function of specific gravity of wood.

Table 4. Coefficients of linear regression line and correlation coefficients between ultimate load of joints and specific gravity of wood. (In case of four rows type of plate connectors)
(Ultimate load) $=$ A $\times$ (Specific gravity of wood) $+$ B

Type	A (kg)	B (kg)	Correlation coefficient
4-3-S	1360	37.6	0.904
4-3-L	1588	20.4	0.918
4-5-S	2081	176	0.813
4-5-L	2584	13.9	0.856

A little differences are, however, observed in these when the ultimate load per tooth is used in place of the ultimate load.

Ultimate load per tooth is taken here too in place of the ultimate load shown in Fig. 7. Coefficients of linear regression and correlation coefficients between ultimate load per tooth and specific gravity of wood are shown in Table 5, and the regression lines are shown in Fig. 8.

With referring Fig. 4, it is observed that ultimate load per tooth of joints with 4 rows type plates is higher than that with 2 rows type plates at the same number of column, for instance 2-5-L type and 4-5-L type, and the same level of specific gravity of wood. This is because a group of teeth at the nearest row from the mated ends of wood blocks is not necessarily effective for strength of the joint, so the ultimate load of joints with 2 rows type plate is mostly affected by this.

In Table 5, the average coefficient "a" is 120. This means that ultimate load per tooth increase by approximately 12.0 kg with increasing specific gravity by 0.1. This value is very close to 12.3 kg obtained by joints with 2 rows type plate connector.

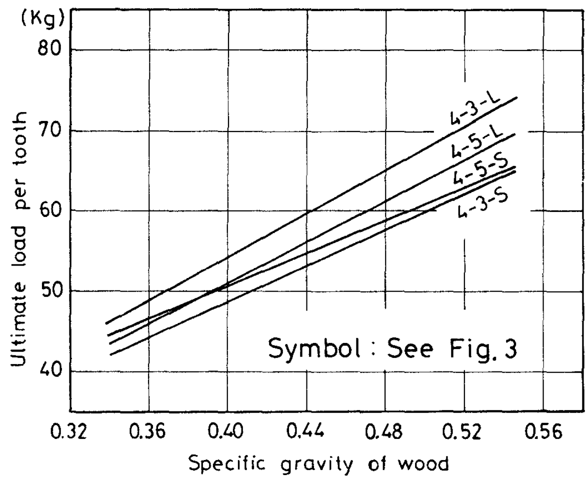

Fig. 8. Ultimate load per tooth as a function of specific gravity of wood. (In case of four rows type plate connectors)

Table 5. Coefficients of linear regression line between ultimate load per tooth and specific gravity of wood. (In case of four rows type of plate connectors) (Ultimate load per tooth) $=$ a $\times$ (Specific gravity of wood) $+$ b

Type	a (kg)	b (kg)
4-3-S	113	3.14
4-3-L	132	1.70
4-5-S	104	8.79
4-5-L	129	6.96

2-2-2 Relative displacement

Figure 9 shows three typical load-displacement curves of 4-5-L type specimens of specific gravity of wood 0.349, 0.480 and 0.520. Relative deformation of the specimen of lower specific gravity was larger than that of higher specific gravity at the same load. This means the resistant capacity of wood against deformation forced on the joint depends on specific gravity as well as in the bearing capacity.

Figure 10 is a similar expression to Fig. 6 of the relation between load level (fraction of the individual ultimate load) and relative displacement of 4-5-L type specimen of specific gravity of wood 0.349, 0.480 and 0.520.

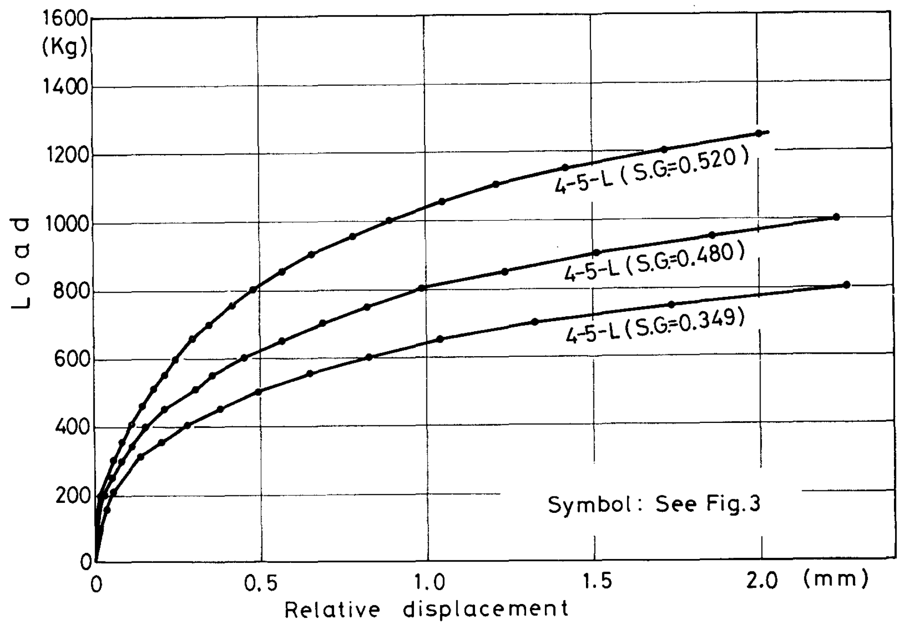

Fig. 9. Load-displacement curves of joints with four rows type plate connectors.

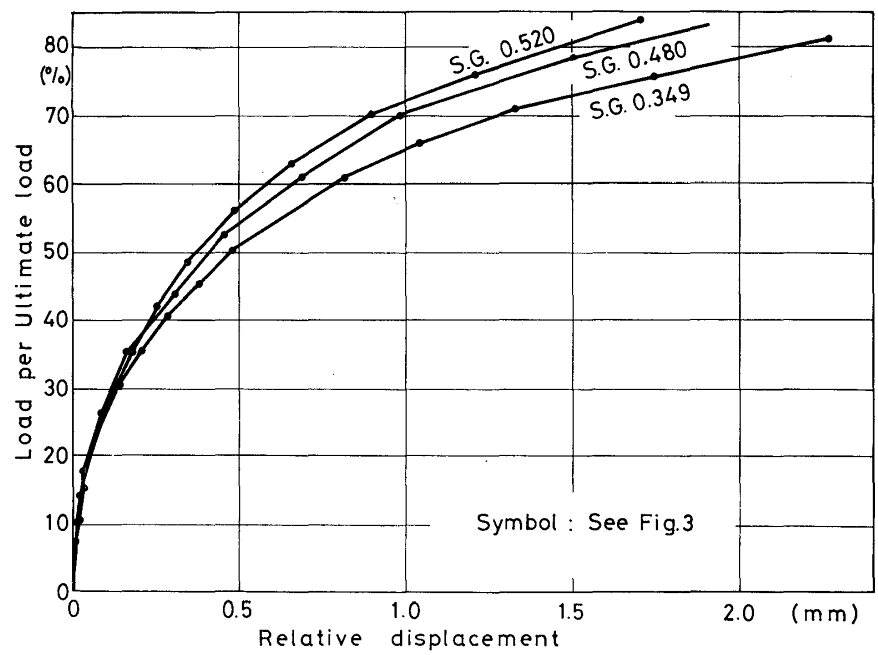

Fig. 10. Relation between fraction of individual ultimate load (load/ultimate load) and relative displacement of joints with four rows type plate connectors.

In comparison of this with Fig. 6, larger deformation are observed on 4 rows type than 2 rows type plates at the same load level. The part of the plate near the mated ends of wood blocks was stretched more than other parts and stress in the particular part of the 4 rows type plate was nearly twice as much as that of 2 rows type at a same load level, thus the larger deformation of the part in 4 rows type plates produced eventually the larger relative displacement of the joints with 4 rows type plates than that with 2 rows type plate.

2-2-3 Relation between ultimate load and number of teeth rows[6].

Fig. 11 shows the relation between ultimate load of joints and number of teeth rows of the plate connectors. From this figure, it is thought that ultimate load of joints is proportional to number of the teeth rows within this range of row numbers where all of the teeth are pulled out of wood blocks at the ultimate load. It is concluded that load is almost evenly distributed onto all teeth of the plate within this range of row number.

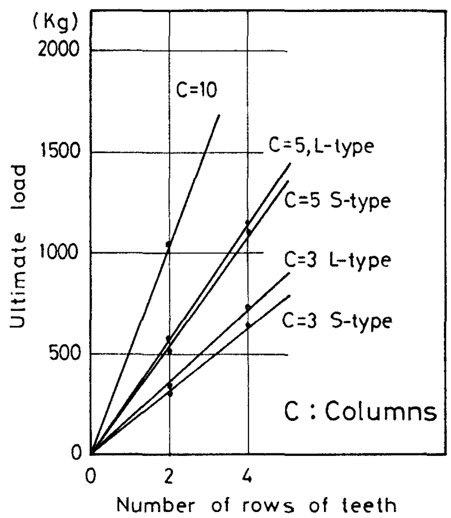

Fig. 11. Relation between ultimate load and number of rows of teeth of plate connectors. (Specific gravity of wood=0.40)

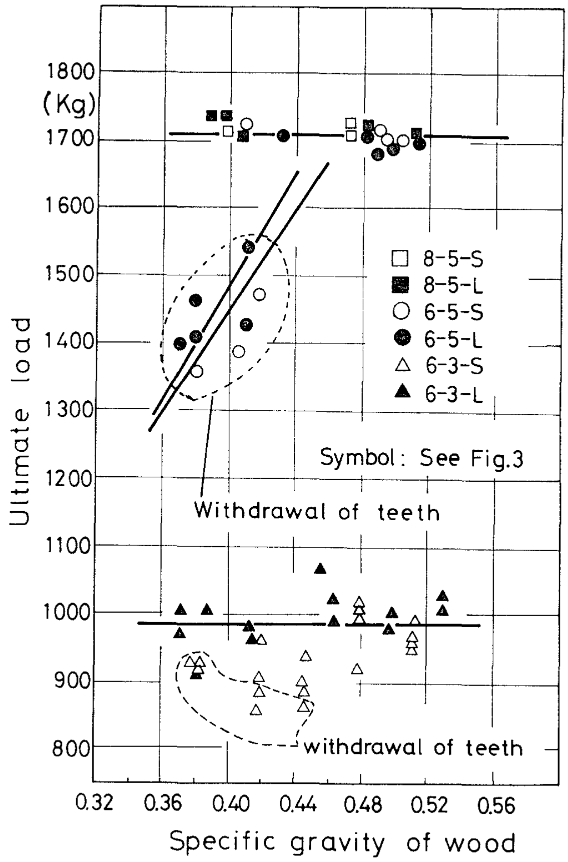

Fig. 12. Ultimate load of joints with six and eight rows types plate connectors as a function of specific gravity of wood.

2-3 Case of 6 rows and 8 rows type plate connectors

2-3-1 Relation between ultimate load and specific gravity of wood

Fig. 12 shows the relations between ultimate load and specific gravity of wood of 6 rows and 8 rows type of plate connectors. As mentioned in the last paragraph, the most feature of these types of joints is that the ultimate load as a function of specific gravity of wood has a plateau and is independent of specific gravity in the region, where the joints broke through tearing-off at the middle part of the plate.

The joint with 6 rows type plate failed in tension at the middle part of the plate when high density wood blocks were used while it failed sometimes through withdrawal of the teeth when wood blocks with lower specific gravity were used. All of joints with the plate of more than 6 rows failed in tension at the middle of the plate. As far as joints fail in tension, there is little difference between ultimate loads of S-type and L-type specimens.

As for 6–10 type specimen, though the test data are not plotted in Fig. 11, the average ultimate load of 10 specimens was 2890 kg and their failure mode was the tearing-off at the middle of the plate.

In case of 6 and 8 rows type plate connectors, it is very interesting that the ultimate loads per column were almost constant if the joints failed in tension at the middle part of the plate: for instance ultimate loads per column of joints with 3, 5 and 10 teeth columns type were 328, 342, and 298 kg, respectively, and the average was 323 kg.

2-3-2 Relative displacement

Fig. 13 shows the load-displacement curves of 6-5-L type specimen of specific gravity of wood 0.397 and 0.498, and 8-5-L type specimen of specific gravity of wood 0.379 and 0.413. Except for the specimen of specific gravity of wood 0.379, the failure mode of the joints was tearing-off of plate.

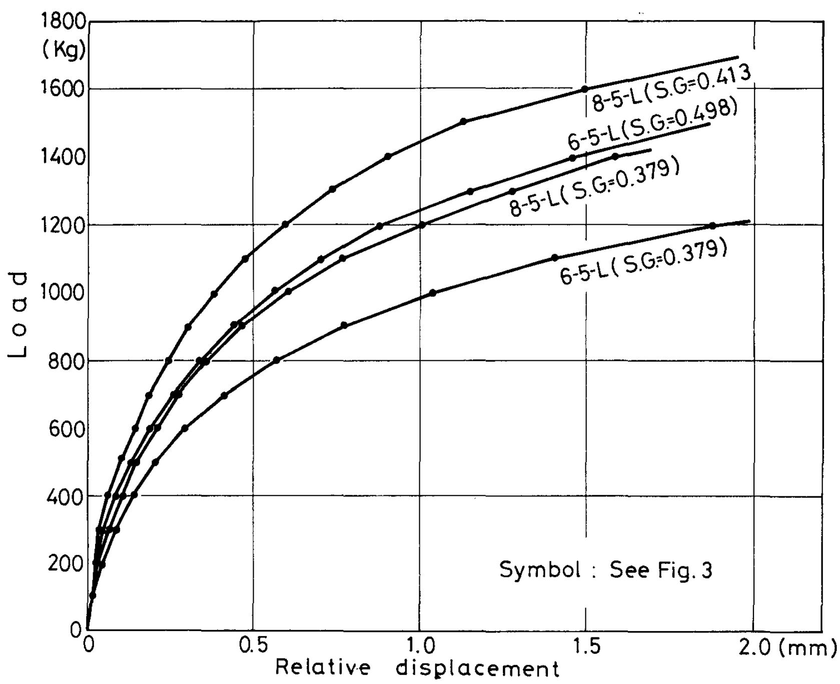

Fig. 13. Load-displacement curves of joints with six and eight rows type plate connectors.

Specimen of lower specific gravity of wood shows lower stiffness of joint.

Though the ultimate load of 8 rows type joint is almost the same as that of 6 rows type joint as far as the joints in tension, the stiffness is different: the former is higher than the latter.

2-3-3 Allowable load[7)]

The allowable load of joint specified in AS is the lower of either one-third of the ultimate load or ten-sixteenths of the load corresponding to 0.762 mm (0.03 inch) relative displacement of the joints.

In this experiment, the former was always smaller than the latter, thus the allowable load was evaluated as one-third of ultimate load.

3. Predicting Ultimate Load and Designing Plate of Joints

From the above results, relations between the ultimate load of joints and geometry of the plate connectors are generalized as Fig. 14.

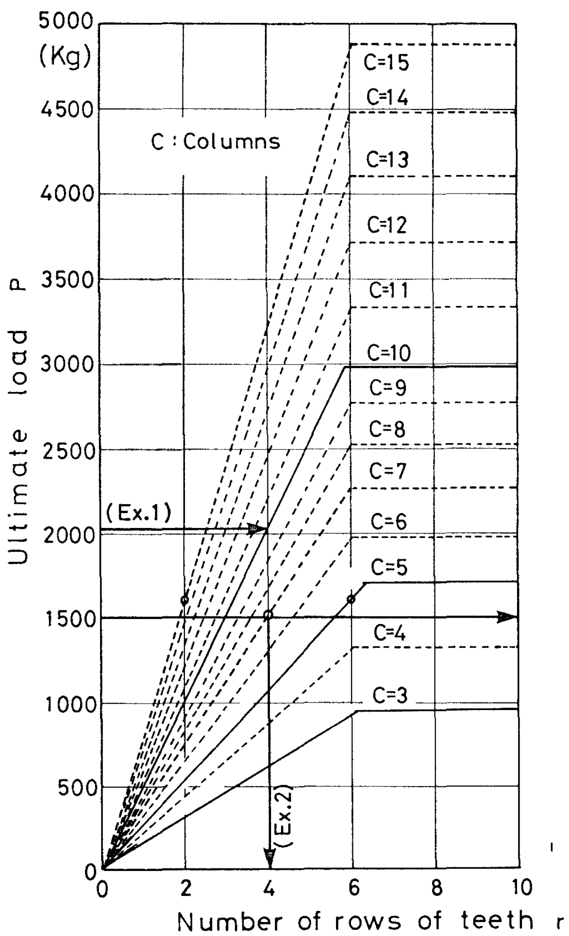

Fig. 14. Ultimate load of joints as a function of number of rows of teeth of plate connectors with a parameter of number of columns of teeth.

This is an example for the joints of specific gravity of wood 0.40. The solid lines are determined from the above experimental data, while the broken lines are determined from the ultimate load per column obtained in paragraph 2-2.

Ultimate load of the joints can be predicted easily from this figure, for example, the ultimate load expected on a 4–10 type specimen is derived from the intersectional point of lines $r=4$ and $c=10$ as shown by the example line (Ex. 1) on the figure. The expected ultimate load is about 2020 kg and the failure mode of the specimen is the withdrawal of teeth of the plate connector.

Designing most rational geometry of the plate for a required load is another useful application of the figure. The following is a proposal to the procedure (Ex.2): Take 500 kg as an example of the requirement (allowable load). First of all, multiply it by three and 1500 kg is the required load on the ordinate of this figure. As the number of rows of the teeth has to be even, lines $r=2$, 4 and 6 is used. Find the intersectional points of "r" lines and "c" lines (inclined) which are over and closest to the required level of load (1500 kg). These points are shown in the figure with small circles. Among these points, the intersection of $c=7$ and $r=4$ is the closest to the 1500 kg level, therefore, 4 rows and 7 columns type plate is the most economic (of the smallest number of teeth required) choice for the joint.

4. Conclusion

(1) Two types of failure mode of the joints were observed. One is withdrawal of all teeth of the plate, which was observed in the joints with plate connectors of small number of the tooth row. The other is tearing-off at the middle part of the plate, which was observed in the joints with plate connectors of large number of the tooth row. These failure mode depended on plate geometry, and the transition was found in case of 6 rows type of the plate.

(2) As far as joints failed in withdrawal of the teeth, a linear relationship between ultimate load of joint and specific gravity of wood existed, and strength per tooth increased by about 12.5 kg with increasing specific gravity by 0.1.

(3) In the case when joints failed in tension at the middle part of the plate, ultimate load of joint did not depend on specific gravity of wood but on the tensile strength of the plate, and strength per tooth decreased as number of the tooth rows of the plate increased.

(4) In accordance with AS, allowable load of all joints tested in this study was evaluated as one-third of the ultimate load.

(5) When load level (fraction of individual ultimate load) is used in place of load, relationships between load and relative displacement of all joints made with two or four rows type plate connectors are expressed in one representative curve.

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