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A new proposal to reinforce planked timber shear walls

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Abstract Timber is one of the most common materials used in traditional buildings worldwide. Our previous research has suggested that timber shear walls play an important role in resisting external loadings, such as earthquakes. Thus, improving the structural performance of in-filled shear walls can also improve that of the entire structure. In the traditional Taiwanese timber shear wall system, the embedment strength of beams and friction between wooden planks and beams significantly affect the strength of the shear wall. This article proposes a new method of reinforcing traditional timber shear walls in Taiwan by inserting teak and padauk strips into the grooves between wooden planks and beams to increase the embedment strength of beams and the friction between wooden planks and the hardwood strips. A total of 18 full-scale specimens were tested under reversed cyclic loading. The results revealed that the strength and energy dissipation capacities of a wooden shear wall can be significantly increased by inserting teak and padauk strips into the grooves between planks and beams. Furthermore, the simplified calculation method proposed in this study can be used to calculate the strength of both reinforced and unreinforced wooden shear walls with satisfactory agreement.

Key words Friction · Partial embedment · Reinforcement · Timber shear walls · Traditional timber structures

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Introduction

Wooden shear walls can be found all over the world; various carpentry traditions and environments surrounding the buildings result in different types of timber shear walls. Many articles have been published on traditional Japanese wooden shear walls and their evaluation methods.[1–4] A field survey has shown that wood and mud are two major materials used to infill the timber frames in traditional Taiwanese buildings,[5] and there exist more than 550 traditional residential houses in the rural areas of Tainan County of Taiwan that have wooden partition walls.[6] Our previous reports have shown the mechanical behavior of traditional Taiwanese timber shear walls,[7,8] and pointed out that they are the main assemblies resisting seismic loads.[9] Past devastating earthquakes have brought about an urgent need to reinforce these buildings, which form a major part of our cultural heritage. Several methods have been proposed to reinforce these traditional timber frames, such as to adopt steel bracing. However, these proposed reinforcement methods have many shortcomings, e.g., they are visible and the materials used are not compatible with wood. Furthermore, they all lack experimental evidence to ensure their effectiveness. Taiwanese wooden shear walls comprise several wooden planks between the beams, and the objective of this study is to propose a new method that uses wood as a material by inserting hardwood strips to reinforce these wooden shear walls, as shown in Fig. 1, and then to verify the effectiveness of this approach experimentally.

Theory

Traditional Taiwanese timber shear walls are usually composed of several wooden planks because it is difficult to find suitable boards with sufficient width to accommodate the whole shear wall. Carpenters make grooves in both the top and bottom beams of timber shear walls and insert the planks. To prevent out-of-plane buckling, half-lap joints are

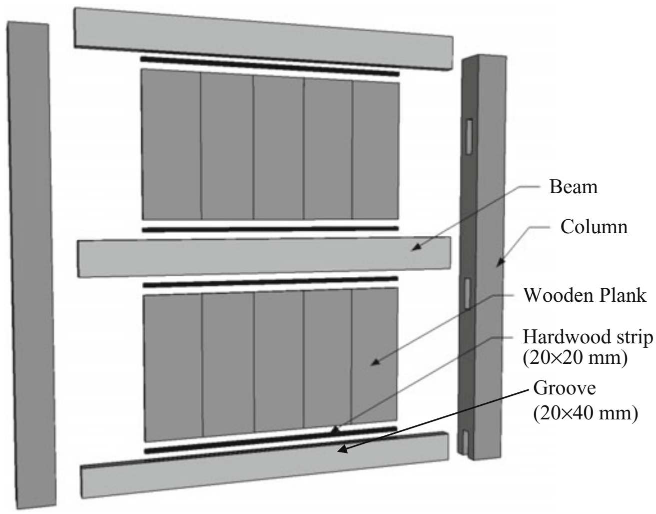

Fig. 1. The structural system of Taiwanese wooden shear walls and the proposed reinforcement method

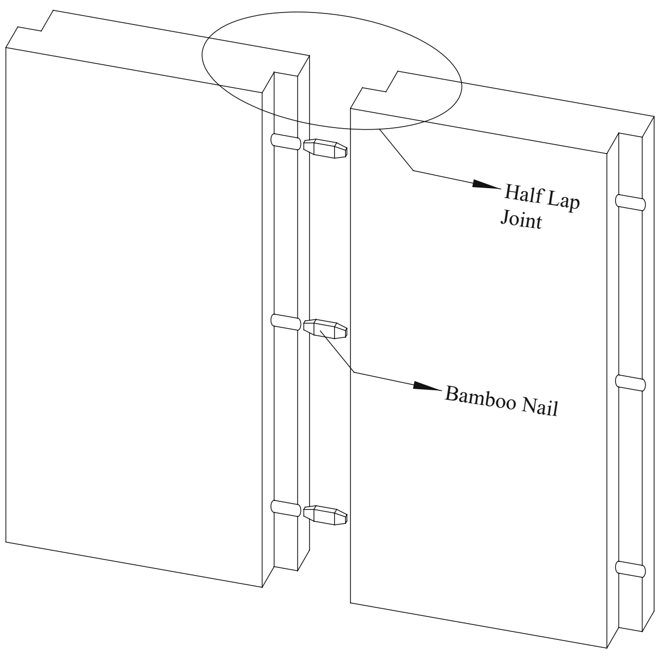

Fig. 2. Half-lap connection and bamboo nails used to connect the planks

made to connect the planks; bamboo nails are used to connect the planks and resist the in-plane relative displacement between boards, as shown in Fig. 2.

As discussed in previous studies,[7,8] the moment resistance of the entire wooden shear wall comes from (1) embedment between planks and beams, (2) friction between planks and beams, and (3) the shear strength of bamboo nails. However, the bamboo shear strength makes a limited contribution to the moment resistance of the entire wooden shear wall and can be neglected. As depicted in Fig. 3, the moment resistance of a wooden shear wall can be expressed as:

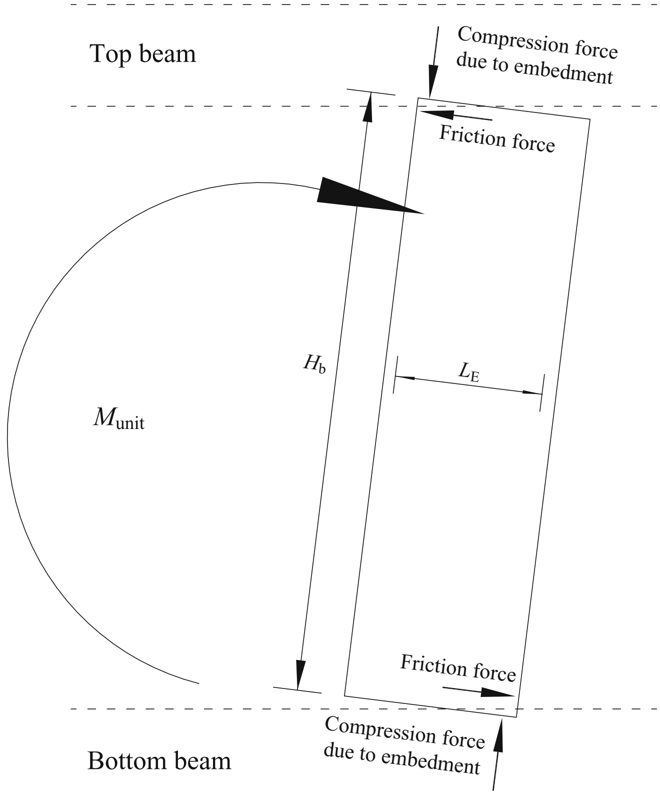

Fig. 3. Free body diagram of wooden planks

$$M(\theta) = n_u \cdot (M_E + M_F) = n_u \cdot (F_{E,t} \cdot L_E + \mu \cdot F_{E,t} \cdot H_b) \quad (1)$$

where n_u is the number of planks in the entire wooden wall, M_E and M_F are moment resistances induced by embedment and friction between the planks and beam, respectively. $F_{E,t}$, L_E, μ, and H_b are, respectively, the resultant force due to embedment between plank and top beam at the elastic stage, the lever arm for embedment, the friction coefficient between surface of planks and beams, and the height of the planks.

A horizontal force applied to a wooden shear wall will result in rotation of the wooden planks and connections. However, with a limited rotation angle, the effect of beams embedded with inclined grain can be omitted. By assuming that the rotation center of a plank is at its geometrical centroid, the resultant force, $F_{E,t}$, and lever arm, L_E, at the elastic stage can then be calculated as:

$$F_{E,t} = \frac{T_b \cdot E_{\perp,t} \cdot \xi^2 \cdot W_b^2}{2 \cdot Bd_t \cdot (1+\xi)^2} \cdot \sin\theta \quad (2)$$

$$L_E = W_b \cdot \left[1 - \frac{2}{3}\left(\frac{\xi}{1+\xi}\right)\right] \quad (3)$$

where T_b, W_b, and $E_{\perp,t}$ are the thickness of the planks (m), the width of the planks (m), and the modulus of elasticity (MOE) perpendicular to the grain (N/m^2), respectively. Bd_t is the depth of the top beam (m) and ξ is the adjustment coefficient for different depths and MOEs of the top and bottom beams, and can be obtained by:

$$\xi = \left(\frac{Bd_t \cdot E_{\perp,b}}{Bd_b \cdot E_{\perp,t}} \right)^{0.5} \tag{4}$$

where Bd_t, Bd_b, $E_{\perp,t}$, and $E_{\perp,b}$ respectively represent the depth of the top beam, the depth of the bottom beam, the MOE perpendicular to the grain direction of the top beam, and that of the bottom beam. If the top and bottom beams have identical material properties and depths, then $\xi = 1$. Notice that the MOE perpendicular to the grain is adopted in the theory instead of using the partial compression model of wood. This is because the authors planned to develop a simple model with acceptable accuracy. The differences were explained in our previous articles.[7,8]

In developing the theory, we used a bilinear model to describe the stress–strain relationship of materials, with the secondary modulus assumed to be 10% of that in the elastic stage. After the material has yielded, the resultant force can be divided into three components, $F_{E,1}$, $F_{E,2}$, and $F_{E,3}$, as shown in Fig. 4. $F_{E,1}$ and $F_{E,2}$ represent the materials that remains at the elastic stage, whereas $F_{E,3}$ represents the materials after the elastic stage. The moment resistance in the post-elastic stage can be calculated by:

$$M_E = \sum_{i=1}^{3} F_{E,i} \cdot L_{E,i} \tag{5}$$

From Eq. 1 we can determine that the friction components play a more important role than that of embedment, as usually the plank height is at least 3 times the plank width, although the friction force might be derived from embedment. Hence we can improve the force resistance of the wooden shear wall by enhancing the moment resistance of embedment.

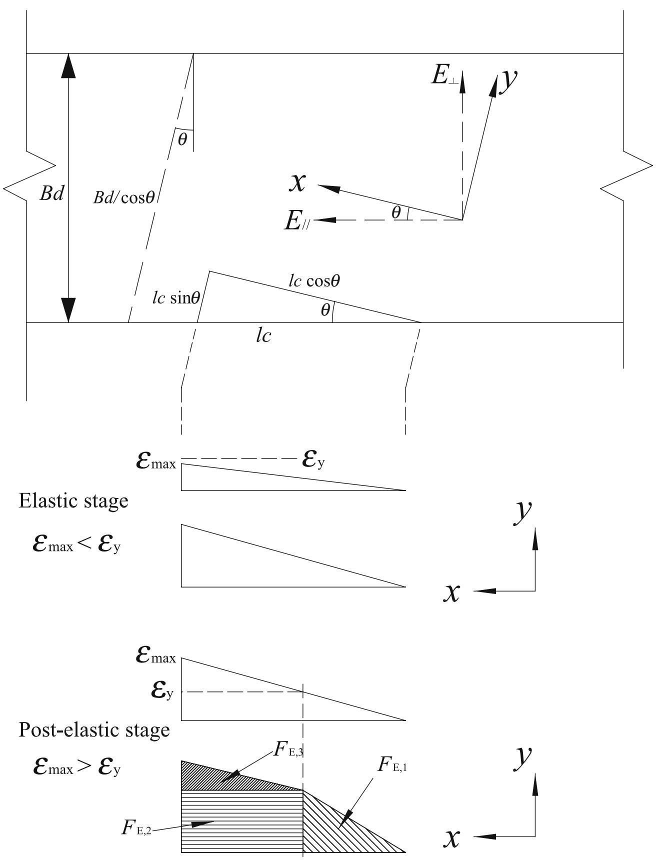

Fig. 4. Resultant forces and lever arm at the post-elastic stage

Experiments

To improve the effect of friction and embedment properties between planks and beams of wooden shear walls, teak (*Tectona grandis*) and padauk (*Pterocarpus* spp.) were selected as reinforcement materials. Square hardwood strips made of teak or padauk with a section of 20 × 20 mm were cut and inserted into the grooves between planks and the wooden beam as demonstrated in Fig. 5. The wood glue polyvinyl acetate was used to glue the hardwood strips into the grooves.

The experiments consisted of material tests and shear wall tests. Material tests measured the friction coefficient between planks and hardwood and the static bending MOE and included a compression test. The test apparatus to measure friction is illustrated in Fig. 6. The dynamic friction coefficient can be calculated as:

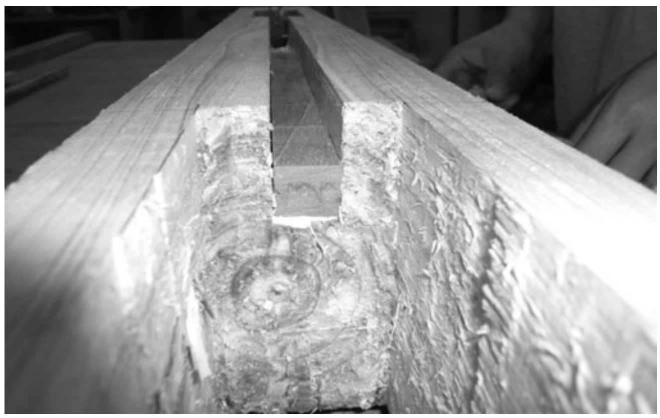

Fig. 5. Hardwood strip inserted into groove between planks and beams

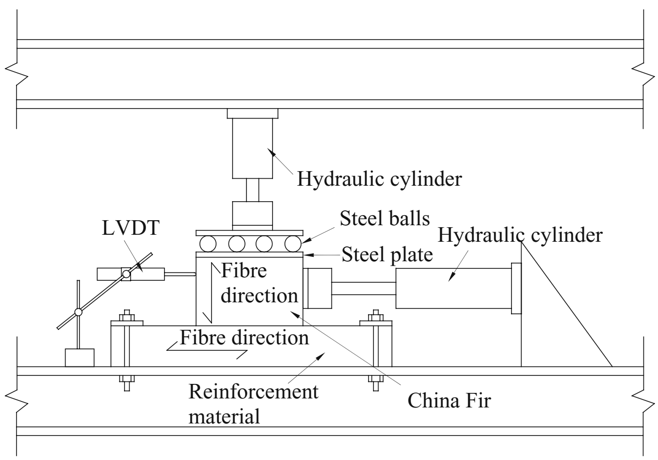

Fig. 6. Experimental setup for friction coefficient testing

$$\mu_d = \frac{F_h}{F_n} \quad (6)$$

where F_h and F_n are, respectively, the horizontal force and vertical load applied to the sliding block (China fir).

As shown in Eq. 1, the friction coefficient is an important factor in resisting seismic loads. However, the friction coefficient is influenced by many factors, such as species, fiber orientation, moisture content, temperature, roughness of the contact surface, and relative velocity. Until now, only a few studies have reported the friction coefficient for wood–wood surfaces. McKenzie and Karpovich[10] proposed a friction coefficient range from 0.1 to 0.65 for various specimens. Murase[11] indicated a value of 0.58 for western hemlock (*Tsuga heterophylla*). Friction coefficients of from 0.5 to 0.7 for all specimens below the fiber saturation point and from 0.7 to 0.9 for those above fiber saturation point have also been reported.[12] Shanks[13] published values of 0.61, 0.59, and 0.47 for perpendicular-to-perpendicular, perpendicular-to-parallel, and parallel-to-parallel contact surfaces for oak. Meng et al.[14] established values of 0.6–0.9 for dynamic frictional coefficient between wood-wood surfaces, and 0.2–0.4 among all combinations of materials.

The specimens for friction tests and the results are given in Table 1, from which we can see that the average friction coefficient between China fir (*Cunninghamia lanceolata*) and teak is 0.61, whilst it is 0.69 between China Fir and padauk. These values will be used in the proposed theoretical model. The static bending tests gave the average MOEs and standard deviations for teak and padauk as 10.23 ± 2.21 and 14.42 ± 1.82 GPa. The compressive tests indicated that the compression MOEs perpendicular to the grain for teak and padauk were 0.48 ± 0.08 and 0.61 ± 0.11 GPa.

For the shear wall tests, a total of eighteen specimens were tested in this study to elucidate the effect of the proposed reinforcing strategy. The factors discussed in this study include the reinforcement materials and the width of the planks. The effective size of the specimens was fixed at 600 × 1200 mm, and the beams located at the top and bottom had sections of 60 × 120 mm. The thickness of planks was controlled at 20 mm. Details of the specimens are given in Table 2. Six series of specimens were designed; each series consisting of three replications. Specimens in series A and B in Table 2 were unreinforced and act as controls. Series C and D specimens were reinforced by inserting teak strips to the top and bottom grooves between planks and beams; series E and F specimens were reinforced by using padauk. Specimens in series A, C, and E contained three planks, while those in series B, D, and F contained four planks.

Planks and exterior frames were made of China fir, and the planks of specimens in series A and B were connected by bamboo (*Bambusa stenostachya*) nails sized 4 × 4 × 75 mm with a pitch of 300 mm. To omit the effect of joint stiffness of the exterior frame, pin connections were used to connect the beams and columns. The experimental setup is illustrated in Fig. 7. For specimens of series A and B, the groove depths were 20 mm in both beams and columns, whereas groove depths in specimens of series C, D, E, and

Table 1. Results of friction tests

	Sliding material	Base material	Result	Standard deviation	No. of samples
μ_{ft}[a]	China fir[a]	Teak[b]	0.61	0.12	20
μ_{fn}[b]	China fir[a]	Padauk[b]	0.69	0.13	20

μ_{ft}, Friction coefficient between China fir and teak; μ_{fn}, friction coefficient between China fir and padauk
[a] Grain direction: perpendicular to the grain
[b] Grain direction: parallel to the grain

Table 2. Details of specimens

Series	Reinforcing material	No. of planks	Plank width (mm)	No. of specimens
A	None	3	200	3
B	None	4	150	3
C	Teak (*Tectona grandis*)	3	200	3
D	Teak (*Tectona grandis*)	4	150	3
E	Padauk (*Pterocarpus* spp.)	3	200	3
F	Padauk (*Pterocarpus* spp.)	4	150	3

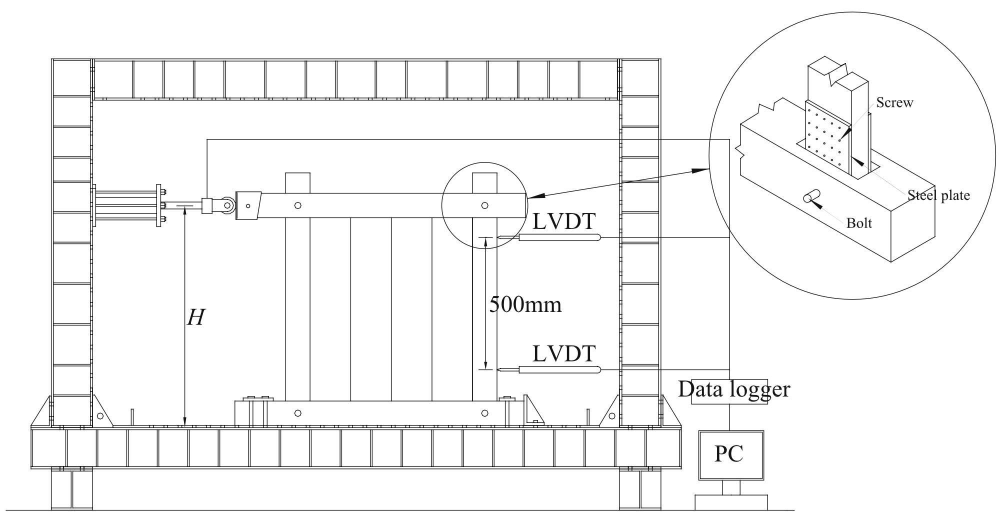

Fig. 7. Experimental setup for shear walls

F were 40 mm so that a hardwood strip of 20 mm thickness could be inserted in the grooves. Reversed cyclic loading was applied by displacement control with the speed of 5×10^{-2} rad/min of rotation; the load scheme is shown in Fig. 8. The experiments were terminated when the maximum stroke of the hydraulic jack was reached. The specimens were stored in the laboratory with good natural ventilation for about 1 month before testing, and moisture content was controlled at less than 16% during testing.

Results and discussion

Failure modes

Two failure modes were observed in the specimens tested: shear failure of the bamboo nails and embedment failure. Due to the relative sliding of planks, the bamboo nails inserted between planks failed in shear as shown in Fig. 9. The shear failure of the bamboo nails make these nails unable to prevent the planks from out-of-plan buckling. Embedment failure occurred in places where planks contacted the beam in grooves. Embedment failure occurred in unreinforced wooden shear walls as shown in Fig. 10a, whereas Figs. 10b and 10c depict failure in specimens reinforced by teak and padauk strip, respectively. From Fig. 10a,

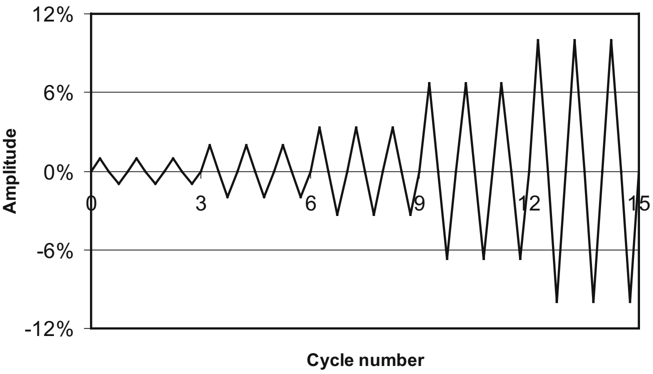

Fig. 8. Loading history of shear wall tests

Fig. 9. Shear failure of bamboo nails

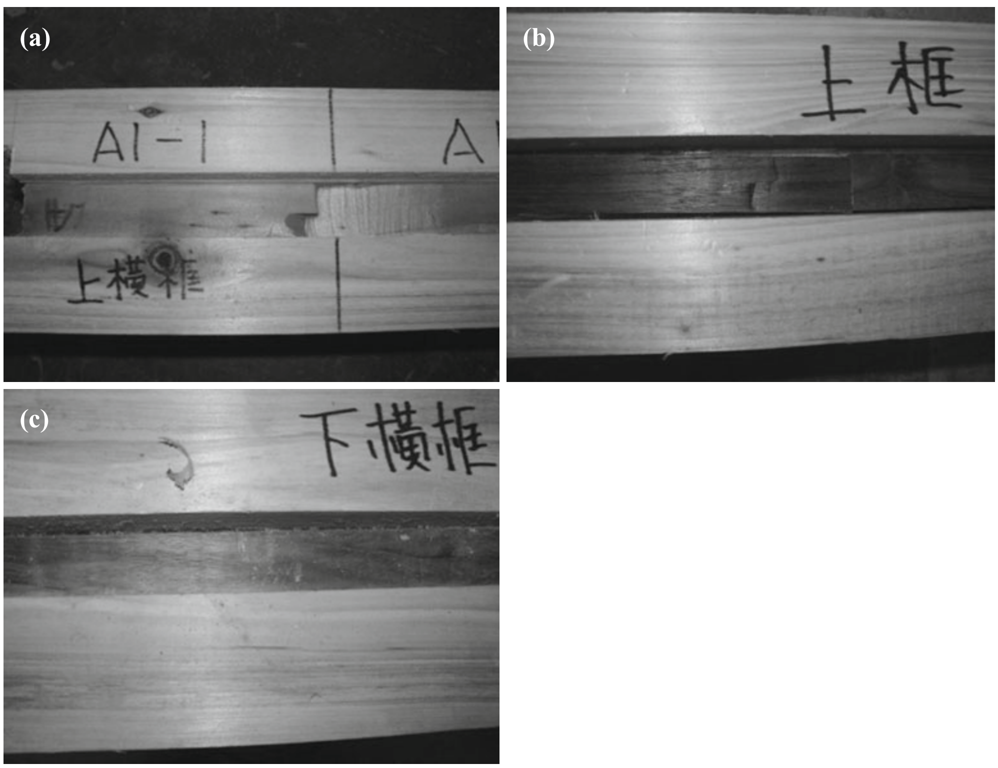

Fig. 10. Failures of each type specimen at the area where planks contact the beam: **a** unreinforced specimen, **b** reinforced by teak, **c** reinforced by padauk

we can learn that the fibers in the beam were cut by shear, and this will result in permanent deformation in grooves between planks and beams; however, no significant failure occurred in specimens reinforced by teak and padauk.

Comparison of proposed model and experimental results

The comparisons of results calculated according to the theoretical model and those obtained from experiments of unreinforced and reinforced specimens are shown in Figs. 11–13. The behavior of reinforced specimens according to the theoretical model was estimated by using the material properties (i.e., MOE and friction) of the reinforced materials, rather than using the material properties of the unreinforced beam, which would have implied that the beams were made of hardwood rather than China fir. In the calculations, actual material properties were adopted to reflect the variation of the wood materials.

The comparisons in Fig. 12 and 13 reveal that the theoretical model tends to overestimate the strength of reinforced specimens but is still within a reasonable range (less than 8% difference); satisfactory agreements can be found for all the specimens tested. This means that the local embedment on hardwood strips dominates the deformation, and the hardwood strips sink only an insignificant amount into the softwood foundation.

Effectiveness of reinforcement

Figure 14 gives the envelopes obtained from hysteretic loops of reinforced and unreinforced specimens, from which we can learn that the stiffness and strength of specimens reinforced by padauk strips are higher than for unreinforced specimens and those reinforced by teak. Reinforcement by using padauk strip appears to be effective; the reason is that the contact area between planks and beams are replaced by padauk wood, which has higher strength. Another important point is that the friction between China fir planks along the grain with padauk wood perpendicular to the grain (friction coefficient of 0.69) is much higher than that between China fir planks and beams (friction coefficient of 0.5); this also increases the resistance of the entire wooden shear wall. The strength of specimens reinforced by teak strips is also significantly higher than for unreinforced specimens for the same reasons; however, because the strength of teak is not as high as padauk wood, and the frictional coefficient between China fir along the grain and teak perpendicular to the grain is lower than that between China fir along the grain and padauk perpendicular to the grain (0.61 versus 0.69), the effectiveness of teak is not as good as reinforcement using padauk strip. Therefore, it appears that partially reinforcing the contact area between planks and the groove on the beam is an effective method.

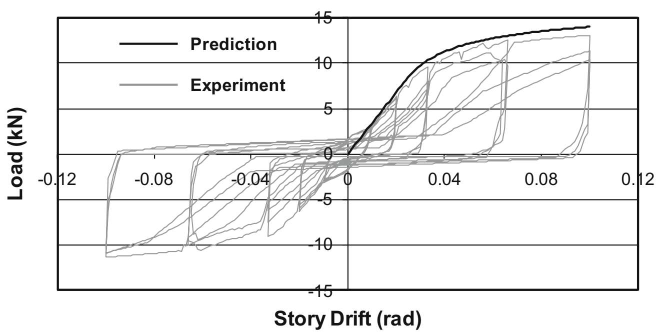

Fig. 11. Comparison of test results for specimen A-3 (unreinforced) and the estimated results

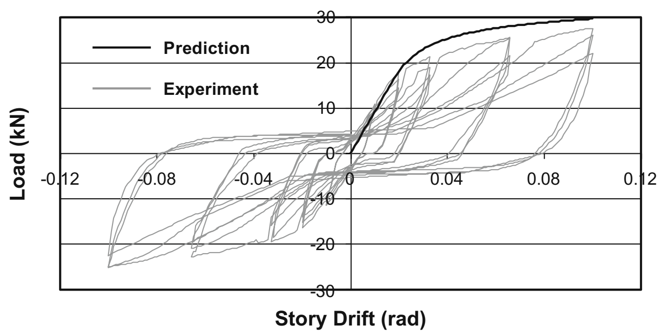

Fig. 13. Comparison of test results for specimen E-3 (padauk reinforced) and estimated results

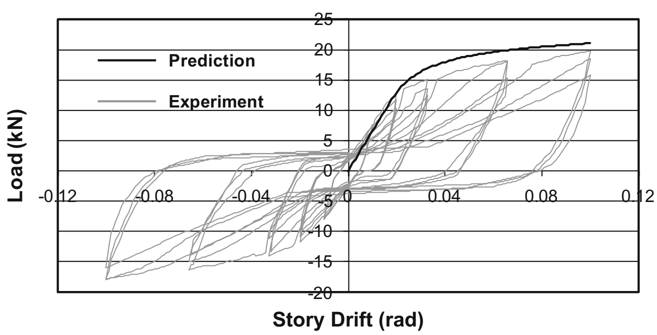

Fig. 12. Comparison of test results for specimen C-2 (teak reinforced) and estimated results

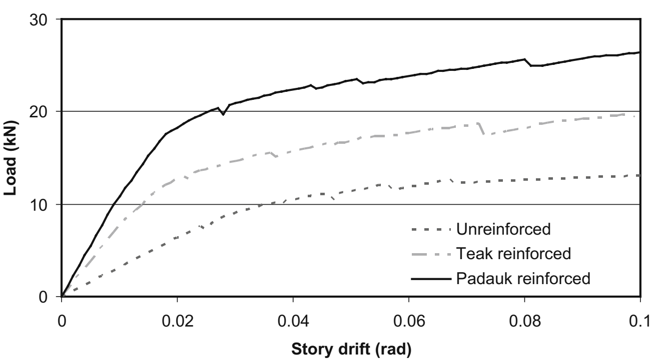

Fig. 14. Comparison of envelopes of reinforced and unreinforced specimens

Hysteretic loop of shear walls

Figures 11–13 show typical hysteretic loops of unreinforced and reinforced specimens. The hysteretic loops show that the moment resistance of these connections gradually increases even at large rotation. This is quite different from plywood-sheathed timber shear walls, but is a typical behavior of Taiwanese timber shear walls. Modern sheathed timber shear walls use nails to connect to the timber frame, and so once the nails are pulled out, the strength decreases. Traditional Taiwanese timber shear walls use partial compression to resist the moment, hence, when the material in the contact area between planks and beam yields, partial compression occurs and the surrounding area will help resist the moment. Furthermore, as the strength of all specimens did not reach a maximum, the ultimate strength and ductility factors could not be established. The hysteretic loops of all specimens exhibited severe pinching, despite the reinforced specimens showing less pinching compared with unreinforced specimens. This is because the planks do less damage to teak or padauk strips, as explained previously. Hence, pinching is another characteristic of the Taiwanese timber shear wall. The pinching phenomenon is attributable to nonrecoverable embedded deformation observed in the beam or the contact area of planks and beams. The pinched hysteretic loop of the connection implies that the walls can no longer dissipate a significant amount of energy during the reverse-cyclic loading. The impairment in moment resistance represents the average drop in bending resistance for every second and third loop compared with the first loop. This is also an important parameter for evaluation of the condition of shear walls. The impairments in moment resistance of all specimens in different rotation of shear walls were less than 10%.

Energy dissipation capacity

The ability of a structure to survive an earthquake largely depends on its ability to absorb the input energy. Thus the energy dissipation capacity of a structure is considered to be a good measure of seismic performance. The energy dissipation ability might be attributed to kinematics energy, viscous damping energy, recoverable elastic energy, and unrecoverable hysteretic energy, among others. The energy dissipation capacity of a structure should be larger than the energy demand so that the structure can withstand the excitation from an earthquake. The dissipated energy can be calculated as the area enclosed by the hysteretic loop in a certain cycle. In this study, the areas corresponding to each loop of all the specimens are calculated. The relationships of averaged cumulated dissipated energy versus averaged cumulated rotation of specimens of series A, C, and E (those wooden shear walls consisting of three planks) are plotted in Fig. 15. Similar trends can be observed in those specimens consisting of four planks. The shear walls reinforced by hardwood strips have a better energy dissipation capacity. Hence it can be concluded that the better hysteretic energy dissipation capacities of these timber shear walls might result from reinforcement by hardwood strips because the rotation of planks in the timber shear wall causes less damage to those hardwood strips than to the China Fir.

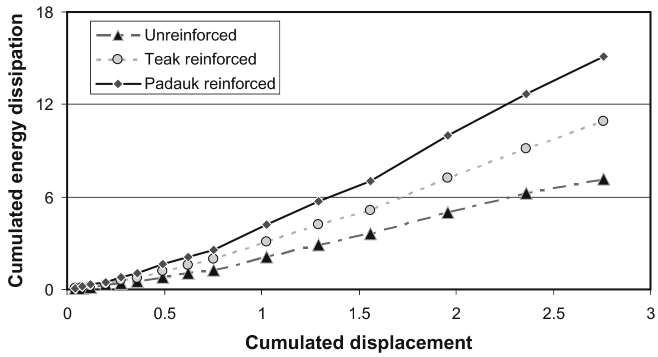

Fig. 15. Averaged cumulated displacement versus cumulated energy dissipation of specimens consisting of three planks

Conclusions

This study not only conducted friction tests of teak–China fir and padauk–China fir surfaces, but also investigated a total of 18 wooden shear wall specimens. By comparing the experimental results and those results obtained from an analytical and experimental process, the following conclusions could be drawn:

1. The simplified calculation method can be used to calculate the strength of both reinforced and unreinforced wooden shear walls with satisfactory agreement.
2. On inserting teak and padauk strips into the grooves where planks contact the beams, the experimental results showed significantly increased strength and energy dissipation capacity of Taiwanese wooden shear walls.
3. Inserting hardwood strips with higher strength and frictional coefficients between the planks and beams appears to be an effective reinforcement method.

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