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ORIGINAL ARTICLE

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Rotational performance of traditional Nuki joints with gap I: theory and verification

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Abstract The Nuki joints in Taiwan and Japan are similar in appearance; however, due to lack of wedges used in Nuki joints in Taiwan, the gap between the column and beam increases the complexity of timber joints. In this article, the rotational performance of traditional timber joints is reported. A theoretical model considering Hook's law and Hankinson's formula was developed for predicting the rotational performance of Nuki joints with gaps. A total of 24 specimens was tested and used to verify the rotational performance of timber joints. The proposed model not only predicts the rotational stiffness of Nuki joints, but can also estimate the initial slip of these joints. Good agreement was found between predicted and experimental data.

Key words Rotational stiffness · Nuki joints · Timber mechanical model

Introduction

The mechanical performance of timber joints has attracted much attention in past decades. Many researchers have focused on the rotational performance of timber joints.[1–3] However, the mechanical performance of timber joints varies from place to place, depending on the handicraft of carpenters, tradition, and geographic and climatic conditions.

Parts of the traditional timber structures of Taiwan are similar to those found in Japan, both of which originated from China long ago. Among the traditional joints in both Taiwan and Japan, Nuki joints are frequently used to connect beam and column. In Japan, Nuki joints are usually used in traditional temples, and are commonly used in rural residential buildings. Much attention has been paid to the study of the structural behavior of these traditional timber joints in Japan.[4–6] One of the significant results was contributed by Inayamal;[7] who developed a model to predict the rotational stiffness of Nuki joints by considering the embedded force between column and beam. This model is frequently applied in Japan. The same timber joints can be found in Chuan-Dou timber frames in rural residential houses in Taiwan. However, unlike those in Japan, the Nuki joints in Taiwan are not fitted with wedges, which means that there is usually a gap between beam and column.

A recent trend in analyzing timber structures involves considering the timber connections as semirigid joints.[8,9] However, little research has focused on traditional timber structures in Taiwan to date. The first research on timber joints in Taiwan was conducted by King et al.,[10] in which one third scale specimens were used to study the rotational stiffness. Chang and Hsu[11] studied the hysteretic behavior of traditional timber joints in Taiwan. Because the rotational stiffness of timber joints needs to be known to properly analyze structures, there is an urgent need to study the mechanical behavior and propose a model for predicting the rotational stiffness of traditional timber joints. This study examined the rotational performance of traditional timber joints in Taiwan.

Field investigations

Because of a lack of background information on traditional timber connections in Taiwan, an extensive survey on a total of 84 historic buildings was carried out, in which 4 of these historic buildings were dismantled. The surveys on these 4 dismantled buildings helped us to clarify the types of timber connections that currently exist. The results of the field survey showed that timber joints used three different types of connection, designated as continuous connections, dovetail connections, and simple-contact connections, as illustrated in Fig. 1. The member-geometry results of the

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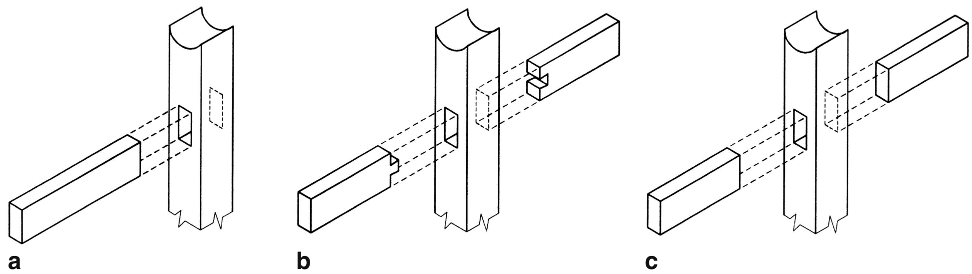


Fig. 1a–c. Three types of traditional timber joints. **a** Continuous connection; **b** dovetail connection; **c** simple contact connection

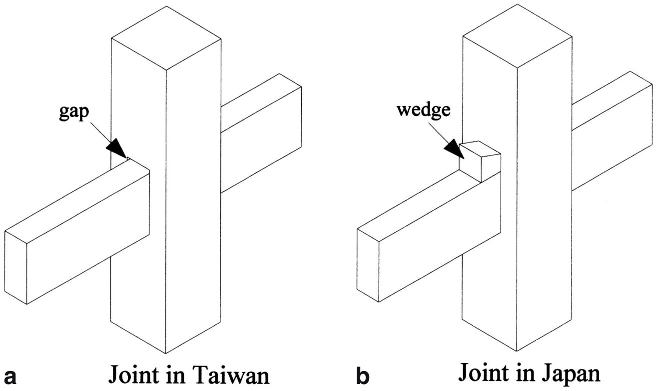


Fig. 2a,b. Comparison of timber joints in **a** Taiwan and **b** Japan

Table 1. Results of field investigation

Measurement	Mean	SD	L_{upper}	L_{lower}
Cw (cm)	14.80	2.05	18.17	11.43
Cd (cm)	15.00	2.00	18.29	11.71
Bw (cm)	7.50	0.95	9.07	5.93
Bd (cm)	14.80	1.90	17.94	11.66
Bw/Cd	0.52	0.07	0.66	0.38
Bd/(height of slot)	0.98	0.004	0.99	0.97
Gap (cm)	0.4	0.08	0.56	0.24

The geometries of the members are assumed to hold normal distribution

L_{upper}, upper limit of 90% of samples; L_{lower}, lower limit of 90% of samples; Cw, column width; Cd, column depth; Bw, beam width; Bd, beam depth

field investigation are shown in Table 1. In this article, only continuous connections are discussed.

It can be found that the continuous-type connections in Fig. 1 are similar to Nuki joints found in Japan; however, several differences can be found. The configuration of timber joints of Japan and Taiwan are illustrated in Fig. 2. It is noted that the Nuki joints in Taiwan are not equipped with a wedge, whereas wedges are usually used to stiffen the Nuki joints in Japan. Furthermore, unlike as found in Taiwan, the beams that cross the column are usually the continuous type in Japan.

The rotation of joints that have an initial gap is illustrated in Fig. 3. Figure 3a shows the initial stage, in which the beam rotates without moment-resisting capacity and acts as rigid body motion until the stage shown in Fig. 3b is reached. The moment resistance of the joint starts increasing when the beam contacts the two edges of the column as shown in Fig. 3b. In the following stage, in Fig. 3c, the compression length (lc) increases with increase of rotation, and results in increased friction between the contact surfaces of the Nuki beam and column. Thus, the presence of the gap increases the complexity of the rotational behavior of the joint.

Theory

To derive the theoretical model, several assumptions are made in this study:

1. The stress and strain distributions of the beam occur in linear and nonlinear stages as plotted in Fig. 4.
2. The rotation θ can be divided into two parts, including the initial rotation θ_0, which is induced by the gap between beam and column in the initial stage, and rotation θ' that occurs after the initial stage (see Fig. 3). Thus $\theta = \theta_0 + \theta'$.
3. The friction between the contact surfaces of beam and column can be neglected in the model.
4. The modulus of elasticity (MOE) of wood parallel to grain is 20 times the MOE perpendicular to grain.

Based upon the assumptions, Hook's law can be expressed as:

$$\sigma = E\varepsilon \tag{1}$$

For beam under rotation θ, the ε can be calculated as:

$$\varepsilon = \frac{lc\tan\theta}{Bd/\cos\theta} = \frac{lc}{Bd}\sin\theta \tag{2}$$

where lc represents the compression length and varies with rotation, and Bd represents depth of beam as shown in Table 1.

The compression length lc can be expressed in terms of column width Cw:

$$lc = Cw \cdot \alpha(\theta) \tag{3}$$

For sugi that is frequently used in Taiwan, assume that $E(\sigma)$ can be expressed in accordance with Hankinson's formula:[12]

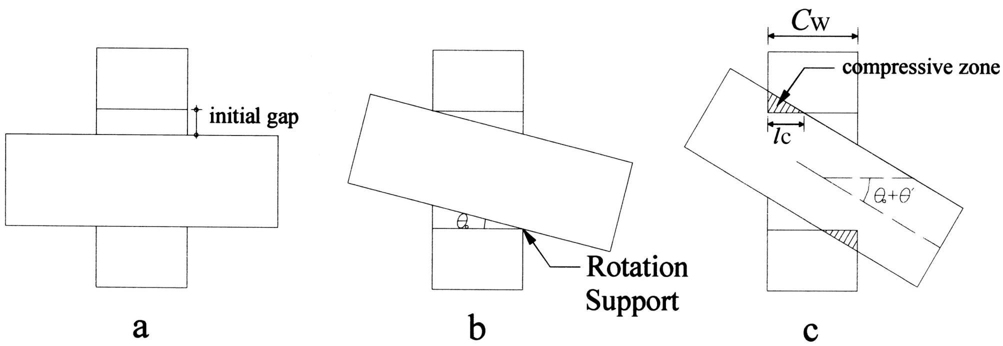


Fig. 3. Rotational behavior of timber joints with initial gap

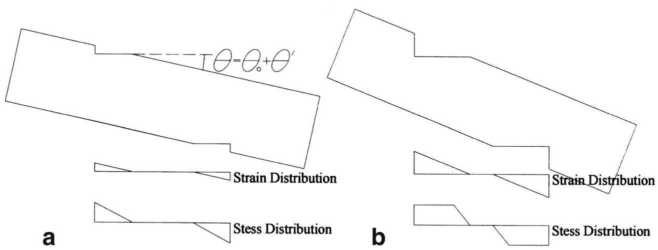


Fig. 4a,b. Stress and strain distributions under **a** linear and **b** nonlinear stages

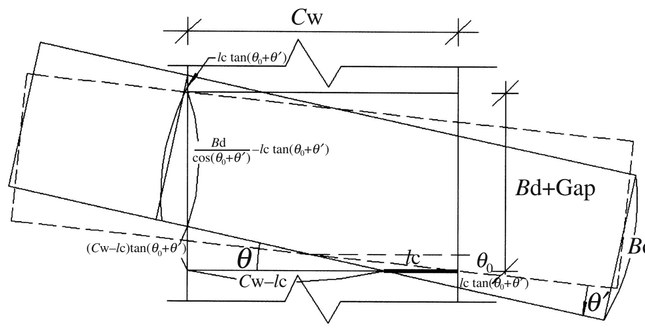


Fig. 5. Geometry of beam under rotation θ

$$E(\theta)=\frac{E_{\perp}\cdot E_{//}}{E_{//}\cos^{3.1}\theta+E_{\perp}\sin^{3.1}\theta} \tag{4}$$

In assuming the MOE parallel to grain of wood is 20 times the MOE perpendicular to grain, Eq. 4 can be modified as:

$$E(\theta)=E_{\perp}\cdot\left(\frac{20}{20\cos^{3.1}\theta+\sin^{3.1}\theta}\right)=E_{\perp}\cdot\beta(\theta) \tag{5}$$

Thus, Hook's law can be modified as:

$$\sigma=\frac{E_{\perp}\cdot Cw}{Bd}\cdot\alpha(\theta)\cdot\beta(\theta)\sin\theta \tag{6}$$

The resultant force induced by the compression in the linear stage can be expressed as:

$$f=\frac{1}{2}lc\cdot B\mathrm{w}\cdot\sigma=\frac{C\mathrm{w}^2\cdot B\mathrm{w}\cdot E_{\perp}}{2\cdot B\mathrm{d}}\cdot\alpha^2(\theta)\cdot\beta(\theta)\cdot\sin\theta \tag{7}$$

The resultant moment can be written in the form of:

$$M=\left(C\mathrm{w}-\frac{2}{3}lc\right)\cdot f(\theta) \tag{8}$$

$$=\frac{3-2\alpha(\theta)}{6}\cdot\frac{C\mathrm{w}^3\cdot B\mathrm{w}\cdot E_{\perp}}{B\mathrm{d}}\cdot\alpha^2(\theta)\cdot\beta(\theta)\cdot\sin\theta \tag{9}$$

According to Fig. 5, $\alpha(\theta)$ can be calculated by:

$$\frac{B\mathrm{d}}{\cos(\theta_0+\theta')}-lc\tan(\theta_0+\theta')+(C\mathrm{w}-lc)\tan(\theta_0+\theta')=B\mathrm{d}+\mathrm{Gap} \tag{10}$$

$$\therefore\ \alpha(\theta)=\frac{lc}{C\mathrm{w}}=\frac{1}{2}+\frac{B\mathrm{d}}{2C\mathrm{w}\sin(\theta_0+\theta')}-\frac{B\mathrm{d}+\mathrm{Gap}}{2C\mathrm{w}\tan(\theta_0+\theta')} \tag{11}$$

Based upon the theoretical analysis, the moment–rotation relation of timber joints can be modified as:

$$M(\theta)=\frac{C\mathrm{w}^3\cdot B\mathrm{w}\cdot E_{\perp}}{B\mathrm{d}}\cdot\gamma(\theta),\quad\text{and} \tag{12}$$

$$\gamma(\theta)=\frac{3-2\alpha(\theta)}{6}\cdot\alpha^2(\theta)\cdot\beta(\theta)\cdot\sin\theta \tag{13}$$

Materials and methods

To study the rotational performance of Taiwan Nuki joints, a total of 24 full-scale specimens were tested. A field survey on a total of 87 historic buildings indicated that 90% of the timber joints had a column width (Cw) and a column depth (Cd) within the range of 15–18 cm, and a beam depth (Bd) and beam width (Bw) within the ranges of 12–18 cm and 6–9 cm, respectively. The dimensions of the actual timber joints were taken into consideration in the planning of experiments as illustrated in Table 1. The experimental instrumentation is illustrated in Fig. 6. The full-scale specimens were fabricated from Chinese fir (*Cunninghamia lanceolata*). The moisture content of the wood specimens was controlled in the range of 18%–19%, and the specimens were stored in the laboratory with good natural ventilation for about 1 month. Monotonic loads were applied by dis-

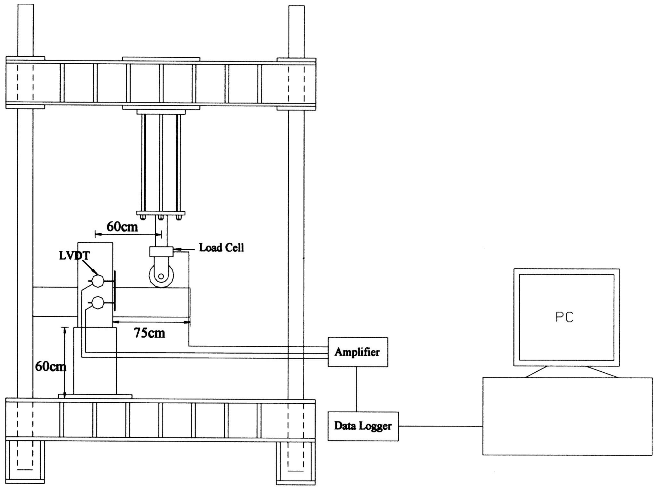


Fig. 6. Experimental setup

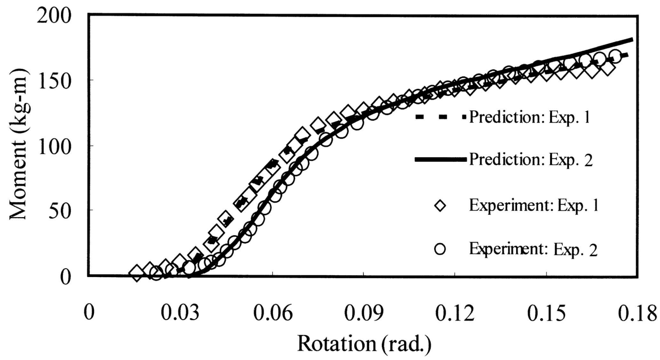


Fig. 7. The predicted and experimental moment–rotation relations

placement control at a speed of 0.75 cm/min at the loading point, which is equal to a rotation speed of about 0.0125 rad/min. The experiments were terminated when the maximum stroke of the hydraulic jack or the maximum rotation of 0.16 rad was reached.

Results and discussions

Verification of theoretical model

From the theoretical model described by Eq. 12, the factors that effect the moment–rotation relation include *C*w, *B*d, *B*w, $E_\perp$, and the gap between beam and column. The column depth (*C*d) does not actually affect the rotational performance of the Nuki joints within the dimensions of 15–18 cm. Two of the moment–rotation relationships obtained from theoretical models and experiments are compared and plotted in Fig. 7. Good agreement can be found between experimental and predicted data, and thus the theoretical model and assumptions can be regarded as valid. It should be noted that because the gap was taken into consideration in the theoretical model, the initial slip of joint could be found in not only experimental data but also in the theoretical model.

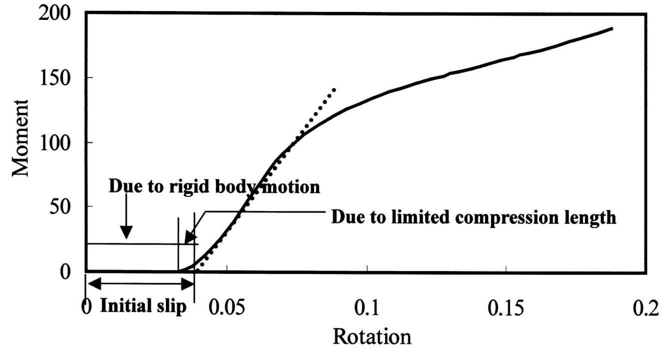


Fig. 8. Typical moment–rotation relationship of timber joints

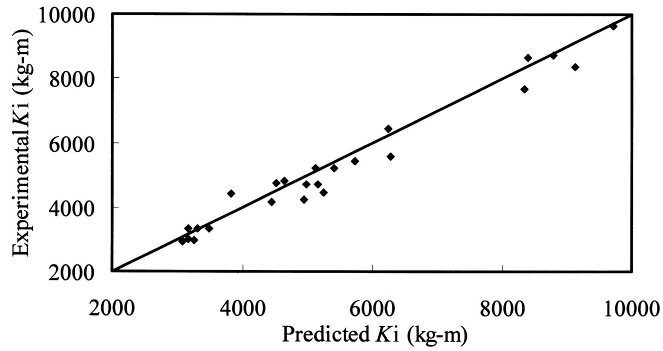


Fig. 9. Comparison of predicted versus experimental values of initial rotational stiffness K_i

The K_i in Fig. 8 represents the initial rotational stiffness of timber joints. The initial rotational stiffness represents the rotational stiffness after the initial slip. Figure 9 demonstrates the comparison of rotational stiffness of joints obtained from experiments with those obtained from prediction by the theoretical model proposed herein. Satisfactory agreement can be found between experimental data and the theoretical approach, the average error is 5.6%.

Initial slip of timber joints

A typical moment–rotation relation of traditional timber joints involves the initial slip due to the gap between beam and column. As illustrated in Fig. 8, the initial slip results from two parts, i.e., slip due to rigid body motion and slip due to limited compression length in the early stage. The structural behavior of timber joints in this stage means that the joints behave as a pin connection without any moment-resistance capacity, and usually can be regarded as hinges. The global behavior of timber joints should be that of a pin connection in the early stage and that of a semirigid connection after the early stage. Estimating the initial slip can help us to understand the range in which the joint behaves as a hinge; Fig. 10 illustrates the slip due to rigid body motion

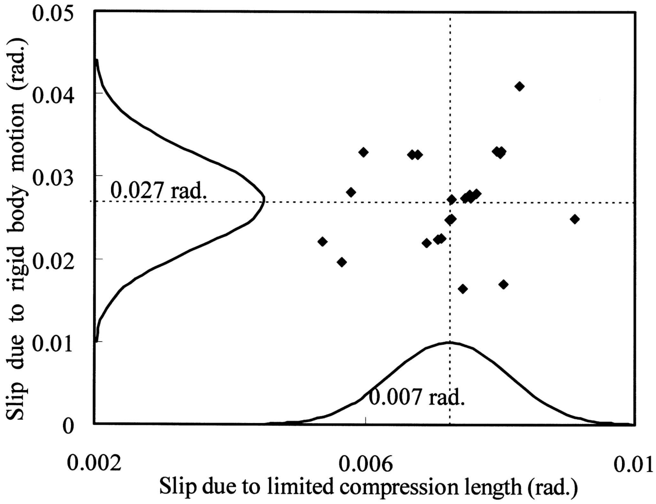
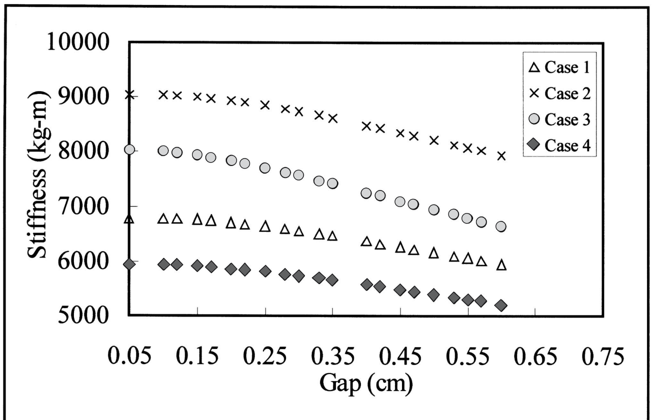


Fig. 10. Slips due to rigid body motion versus slips due to limited compression length



	C_W (cm)	B_W (cm)	B_d (cm)	$E_{\perp}$ (kg/cm^2)
Case 1	18	6	18	4000
Case 2	18	8	18	4000
Case 3	18	6	15	4000
Case 4	18	6	18	3500

Fig. 11. Effect of gap size on rotational stiffness

versus limited compression length in the timber joint. From Fig. 10, no significant relation could be found between the two types of slips; however, the averaged slip due to limited compression length was about 27% of that induced by rigid body motion. In the other words, the initial slip of joints can be estimated as 1.3 times the slip due to rigid body motion, i.e., initial slip = $1.3\sigma_0$ in Fig. 3.

The theoretical model proposed in this study can be used for parametrical study of rotational stiffness of timber joints. Figure 11 illustrates the relation of gap versus rotational stiffness in four conditions. It should be noted that the stiffness of joints does not degrade obviously until the gap reaches 0.15 cm in most of the cases. Thus, it is obvious that gaps between beam and column have a significant effect on the rotational stiffness of joints when the dimensions of the joints are in the range used in this study.

Conclusions

Gaps in Nuki joints increase the complexity of analysis, and change the rotational performance of the joints. A new theoretical model was developed to estimate the rotational stiffness of traditional Nuki joints with the gap, and the model corresponded well with experimental results. The theoretical model can demonstrate not only the initial stiffness of Nuki joints with gaps, but can also demonstrate the initial slip stage, which should be regarded as a pin connection in the early stage.

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