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ORIGINAL ARTICLE

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On mechanical behavior of traditional timber shear wall in Taiwan I: background and theory derivation

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Abstract The objectives of this study were to explore the mechanical behavior of traditional timber shear walls in Taiwan and to propose a theoretical model to predict their lateral force resistance. An extensive field investigation was conducted, and the dimensions, tectonic detail, and materials used were recorded. The data collected were used as the reference for theoretical derivation and experimental design. In the theoretical model, the moment resistance of entire shear walls was derived from the contributions of the moment-resisting capacity supplied not only by embedment and friction action between board units and beams but also the dowel action of bamboo nails. Timber shear walls with various geometric conditions and material properties are considered. The theoretical model demonstrated in this study can be used to predict the mechanical behavior of timber shear walls and will be verified by experiments in our next article.

Key words Timber shear wall · Lateral force resistance

Introduction

Timber shear walls are usually used not only as partitions but also to withstand lateral force, such as wind and seismic loads that are applied on the wood-framed structures. All over the world, various traditional, climatic, and territorial situations result in different wall systems even though the same materials are used. Further study is required into these various wall systems. Much research[1–3] has been conducted to study the mechanical performance of modern timber shear wall, such as oriented strand board (OSB) walls. For traditional timber shear walls in Japan, few research studies have been reported,[4,5] while other research[6–8] has focused on timber shear wall systems modified from the traditional wall system in Japan. The mechanical properties of traditional timber shear walls were then transferred into the wall ratios based upon the experimental results obtained from previous research.

Unlike in Japan, research on the mechanical properties of traditional timber shear wall in Taiwan is still lacking. Recently an urgent need to understand the mechanical behavior of structural components, such as joints and walls, in timber structures has been driven by the increasing trend of renovation and rehabilitation of historic timber structures in Taiwan. The importance of understanding these kinds of structural elements has been known for some time; however, the structural performance of the traditional timber shear walls used in Taiwan has not been explored to date. Thus, it is important to establish a method to predict the behavior of these traditional timber shear walls for safety evaluation in the future. This article represents part of a series of studies in which the objective was to obtain knowledge on mechanical performance and to propose a method for estimation of the mechanical properties for this type of timber shear wall.

Preliminary investigation

Due to a lack of background information on tectonic, geometric, and material data for traditional timber shear walls that exist in Taiwan, an extensive territorial survey was conducted. The objective of this investigation was to establish a reliable database for these timber shear walls of interest. Over 40 traditional residential houses with this type of timber shear wall were investigated in southern Taiwan. The data collected are used for theoretical model deviation and experimental design in this series of articles and are given in our previous report.[9]

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The results of the preliminary investigation showed that the two major materials used for shear walls in traditional wooden houses in Taiwan are mud and wood. Timber shear walls are usually used in the lower level of the timber frame. As shown in Fig. 1, the results of our field investigation show that 79% of walls are made of wood at level C; the proportion of wood drops to 54% at level B, and only 9% of partition walls are made of wood at level A.

Traditional timber shear walls are usually composed of several board units because it is difficult to find suitable boards with sufficient width for the whole shear wall. Carpenters make grooves in the top and bottom beams of timber shear walls and align the board units. To prevent out-of-plane bulking, stepped mechanisms are made at the connections of board units; bamboo nails are used to connect the board units and resist the in-plane relative displacement between boards, as shown in Fig. 2.

The preliminary investigation showed that most of the timber shear walls are made from Chinese cedar (*Cunninghamia lanceolata*), with only a few of them made by Taiwan hinoki (*Chamaecyparis formosensis* Mats.). The average height and width of the board units are, respectively, 800 and 150 mm with standard deviations of 99 and 49 mm. The mean thickness of the panel unit is 19 mm with a standard deviation of 4 mm. Most of the bamboo nails used are approximately 4×4 mm in cross section and 75 mm in length. The results of the field survey and interviews with carpenters showed that for board units higher than 800 mm, three bamboo nails are usually applied; by contrast, only two bamboo nails are used for board units shorter than 800 mm.

Timber shear wall systems are commonly used throughout Asia, and can be found in Japan, Taiwan, and China. However, significant differences can be found within timber shear wall systems in Japan and Taiwan. One of the significant differences between these two systems is that the board units are aligned vertically in Taiwan rather than horizontally as used in Japan. Another significant difference is that instead of using strong dowel, the timber shear wall systems in Taiwan use only small-sectioned bamboo nails. Furthermore, the timber shear wall systems used in Taiwan are much smaller than those used in Japan. These significant differences results in different structural behavior of timber shear walls in Taiwan and Japan when subjected to lateral force.

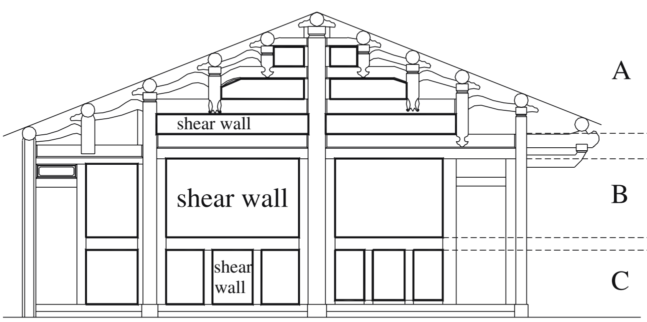

Fig. 1. Section of a traditional timber frame in Taiwan

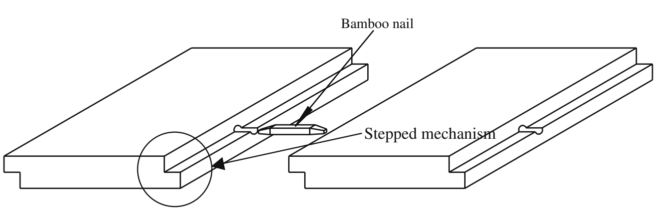

Fig. 2. Connection mechanism of panel units

Theory

The configuration of the traditional timber shear wall is shown in Fig. 3. It can be found that rails are fabricated on both beams and columns. On the columns, it is inevitable that gaps will be left between board units and columns due to errors in craftsmanship. In the words, the board units are not confined in the horizontal direction and have a certain freedom of movement. In the vertical direction, it is easy for carpenters to avoid gaps, and thus the clearance between the board and beam is negligible.

To establish the theoretical model for prediction of mechanical performance of timber shear walls, the following assumptions were made during the theory derivation:

1. The material properties can be described by a bilinear model.
2. The friction between vertical contact surfaces of board units can be ignored, due to lack of horizontal confinement as previously described.
3. The modulus of elasticity (MOE) of wood parallel to grain is 20 times the MOE perpendicular to grain, which is suitable for softwood.
4. The rotation center of the side column is at joints that connect beams and side columns; whereas the rotation

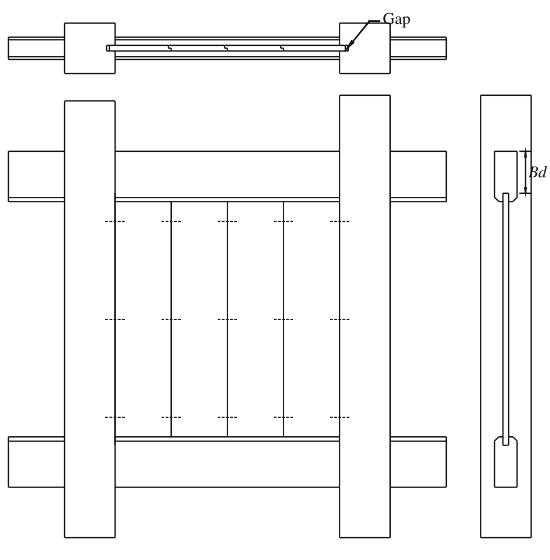

Fig. 3. Configuration of timber shear wall

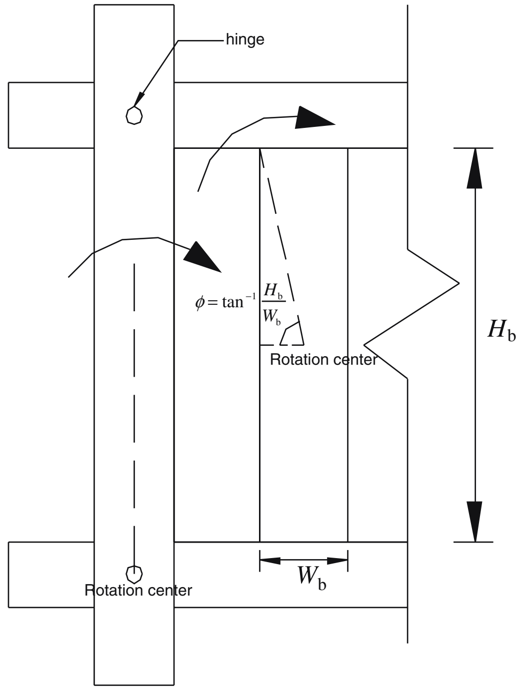

Fig. 4. Concept of rotation center

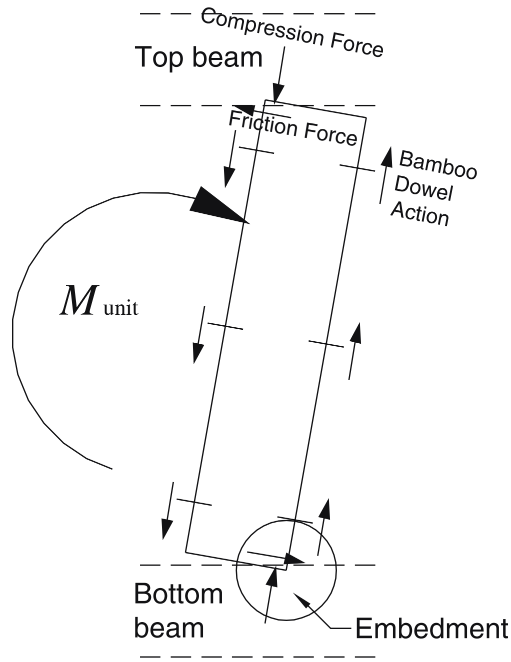

Fig. 5. Free body diagram of panel unit

center of the board unit is at the geometrical centroid of the board (see Fig. 4).

5. To discuss the mechanism of force resistance, the joint stiffness and shear resistance of the wall are considered separately. In this article, only timber shear walls are considered, i.e., the stiffness of the joint is omitted, and joints are considered as pin connections.
6. Rotation of the board units is synchronous, in other words, they have the same rotation angle.
7. The flexural behavior of beams and columns can be omitted; they act as rigid bodies. The shear deformation of board units is negligible.
8. The board units used in a timber shear wall have the same width and thickness.

The total moment borne by a timber shear wall is supplied by the moment resistance induced by the board unit within a timber shear wall, therefore

$$M_{\text{total}} = n_u \times M_{\text{unit}} \tag{1}$$

where n_u is the number of board units within the timber shear wall and M_{unit} is the moment resistance provided by the board unit.

After rotation, some embedment occurs at the beams, and the board units will have relative displacement. In such a case, the bamboo nails are subjected to dowel action. The free body diagram of the board unit is demonstrated in Fig. 5. As shown in Fig. 5, the moment resistances of the board unit come from embedment, friction between the board unit and beam, and the bamboo nails. Thus, the moment resistance of a board unit can be expressed as

$$M_{\text{unit}} = M_E + M_F + M_B \tag{2}$$

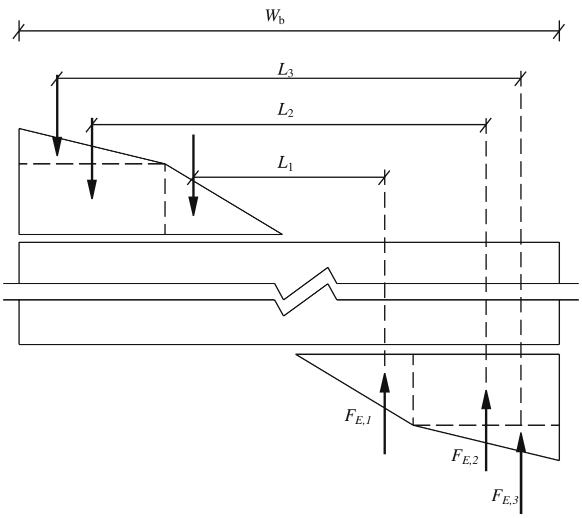

Fig. 6. Embedment distribution on beam

where M_E, M_F, and M_B are moment resistance induced by embedment, friction, and bamboo nails, respectively.

Top and bottom beam have same MOE and depth

Embedment-supplied moment resistance

Suppose the board unit has the rotation θ, the board unit embeds into the beam at the contact surfaces between the beam and the board unit, as illustrated in Fig. 6. The maximum embedded strain can be written as

$$\varepsilon_{\max} = \frac{\mathrm{lc} \cdot \sin\theta \cdot \cos\theta}{\mathrm{Bd}} \tag{3}$$

where lc is compression length and Bd is beam depth. Thus, the strain along the X-axis can be expressed in terms of

$$\varepsilon(x, \theta) = \frac{x \cdot \sin\theta}{\mathrm{Bd}} \tag{4}$$

In dealing with the case in which the grain is inclined, Hankinson's formula is usually used. Wang[10] reported that the value of 3.1 is suitable for the constant used in this formula for Chinese cedar (*Cunninghamia lanceolata*) in the elastic stage. Upon setting the constant $n = 3.1$, MOE can be expressed as

$$\begin{aligned} E(\theta) &= \frac{E_{\perp} \cdot E_{//}}{E_{//} \cos^{3.1}\theta + E_{\perp} \sin^{3.1}\theta} \\ &= E_{\perp} \cdot \frac{20}{20 \cdot \cos^{3.1}\theta + \sin^{3.1}\theta} \\ &= E_{\perp} \cdot \alpha(\theta) \end{aligned} \tag{5}$$

Because the material property is described by a bilinear model, as shown in Fig. 6, the MOE perpendicular to the grain can be expressed as

$$E_{\perp} = \begin{cases} E_{\perp,e} & (0 \le \varepsilon \le \varepsilon_y) \\ E_{\perp,p} & (\varepsilon_y < \varepsilon) \end{cases} \tag{6}$$

Combining Eqs. 5 and 6, we obtain

$$E(x, \theta) = \begin{cases} E_{\perp,e} \cdot \alpha(\theta) & (0 \le \varepsilon \le \varepsilon_y) \\ E_{\perp,p} \cdot \alpha(\theta) & (\varepsilon_y < \varepsilon) \end{cases} \tag{7}$$

According to Hook's Law

$$\sigma = E \cdot \varepsilon \tag{8}$$

The resultant force can be expressed as

$$F_{\mathrm{E}} = T_{\mathrm{b}} \cdot \int_0^{\mathrm{lc}\cdot\cos\theta} E(x, \theta) \cdot \varepsilon(x, \theta) dx \tag{9}$$

where T_{b} represents the thickness of the board unit.

In the elastic stage, the resultant force can be written as

$$F_{\mathrm{E,elastic}} = \frac{\mathrm{lc}^2 \cdot T_{\mathrm{b}} \cdot E_{\perp,e}}{2 \cdot \mathrm{Bd}} \cdot \alpha(\theta) \cdot \sin\theta \cdot \cos^2\theta \tag{10}$$

The lever arm for embedment at the elastic stage can be calculated as

$$L_{\mathrm{E}} = W_{\mathrm{b}} - \frac{2}{3} \cdot \mathrm{lc} \cdot \cos\theta \tag{11}$$

where W_{b} stands for the width of the board unit. Thus, the moment resistance at this stage due to embedment of a single board can be expressed as

$$M_{\mathrm{E,elastic}} = F_{\mathrm{E}} \cdot L_{\mathrm{E}} \tag{12}$$

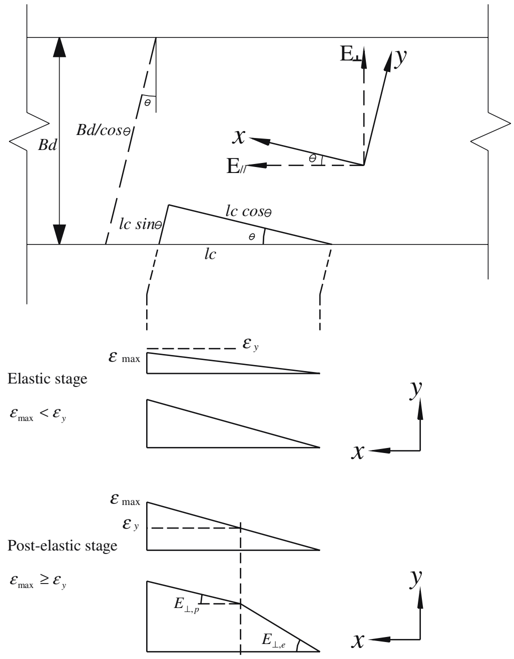

Fig. 7. Resultant forces and lever arms at postelastic stage

For the case that $\varepsilon_{\max} > \varepsilon_y$, the resultant force can be divided into three components, as shown in Fig. 7. The moment resistance at this stage can be obtained by

$$M_{\mathrm{E}} = \sum_{i=1}^{3} F_{\mathrm{E},i} \cdot L_{\mathrm{E},i} \tag{13}$$

Moment-resisting capacity induced by friction

Consistent with Eq. 9, the resultant force of friction can be written as

$$F_{\mathrm{F}} = \mu \cdot T_{\mathrm{b}} \cdot \int_0^{\mathrm{lc}\cdot\cos\theta} E(x, \theta) \cdot \varepsilon(x, \theta) dx \tag{14}$$

where μ is the friction coefficient for wood–wood surfaces.

In the elastic stage, the resultant force of friction can be expressed as

$$F_{\mathrm{F,elastic}} = \frac{\mu \cdot \mathrm{lc}^2 \cdot T_{\mathrm{b}} \cdot E_{\perp,e}}{2 \cdot \mathrm{Bd}} \cdot \alpha(\theta) \cdot \sin\theta \cdot \cos^2\theta \tag{15}$$

Many factors influence the coefficient of friction, such as species, fiber orientation, moisture content, temperature, roughness of the contact surface, and relative velocity for friction. Only few studies have reported the value of friction coefficient for wood–wood surfaces. McKenzie and Karpovich[11] investigated the sliding coefficient of friction for wood–wood surfaces with various species, roughness, and velocities; the value was in the range of 0.1–0.65. Murase[12] indicated a value of 0.58 for western hemlock (*Tsuga heterophylla*), while Inayama[5] used 0.4–0.5 for calculation of yield strength and stiffness of traditional Otoshikomi timber shear walls in Japan. The value of 0.5

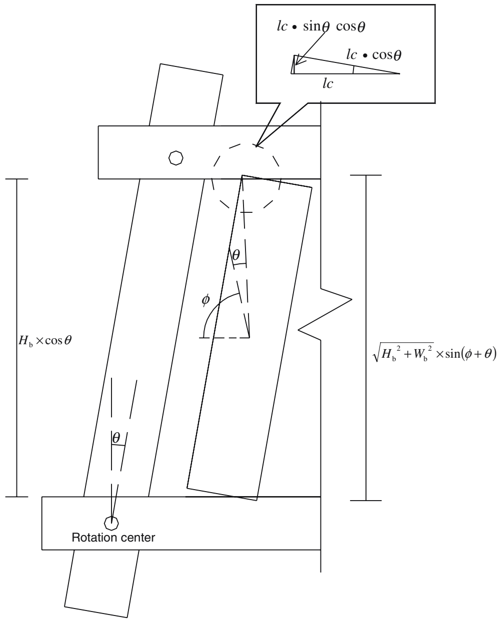

Fig. 8. Timber shear wall after rotation

was used in this study as it is reasonable and corresponds to the experimental results.

The lever arm for friction resistant is constantly equal to height of panel unit, H_b. Thus, the moment-resisting capacity due to friction can be expressed as:

$$M_F = F_F \times H_b \tag{16}$$

Note that each rotation degree will result in a certain compression length. Once the top and bottom beams have the same MOE and depth, the compression length at top beam should equal that at the bottom beam. As illustrated in Fig. 8, the difference of vertical components of side column and panel unit, Δ, should be equal to the total embedment that occurs at the top and bottom beams. The following relation can be constructed

$$\begin{aligned}\Delta &= 2 \cdot \mathrm{lc} \cdot \sin\theta \cdot \cos\theta \\ &= \sqrt{\mathrm{H}_b^2 + W_b^2} \cdot \sin(\phi + \theta) - H_b \cdot \cos\theta\end{aligned} \tag{17}$$

where $\phi = \tan^{-1} \dfrac{H_b}{W_b}$.

Thus, lc can be obtained as:

$$\mathrm{lc} = \frac{\sqrt{H_b^2 + W_b^2} \cdot \sin(\phi + \theta) - H_b \cdot \cos\theta}{2 \cdot \sin\theta \cdot \cos\theta} \tag{18}$$

Moment-resisting capacity due to bamboo nail

To obtain the load–displacement relation of bamboo nail, the double shear test for bamboo nails was performed. The deformation of bamboo nail, as illustrated in Fig. 9, can be obtained by the relation

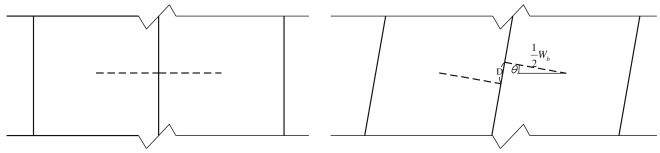

Fig. 9. Displacement of bamboo nail

$$D = W_b \times \tan\theta \tag{19}$$

where D represent the relative slip of bamboo nails in adjacent board units.

Thus, the resistance provided by the bamboo nail can be written in form

$$F_B = k_b \cdot D = k_b \cdot W_b \cdot \tan\theta \tag{20}$$

where k_b is the stiffness of bamboo nail obtained from double shear test. The lever arm of the bamboo nail is constantly equal to the width of the panel, W_b. The moment-resisting capacity induced by bamboo nail can then be expressed in the form

$$M_B = F_B \times W_b \times n_b \tag{21}$$

where F_B is the load carried by bamboo nail at certain rotation and n_b is the number of bamboo nails used in the single panel.

Top and bottom beams have different MOE and depths

The case that top and bottom beams have the same MOE and depth does not necessarily occur in reality. It is more realistic to consider the case that the values of MOE and depth for the top and bottom beams are different. Assuming the depth and MOE of the top beam are, in turns, Bd_t, $E_{\perp,e,t}$ and $E_{\perp,p,t}$, whereas the bottom beam has these characteristics of Bd_b, $E_{\perp,e,b}$, and $E_{\perp,p,b}$, respectively. Hence, the strain and MOE for the top and bottom beams can be expressed as

$$\begin{cases}\varepsilon_t(x_t, \theta) = \dfrac{x_t \cdot \sin\theta}{\mathrm{Bd}_t} \\ \varepsilon_b(x_b, \theta) = \dfrac{x_b \cdot \sin\theta}{\mathrm{Bd}_b}\end{cases} \tag{22}$$

$$E_t(x_t, \theta) = \begin{cases}E_{\perp,e,t} \cdot \alpha(\theta) & (0 \le \varepsilon \le \varepsilon_y) \\ E_{\perp,p,t} \cdot \alpha(\theta) & (\varepsilon_y < \varepsilon)\end{cases} \tag{23}$$

$$E_b(x_b, \theta) = \begin{cases}E_{\perp,e,b} \cdot \alpha(\theta) & (0 \le \varepsilon \le \varepsilon_y) \\ E_{\perp,p,b} \cdot \alpha(\theta) & (\varepsilon_y < \varepsilon)\end{cases} \tag{24}$$

The resultant forces due to compression at the top and bottom beams can be written as

$$F_{E,t} = T_b \cdot \int_0^{1c_t \cdot \cos\theta} E_t(x_t, \theta) \cdot \varepsilon_t(x_t, \theta)\, dx_t \tag{25}$$

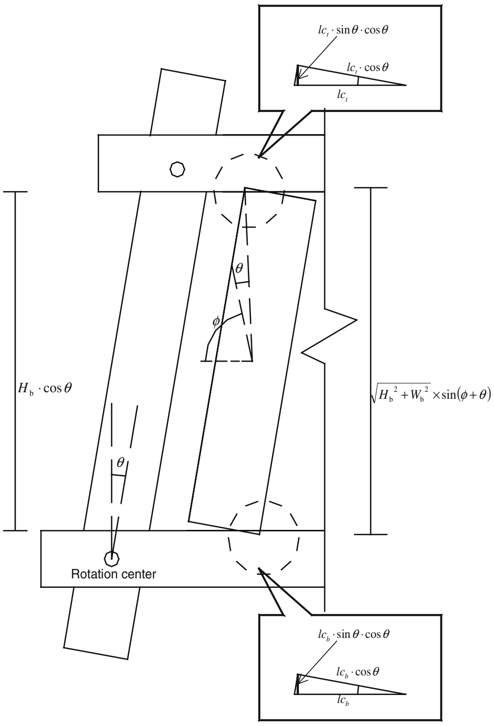

Fig. 10. Timber shear wall with unequal modulus of elasticity for top and bottom beam subjected to rotation

$$F_{\mathrm{E,b}} = T_{\mathrm{b}} \cdot \int_0^{1c_b \cdot \cos\theta} E_{\mathrm{b}}(x_{\mathrm{b}}, \theta) \cdot \varepsilon_{\mathrm{b}}(x_{\mathrm{b}}, \theta) dx_b \tag{26}$$

In the elastic stage, the resultant forces at the top and bottom beams become

$$F_{\mathrm{E,t,elastic}} = \frac{\mathrm{lc}_{\mathrm{t}}^2 \cdot T_{\mathrm{b}} \cdot E_{\perp,\mathrm{t}}}{2 \cdot \mathrm{Bd}_{\mathrm{t}}} \cdot \alpha(\theta) \cdot \sin\theta \cdot \cos^2\theta \tag{27}$$

$$F_{\mathrm{E,b,elastic}} = \frac{\mathrm{lc}_{\mathrm{b}}^2 \cdot T_{\mathrm{b}} \cdot E_{\perp,\mathrm{b}}}{\mathrm{Bd}_{\mathrm{b}}} \cdot \alpha(\theta) \cdot \sin\theta \cdot \cos^2\theta \tag{28}$$

The resultant forces due to compression at the top beam should be equal to those at the bottom beam. In the other words, Eqs. 27 and 28 should be equal. Thus, the following relation can be established

$$\frac{\mathrm{lc}_{\mathrm{t}}^2 \cdot E_{\perp,\mathrm{t}}}{\mathrm{Bd}_{\mathrm{t}}} = \frac{\mathrm{lc}_{\mathrm{b}}^2 \cdot E_{\perp,\mathrm{b}}}{\mathrm{Bd}_{\mathrm{b}}} \tag{29}$$

From Fig. 10, the difference of vertical components of rotated beam and the panel unit should be equal to total embedment, Δ', at the top and bottom beams; thus, the following relation can be written:

$$\begin{aligned} \Delta' &= \mathrm{lc}_{\mathrm{t}} \cdot \sin\theta \cdot \cos\theta + \mathrm{lc}_{\mathrm{b}} \cdot \sin\theta \cdot \cos\theta \\ &= \sqrt{H_{\mathrm{b}}^2 + W_{\mathrm{b}}^2} \cdot \sin(\phi + \theta) - H_{\mathrm{b}} \cdot \cos\theta \end{aligned} \tag{30}$$

Combining Eqs. 29 and 30, we obtain:

$$\mathrm{lc}_{\mathrm{t}} = \frac{\sqrt{\dfrac{\mathrm{Bd}_{\mathrm{t}} \cdot E_{\perp,\mathrm{b}}}{\mathrm{Bd}_{\mathrm{b}} \cdot E_{\perp,\mathrm{t}}}} \times \Delta'}{\left(1 + \sqrt{\dfrac{\mathrm{Bd}_{\mathrm{t}} \cdot E_{\perp,\mathrm{b}}}{\mathrm{Bd}_{\mathrm{b}} \cdot E_{\perp,\mathrm{t}}}}\right) \cdot \sin\theta \cdot \cos\theta} = \frac{\xi \cdot \Delta'}{(1+\xi) \cdot \sin\theta \cdot \cos\theta} \tag{31}$$

$$\mathrm{lc}_{\mathrm{b}} = \frac{\Delta'}{\left(1 + \sqrt{\dfrac{\mathrm{Bd}_{\mathrm{t}} \cdot E_{\perp,\mathrm{b}}}{\mathrm{Bd}_{\mathrm{b}} \cdot E_{\perp,\mathrm{t}}}}\right) \cdot \sin\theta \cdot \cos\theta} = \frac{\Delta'}{(1+\xi) \cdot \sin\theta \cdot \cos\theta} \tag{32}$$

where ξ is the adjustment coefficient for geometric and material properties of the top and bottom beams. Once $\xi = 1$, Eqs 18, 31, and 32 become equivalent.

The lever arm of couple induced by embedment at the elastic stage can be calculated as:

$$L'_{\mathrm{E}} = W_{\mathrm{b}} - \frac{1}{3}(\mathrm{lc}_{\mathrm{t}} + \mathrm{lc}_{\mathrm{b}}) \cdot \cos\theta \tag{33}$$

Thus, the moment-resisting capacity due to embedment of a single panel at this stage can be expressed as:

$$M'_{\mathrm{E}} = F_{\mathrm{E,t}} \times L'_{\mathrm{E}} \tag{34}$$

Moment resistance due to friction

Recalling the resultant force at the top beam, the resultant friction force can be written as:

$$F'_{\mathrm{F}} = \mu \cdot T_{\mathrm{b}} \cdot \int_0^{\mathrm{lc}_t c \cdot os\theta} E_{\mathrm{t}}(x_{\mathrm{t}}, \theta) \cdot \varepsilon_{\mathrm{t}}(x_{\mathrm{t}}, \theta) dx_{\mathrm{t}} \tag{35}$$

The moment resistance due to friction can be expressed as:

$$M'_{\mathrm{F}} = F'_{\mathrm{F}} \times H_{\mathrm{b}} \tag{36}$$

The differences in MOE and beam depth of the top and bottom beams do not affect the moment-resisting capacity induced by bamboo nails. Thus, the moment resistance due to bamboo nails can be obtained by using Eq. 21.

Conclusions

This study focused on the structural behavior of traditional timber shear wall of Taiwan. Based on an extensive field investigation of fundamental properties, such as tectonic, geometric, and material data, this article proposes a theoretical model to predict the lateral force-resistance capacity of traditional timber shear wall of Taiwan. However, the theoretical model needs to be verified by experimental results, which will be reported in the next study.

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