COMPARISON OF EVALUATION RESULTS OF NAILED JOINTS IN SHEAR PROPERTIES OBTAINED FROM TWO METHODS

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Abstract. Shear properties of nailed joints must be evaluated to understand the mechanical property of structural elements using nailed joints. Numerous studies regarding this evaluation exist. However, the testing methods differ among the studies. Thus, clarification of the difference in the evaluated results of the testing methods becomes important. Therefore, this study aims to clarify this difference by conducting shear tests on nailed-joint specimens. This study adopts two methods, which are described in ASTM and Japanese Agricultural Standard, respectively. The evaluated results of the tests are compared. The comparison clarifies that there is no difference in the average values of the characteristics. Meanwhile, a difference is observed in the variance. In addition, this study discusses the reasons for this difference. The author posits a hypothesis that the difference in variance is due to the difference in the number of nails in the joint specimens and presents the validity of this hypothesis with an analysis using the Monte Carlo method.

Keywords: Nailed joint, shear property, evaluating method, Monte Carlo method.

INTRODUCTION

In wooden constructions, nails are widely used to join wooden sheet materials and wooden members. Numerous types of structural elements contain nailed joints. It is well known that the shear property of nailed joints plays an important role in the mechanical properties of these elements. Panel-sheathed bearing walls are considered as representative examples of elements using nailed joints. Tuomi and McCutcheon (1978) blazed the trail in terms of theoretical analysis of the mechanical properties of walls; they derived an estimation method for the maximum load of plywood-sheathed bearing walls in in-plane shear loading. Following this research, many researchers attempted to theoretically estimate the mechanical behavior of walls joined with nails (Kamiya 1981; Easley et al 1982; McCutcheon 1985; Ogawa et al 2015). These mechanical behaviors of walls were estimated using the evaluated results obtained from shear tests of joint specimens. Therefore, the evaluation of joint specimens has become an important issue.

Numerous studies on evaluating the shear properties of nailed joints have been conducted and the collection of data are in process (Foschi and Bonac 1977; Gromala 1985; Pellicane 1993; Ogawa 2018; Ogawa et al 2018). Most of these studies conducted the mechanical tests with standardized methods. However, a few standardized methods exist. For example, the methods described in ASTM (2017) and Japanese Agricultural Standard (JAS) (2013) differ with regard to the number of nails used in the joint specimens (further detail provided later). Some previous studies were conducted according to ASTM (Scholten 1965; Gromala 1985; Sekino and Morisaki 1987; Hirai et al 1991; Toda et al 2013) and others according to JAS (Mii et al 2004; Ogawa et al 2016; Toda et al 2016; Fukuta et al 2017; Ogawa et al 2018). In addition, the method about shear test is also described in the

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European Norm (EN). According to the EN 1380: 2009 (European Committee for Standardization 2009), the joint specimen is made by connecting a middle member and two side members with eight nails (it is twice of JAS in the number of nails used). The method was adopted by researchers (Kevarinmäki 2005; Sosa Zitto et al 2014). This is problematic. It is difficult to compare the properties obtained from different studies if different testing methods were used. Clarification of the difference in the evaluated results of the testing methods is meaningful to enable effective use of the existing data.

This study aims to clarify this difference by conducting shear tests with nailed-joint specimens. The author adopts the two methods described in ASTM and JAS and the evaluated results of the tests are compared. In addition, the author adds a simulating discussion to explain why this difference occurs. Although this study adopted only the methods of ASTM and JAS, it is important to conduct the test with the method of EN in near future and include its result into the comparison.

MATERIALS AND METHODS

Material Preparation

A base material, side panel, nail, and Teflon sheet were prepared to make the joint specimens described in ASTM and JAS. A solid wood made of Japanese cedar (*Cryptomeria japonica* D. Don) harvested in Ibaraki prefecture, Japan, was used as the base material. As is generally known, the shear property of nailed joints is strongly affected by the density of the materials. To remove the effect of density, the author gathered a lot of Japanese cedar pieces and sorted to become to reduce the density variance. The density of the base material is listed in Table 1. Because the difference in average and standard deviation is sufficiently small, the effect of density was ignored. Structural plywood classified as Class 2 structural plywood in accordance with JAS (2014) was used as the side panel. The plywood was made in Japan, with five plies and a thickness of 12 mm. The density and MC of the plywood are also listed in Table 1. The solid wood and plywood were placed in a conditioned testing room at a temperature of 20°C and 65% RH for more than 1 mo before testing. CN50 nails (Japanese Industrial Standard 2009) with a trunk diameter of 2.87 mm and a length of 50.8 mm were used to join the base material and side panel. A Teflon sheet (Daikin Industries Ltd., Japan, NR0538-03) with a thickness of 0.1 mm was used to reduce the effect of friction in the test results.

Table 1. Density and MC of the materials.

		Base material		Side panel	
Series		ρ^a (kg/m^3)	MC^b (%)	ρ^a (kg/m^3)	MC^b (%)
ASTM	Average	397.2	10.7	444.4	9.7
	SD^c	8.2	0.6	19.0	0.9
	CoV^d (%)	2.1	5.6	4.3	8.8
JAS	Average	394.3	10.1	433.9	9.3
	SD	14.0	0.5	11.6	0.2
	CoV (%)	3.6	5.3	2.7	2.6

[a] Density.
[b] Moisture contents.
[c] Standard deviation.
[d] Coefficient of variation.

Joint Specimen and Testing Method

This section describes the joint specimens and testing methods according to ASTM, and then JAS.

The joint specimen was made according to the description in ASTM D1037-12 (2017), as shown in Fig 1. The sizes of the base material and side panel were 51 × 51 × 300 mm and 12 × 51 × 300 mm, respectively. The two members overlapped 100 mm in the longitudinal direction, and one nail was used for joining. A Teflon sheet was installed between the base material and side panel. The number of joint specimens was 17.

The joint specimen was tested with an Instron-type tension–compression testing machine (Minebea Mitsumi, Inc. [formerly Shinko Co., Ltd.], Japan, TOM-5000X; capacity: 49.5 kN). The upper part of the base material and lower part of the side panel were fixed to the machine with 16-mm diameter bolts. The load was applied in the direction of the arrows in Fig 1. Then, an alignment support was adjusted to correct the load axis during testing.

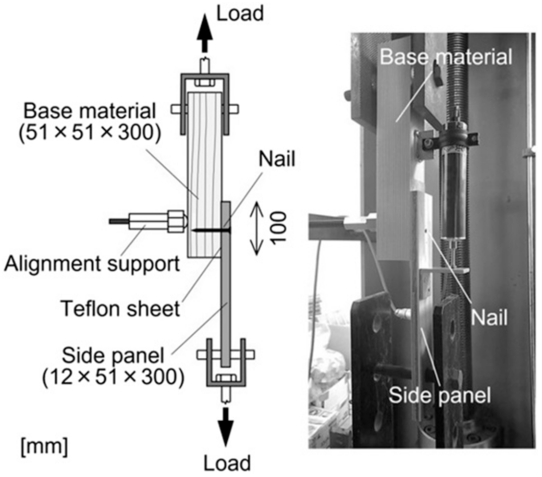

Figure 1. ASTM joint specimen and testing method.

The load was measured with a load cell (Minebea Mitsumi, Inc. [formerly Shinko Co., Ltd.], Japan, TT3-5T; capacity: 49.5 kN). A displacement transducer (Tokyo Measuring Instruments Laboratory Co. Ltd., Japan, CDP-50; capacity: 50 mm) and a target were attached to the base material and side panel, respectively, to measure the slip between the members. As shown in Fig 1, the load direction was parallel to the grain direction of the base material. The load was applied at a speed of 2.0 mm/min. After reaching a maximum, the load was applied continuously until it decreased to 80% of the maximum, or the slip reached 30 mm.

The second type of joint specimen was made according to the description in JAS (2013), as shown in Fig 2. The sizes of the base material and side panel were 38 × 89 × 300 mm and 12 × 100 × 300 mm, respectively. Two side panels were attached to the base material and four nails were used for joining. A Teflon sheet was installed between the base material and side panel, and the number of joint specimens was 17.

The same testing machine was used for testing. As shown in Fig 2, the joint specimen was set on a rigid plate and a vertical downward load was applied to the top of the base material. Two displacement transducers (Tokyo Measuring Instruments Laboratory Co. Ltd., Japan, CDP-50) were attached to the opposite sides of the base material, and the targets were attached to the side

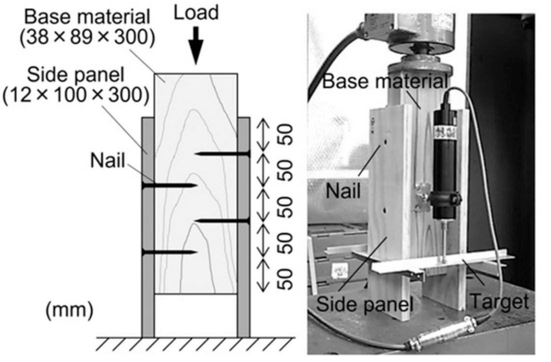

Figure 2. JAS joint specimen and testing method.

panels. The average of the values read from the two transducers was adopted as the slip. As shown in Fig 2, the load direction was parallel to the grain direction of the base material. As with the ASTM test, the load was applied at a speed of 2.0 mm/min. After reaching a maximum, the load was applied continuously until it decreased to 80% of the maximum or the slip reached 30 mm.

RESULT AND DISCUSSION

Experimental Results

Load–slip relationships of all specimens are presented in Fig 3. The result of ASTM is shown in Fig 3(a) and the result of JAS is in Fig 3(b). The solid lines represent the load–slip relationships. In the results of JAS, the load value of the vertical axis was obtained by dividing the value read from the load cell by the number of nails; therefore, it represents the load per nail.

In both series, the common behavioral features were observed. At the beginning of the loading, the load increased linearly with the increment of slip. When the load reached approximately 0.6-0.7 kN, the slope of the load–slip relationships decreased. After reaching a load of approximately 1.0 kN, the load remained almost constant. When the slip exceeded approximately 20 mm, the load decreased gradually in most of the load–slip relationships. In the large-slip range (20-30 mm), the nail head was embedded in the side panel, which is similar to the failure mode described in the previous article (Ogawa et al 2018).

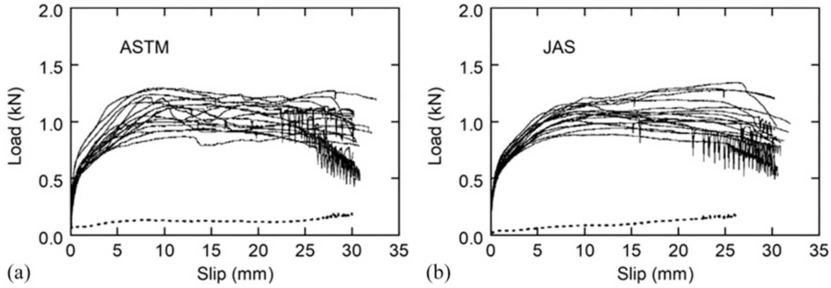

Figure 3. Load–slip relationships obtained from the two tests, where the dotted lines represent the standard deviation of the load values of the 17 specimens under the same slip.

A difference between the ASTM and JAS series was observed in the load variance value around the yield area. Figure 3 shows the standard deviation as dotted lines; this was obtained by calculating the standard deviation of the load values of the 17 specimens under the same slip condition. According to the dotted lines, ASTM exhibits a higher standard deviation than that of JAS until the slip reaches 18.2 mm.

The characteristic values were obtained from the load–slip relationships. In this study, the loads at specific slip were obtained according to ASTM D1037-12 (2017), which are the load at a slip of 0.25, 0.38, 1.27, 2.54, 5.08, and 7.62 mm. They are symboled as $P_{0.25}$, $P_{0.38}$, $P_{1.27}$, $P_{2.54}$, $P_{5.08}$, and $P_{7.62}$, respectively. In addition, the maximum load, P_{max}, was also obtained.

The characteristic values of each series are shown in Table 2. There is little difference between the average values of the ASTM and JAS series in each characteristic. However, there are differences in variance. Excepting P_{max}, the values of coefficient of variance in ASTM are much higher than those of JAS. Hereafter, the values are discussed with statistical testing.

At first, the normality of each data was investigated with the Shapiro–Wilk test. The results are shown in Table 2 as *p*-values. The *p*-values in ASTM are low and some are less than 0.05. Thus, it is difficult to decide they really have normality or not. In addition, according to Ikeda (2013a, 2013b), more than 30 specimens are required to judge the normality of samples. He also mentioned that if the number of specimens was insufficient, the tests should be conducted under two cases: when normality is recognized and when it is not. In this study, first, statistical tests were conducted with the assumption that the characteristic values had a normality. T-tests were conducted to investigate the difference in averages. The results showed that no significant difference was recognized in any characteristic values at a significance level of 0.05. In addition, F-tests were conducted to investigate the difference in variance. The results showed that there were significant differences in the characteristics

Table 2. Characteristic values of each series obtained by the experiments.

Series		$P_{0.25}$[kN]	$P_{0.38}$[kN]	$P_{1.27}$[kN]	$P_{2.54}$[kN]	$P_{5.08}$[kN]	$P_{7.62}$[kN]	P_{max}[kN]
ASTM	Average	0.37	0.44	0.63	0.75	0.94	1.05	1.12
	SD	0.07	0.07	0.07	0.09	0.12	0.13	0.12
	CoV (%)	18.06	16.40	11.76	11.66	12.96	12.83	11.11
	p-value[a]	0.107	0.086	0.004	0.028	0.184	0.452	0.180
JAS	Average	0.40	0.46	0.64	0.76	0.93	1.02	1.10
	SD	0.03	0.03	0.04	0.04	0.06	0.08	0.12
	CoV (%)	6.78	7.25	6.41	5.82	6.85	7.71	11.26
	p-value[a]	0.514	0.418	0.076	0.434	0.778	0.623	0.575

$P_{0.25}$, $P_{0.38}$, $P_{1.27}$, $P_{2.54}$, $P_{5.08}$, and $P_{7.62}$, load at slip 0.25, 0.38, 1.27, 2.54, 5.08, and 7.62 mm. P_{max}, maximum load.
[a] *p*-value obtained by the Shapiro–Wilk test.

relating with the load at specific slips ($P_{0.25}$, $P_{0.38}$, $P_{1.27}$, $P_{2.54}$, $P_{5.08}$, and $P_{7.62}$) at a significance level of 0.05. Second, statistical tests were conducted with the assumption that the characteristic values did not have a normality. A Wilcoxon rank sum test was conducted to investigate the difference in median value, and the results showed that there was significant difference only in $P_{0.25}$, and no significant difference is recognized in the other characteristics. The reason for recognition of significant difference in $P_{0.25}$ is not certain. One possible reason is due to the microstructure of wood around a nail. Because $P_{0.25}$ represents the initial behavior, it might be affected by the nailed position, eg on the latewood or earlywood, especially in the ASTM specimen. A Kolmogorov–Smirnov test was also conducted to investigate the difference in the distribution form. The characteristics of $P_{0.25}$ and $P_{0.38}$ showed a significant difference.

The statistical results are summarized in Table 3. It was revealed that there is no significant difference in the average of any characteristic values. Meanwhile, there are significant differences in the variance of $P_{0.25}$, $P_{0.38}$, $P_{1.27}$, $P_{2.54}$, $P_{5.08}$, and $P_{7.62}$. The author assumes that this difference is due to the difference in the number of nails used in the joint specimens. Although the nails are in the same wood piece, there is a slight difference in the resistance performance. The JAS specimen contains four nails, which may offset this difference.

Analytical Discussion for Validating the Assumption

In the previous section, the author assumed that the difference in variance of the characteristics relating with the load at specific slips ($P_{0.25}$, $P_{0.38}$, $P_{1.27}$, $P_{2.54}$, $P_{5.08}$, and $P_{7.62}$) occurred as a result of the difference in the number of nails in the joint specimens. Here, the author attempts to validate this assumption using the Monte Carlo method. This analysis attempts to simulate the variance of the JAS characteristics using the ASTM experimental results.

The analysis steps are as follows. 1) The experimental result of the cumulative frequency of P_δ according to ASTM was obtained as shown in Fig 4, where the suffix δ means the specific slips, which are substituted to the 0.25, 0.38, …, 7.62 mm. 2) A random number, R_i, with a closed section [0, 1] was generated. R_i was irradiated to the curve of cumulative frequency from the vertical axis, as shown by the dotted arrow in Fig 4, and the corresponding value on horizontal axis was obtained as pseudo data of P_δ according to ASTM ($P_{\delta-\mathrm{ASTM}-Ri}$). 3) In addition, three random numbers were generated and three additional pseudo data were obtained (a total of four pseudo data). The simulated value of P_δ according to JAS ($P_{\delta-\mathrm{Sim}}$) was calculated as their sum:

$$P_{\delta-\mathrm{Sim}} = \sum_{i=1}^{4} P_{\delta-\mathrm{ASTM}-Ri}. \qquad (1)$$

After calculation of $P_{\delta-\mathrm{Sim}}$, the value was divided by 4 because this study discussed with a load per nail throughout. 4) Repetition of these steps resulted in a large amount of $P_{\delta-\mathrm{Sim}}$ data, and the

Table 3. Comparison summary of ASTM and JAS statistical tests at a significance level of 0.05.

Test method	$P_{0.25}$	$P_{0.38}$	$P_{1.27}$	$P_{2.54}$	$P_{5.08}$	$P_{7.62}$	P_{max}
T-test	ns	ns	ns	ns	ns	ns	ns
F-test	a	a	a	a	a	a	ns
WRS test[b]	a	ns	ns	ns	ns	ns	ns
KS test[c]	a	a	ns	ns	ns	ns	ns

$P_{0.25}$, $P_{0.38}$, $P_{1.27}$, $P_{2.54}$, $P_{5.08}$, $P_{7.62}$, and P_{max}: refer Table 2.
[a] Significant difference was recognized; ns, significant difference was not recognized.
[b] Wilcoxon rank sum test.
[c] Kolmogorov–Smirnov test.

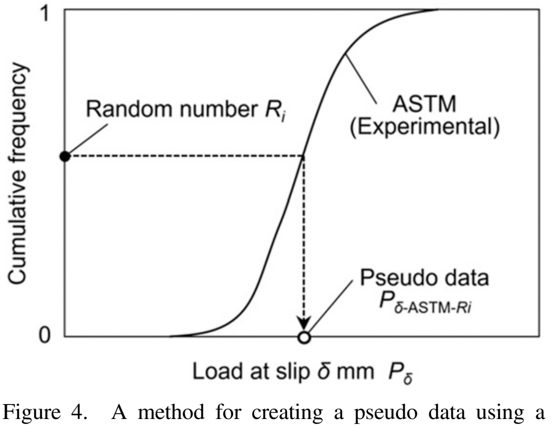

Figure 4. A method for creating a pseudo data using a random number R_i.

cumulative frequency was simulated. In this study 20,000 random numbers were generated and 5000 simulated values $P_{\delta-\mathrm{Sim}}$ were obtained. The RAND function in Excel (Microsoft Co., Redmond, WA, Ver. 16.0.10346.20002) was used to generate random numbers. The author confirmed that the simulated cumulative frequency remained almost constant despite the updating of the random numbers.

As an example, the simulated result of $P_{0.38}$ is shown in Fig 5. The solid line represents the simulated cumulative frequency. The black lines with round white and black round plots represent the ASTM and JAS experimental results, respectively. From the graph, it seems that the simulated result has a lower variance than the ASTM experimental result, and a similar variance to the JAS experimental result. The simulated values are summarized and the average value is 0.44, the standard deviation is 0.03, and the coefficient of variation is 7.63%. The standard deviation and coefficient of variation values are very similar to the JAS experimental results (0.03 and 7.25%, see Table 2). Therefore, it was revealed that the variance of $P_{0.38}$ observed in the JAS testing method could be simulated using the ASTM results. Figure 6 shows the coefficients of variation of other characteristics. In all the characteristics included in the figure, the simulated value is close to that of the JAS experimental values. This simulated result gives validity to the assumption that the difference in variance of the characteristics relating with the load at specific slip occurred because of the difference in the number of nails used in the joint specimens.

The validation is not adopted in $P_{\max}$. Because the slip at the maximum load is different between specimens, Eq 1 is unsuitable for adoption. If the mathematical validation is required about $P_{\max}$, another approach is required.

CONCLUSION

This study conducted shear tests using two methods to clarify the effect of the testing method on the evaluated results of the shear property of nailed joints. The testing methods described in ASTM and JAS were applied. The load-slip relationships were obtained and characteristics values ($P_{0.25}$, $P_{0.38}$, $P_{1.27}$, $P_{2.54}$, $P_{5.08}$, $P_{7.62}$, and $P_{\max}$) were calculated. Comparison of the two methods shows little difference in the average values of almost characteristics. However, there was a difference in the variance in the characteristics relating with the load at specific slip. The ASTM result showed higher coefficient of variation than that of JAS. The author assumed that this difference occurred because of the difference in the number of nails in the joint specimens. In addition, this study discussed the confirmation of the validity of this assumption. The Monte Carlo method was used to simulate the variance of the

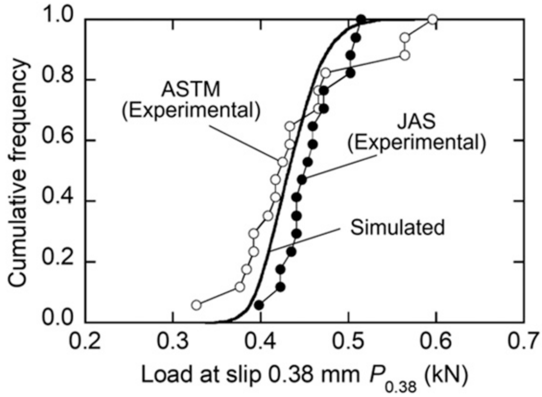

Figure 5. Cumulative frequency of experimental results (ASTM and JAS) and the simulated result in the load at slip 0.38 mm $P_{0.38}$.

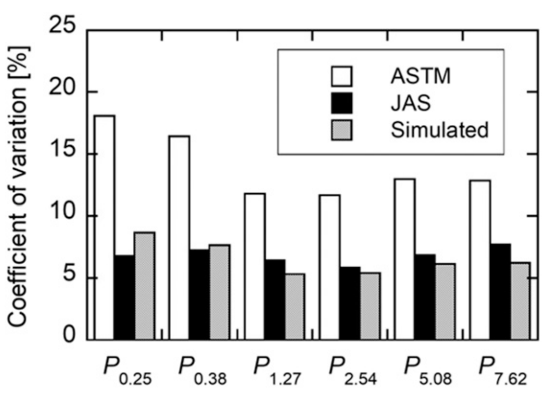

Figure 6. Coefficients of variation in experimental results (ASTM and JAS) and the simulated result.

characteristics observed in the JAS test using the result of the ASTM test. The simulated results showed good agreement with the experimental results, which indicates the validity of the assumption.

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