Compressive Bracing Model for Panel Wall Used to Infill Traditional Wooden Frames

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SUMMARY:
In this study , in order to investigate the contribution of earthquake resistance of wooden panel wall that often used in traditional wooden building in Taiwan , we try to model the panel wall as an equivalent compressive bracing. For modeling , firstly , the loading-displacement relationship curve of the panel wall is calculated. The dowel action of bamboo nails between two panel unit and the rocking behavior of the panel were counted in the calculation. Second , the effective width of the equivalent bracing is defined in accordance with the stiffness of the panel wall in the elastic stage. Four performance stages of the bracing have been suggested to define the plastic hinge properties.
Using the bracing model , a pushover analysis for a traditional wood frame building has been executed. According to the analysis , it is observed that the panel walls do improve the building stiffness and increase ultimate resistant loading. Besides , the analysis also shows the panel walls occurred damage visibly after the frame joints have been seriously damaged. This behavior could be adopted to explain why the traditional wood buildings scarcely completely collapsed after 1999 Chi-Chi earthquake even the frame has seriously damaged and large deformation has reached.

Keywords: wooden wall , In-plane Loading , shear wall , wooden panel , Taiwanese wooden building

1. INTRODUCTION

In Taiwan's traditional wood building , the wooden panel wall is often adopted to partition the interior space. The panel wall is infilled piece by piece in the wooden frame. According to the building damage investigation after earthquake , it is found that these wooden panel walls were helpful to reduce the damage degree of the building in the earthquake , especially to avoid collapse of the traditional building. Thus , it is reasonable to require the wooden panel wall well considered in the analyzing model for seismic assessment.
The main purpose of this study focus on (1)modelling the panel wall as an equivalent compressive bracing and (2) defining the plastic hinge properties of different performance stages for this bracing. Furthermore , in this study , a traditional building is selected to examine the structural influence of the wooden panel walls during push-over analysis.

2. THE CONSTRUCTION OF THE WOODEN PANEL WALL

Fig. 1 is the traditional wooden panel wall in Taiwan. The wooden wall is constructed with a main wooden frame , and the wooden panels are infilled piece by piece in the frame. For reducing the height/width ratio of the panel to avoid panel buckling , in construction , horizontal auxiliary wooden member and vertical auxiliary members are arranged , which divide the wall into several small parts. Fig. 2 shows the connection detail of the wooden panel wall. The wooden panels are inserted into the groove of the wooden beam . Between two adjoining panels, bamboo nails are driven in both of the panels to prevent panel sliding .

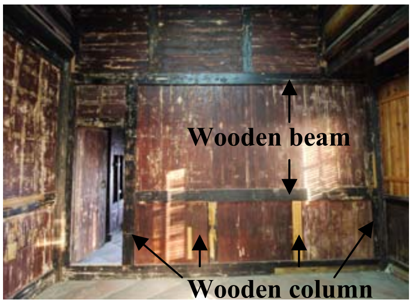

Figure 1. The wooden panel wall in Taiwan's traditional wood building

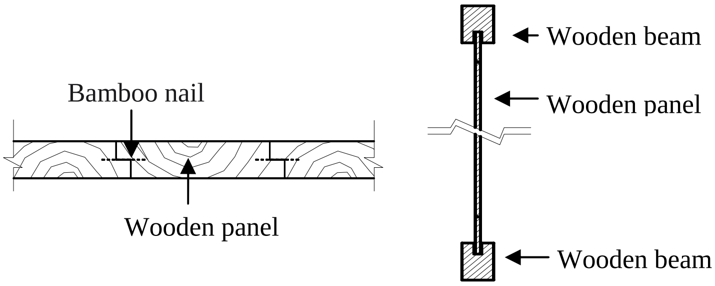

Figure 2. Connection details of the wooden panel wall

3. THE BEHAVIOR OF THE WOODEN PANEL UNDER IN-PLANE HORIZONTAL LOAD

For the wooden panel wall , because the contact surface between the panel and wooden beam can't take tensile stress , the panel will rock under in-plane loading. As shown in Fig. 3. , the diagonal of the rocking panel act as a compressive bracing to resist the in-plane loading. The bamboo nails between two adjoining panels also provide shear strength for preventing the slide of panel interface. On the other hand , the reaction from the bracing wall will cause beam to have compressive deformation. This deformation of the beam will lead the panel to have additional rotation and increase the total horizontal displacement of the wall.

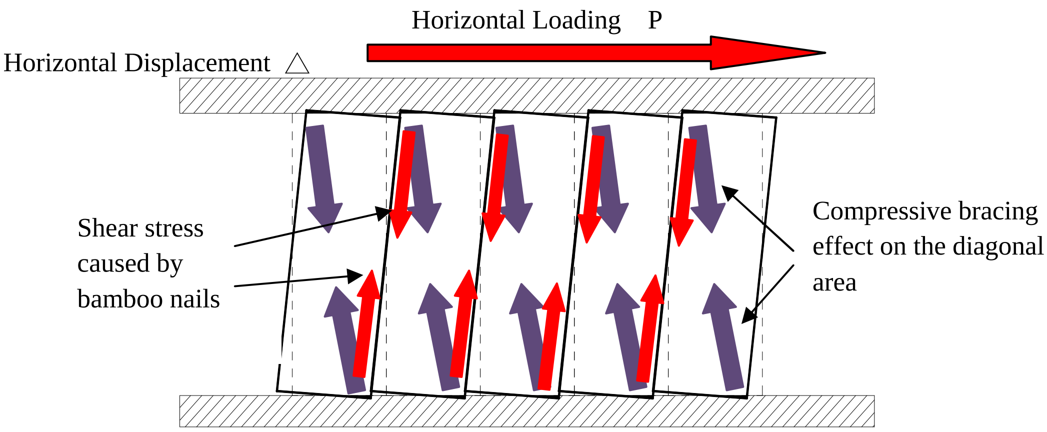

Figure 3. In-plane behavior of the wooden panel under horizontal load

3.1. Compressive Bracing Effect of Individual Panel Diagonal Area

In assessment , the individual panel can be simplified as a compressive brace on the diagonal of the panel . As shown in Fig. 4. , we can get the expression of strain ε_D of the compressive brace(Eqn. 3.1) when the horizontal displacement of the panel unit is $\triangle_S$. Further , we can also get the expression of stress by Eqn. 3.2. The stress-strain relationship of the wood is assumed as Fig.5. The modulus of elasticity of the compressive brace is derived from the Hankinson's equation and the modified parameter setting for Chinese cedar by Wang.

$$\varepsilon_D = \frac{\Delta_S \sin\theta}{L_D} = \frac{\Delta_S \times W}{H^2 + W^2} \qquad (3.1)$$

$$\sigma_D = \varepsilon_D \times E_D = \left(\frac{\Delta_S \times W}{H^2 + W^2}\right) \times E_D \qquad (3.2)$$

$$E_D = \frac{E_{//} \times E_{\perp}}{E_{//} \times \sin^{3.1}\theta + E_{\perp} \times \cos^{3.1}\theta} \tag{3.3}$$

L_D :The diagonal length of the panel unit
H : The height of the panel unit
W : The width of the panel unit
$E_{//}$: MOE parallel to wood grain
$E_{\perp}$: MOE perpendicular to wood grain
ϕ : the angle between the diagonal line and wood grain

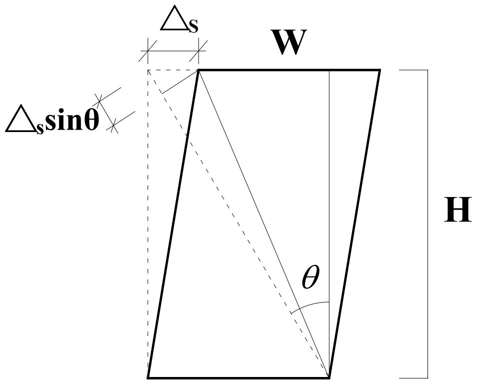

Figure 4. The deformation of individual panel

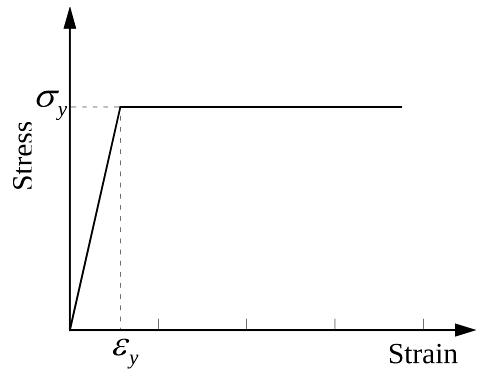

Figure 5. The stress-strain relationship of the wood

As shown in Fig. 6. , the stress of a panel element can be obtained from the stress of the compressive brace. Eqn. 3.4 to Eqn. 3.6 are the normal stress and shear stress on the interface between wooden panel and beam. Because the interface between wooden panel and beam can't resist the tensile stress , a half width of the panel would separate from the beam when the panel rocks. Thus we assume the effective acting width of the compressive brace is a half width of the panel. The calculated shear force P_S and vertical force P_V of the compressive brace are shown in Eqn. 3.7 and Eqn. 3.8.

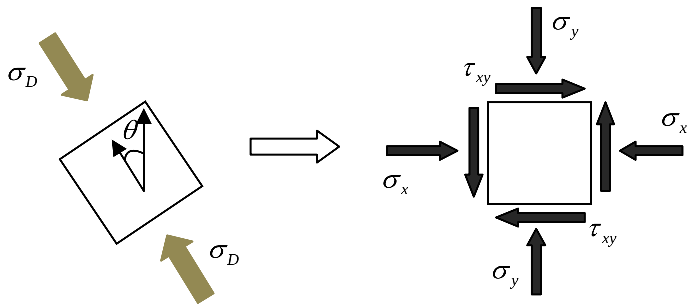

Figure 6. Stress transformation of compressive brace

$$\sigma_x = (\frac{\Delta_S \times W}{H^2 + W^2}) \times E_D \times \sin^2\theta \tag{3.4}$$

$$\sigma_y = (\frac{\Delta_S \times W}{H^2 + W^2}) \times E_D \times \cos^2\theta \tag{3.5}$$

$$\tau_{xy} = (\frac{\Delta_S \times W}{H^2 + W^2}) \times E_D \times \sin\theta\cos\theta \tag{3.6}$$

$$P_S = \frac{W \times t}{2} \times \tau_{xy} = \frac{W \times t}{2}(\frac{\Delta_S \times W}{H^2 + W^2}) \times E_D \times \sin\theta\cos\theta \tag{3.7}$$

$$P_V = \frac{W \times t}{2} \times \sigma_y = \frac{W \times t}{2}(\frac{\Delta_S \times W}{H^2 + W^2}) \times E_D \times \cos^2\theta \tag{3.8}$$

3.2 The displacement of the panel caused by the compressive deformation of the beam

As the panel rocks under in-plane loading , it will act compressive force to the beam and cause the beam to have compressive deformation. Fig.7. shows the additional displacement $\triangle_R$ of the panel caused by the compressive deformation of the beam. In the compressive area of the beam , the deformation distribution assumption is illustrated in Fig.8. The compressive deformation decreases linearly from edge corner to the panel center, and the maximum deformation $\triangle_{HB}$ on the beam edge corner can be formulated as Eqn. 3.9.

$$\Delta_{HB} = \frac{W \times \Delta_R}{2H} \tag{3.9}$$

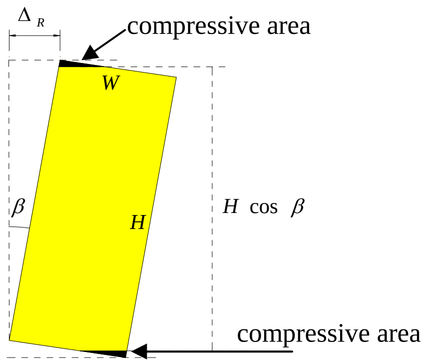

Figure 7. The displacement caused by the compressive deformation of the beam

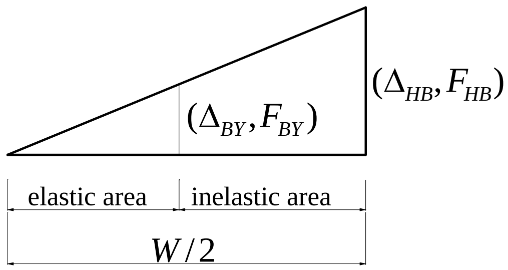

Figure 8. The deformation assumption of the beam

The compressive stress and deformation of the beam are related to both the dimension of the beam and the fillister(Fig. 9.). For estimating the compressive force and deformation of the beam , the strength F_{BY} (Fig. 10.) of the unit length of the beam is assumed that the stress on the surface of the fillister is equal to the compression strength perpendicular to the grain. The strength F_{BU} is depended on the situation when the average stress of the beam reaches the strength perpendicular to the grain. According to this assumption , the compression strength and deformation can be obtained as:

$$F_{BY} = \sigma_{By} \times b \tag{3.10}$$

$$\Delta_{BY} = \frac{\sigma_{By} \times b}{B \times E_{\perp}} \left[\frac{(B-b)^2}{4b} + D - d \right] \tag{3.11}$$

$$F_{BU} = \sigma_{By} \times B \tag{3.12}$$

$$\Delta_{BU} = \frac{B-b}{2} + \frac{\sigma_{BY}(2D - 2d - B + b)}{2E_{\perp}} \tag{3.13}$$

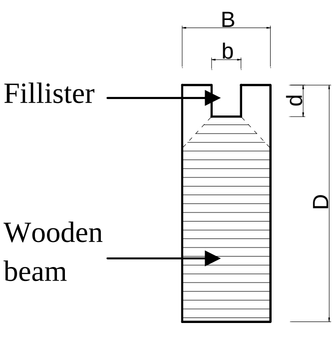

Figure 9. The Cross-sectional detail of the beam

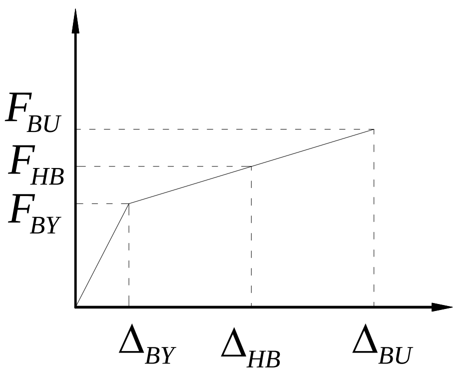

Figure 10. The force-deformation relationship of the unit length of the beam

Then , the final expressions of compressive force F_{Bc} of rocking panel in the range is given as following:

For $\Delta_{HB} \leq \Delta_{BY}$

$$F_{Bc} = \frac{1}{2} \times \frac{W}{2} \times F_{HB} = \frac{W^2 \times \Delta_R}{8H} \left[\frac{B \times E_{\perp}}{\frac{(B-b)^2}{4b} + D - d} \right] \quad (3.14)$$

For $\Delta_{BY} < \Delta_{HB} \leq \Delta_{BU}$

$$F_{Bc} = \frac{H \times \Delta_{BY} \times F_{BY}}{2\Delta_R} + \frac{1}{2}\left(\frac{W}{2} - \frac{H \times \Delta_{BY}}{\Delta_R}\right)\left[2F_{BY} + \frac{F_{BU} - F_{BY}}{\Delta_{BU} - \Delta_{BY}}\left(\frac{W \times \Delta_R}{2H} - \Delta_{BY}\right)\right] \quad (3.15)$$

Because the compressive force F_{Bc} of rocking panel is the reacting force of vertical force P_V of the compressive brace, the relationship between F_{Bc} and P_V can be got by Eqn. 3.16.

$$P_V = F_{Bc} \quad (3.16)$$

3.3 The contribution of bamboo nails

From the moment balance of the panel , as shown in Fig.11. , the resisting contribution of bamboo nails can be obtained by Eqn. 3.17. Further , from Fig.12 , the relationship between the displacement △ of the panel and shear deformation of the bamboo nails can be generated. The shear deformation of the bamboo nails is equal to $W\tan\alpha$. For the angle α is very small , we can replace $\tan\alpha$ with $\sin\alpha$ and get the Eqn.3.18.

$$P_N = \frac{F_N \times N \times W}{H} \quad (3.17)$$

$$\Delta_N = W \tan\alpha \cong W \sin\alpha = \frac{\Delta \times W}{H} \quad (3.18)$$

F_N :the dowel force per bamboo nail

N :the number of bamboo nails

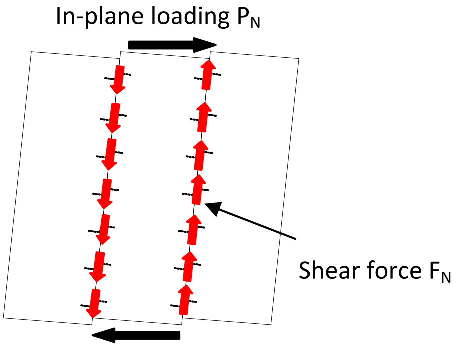

Figure 11. The shear force of bamboo nails

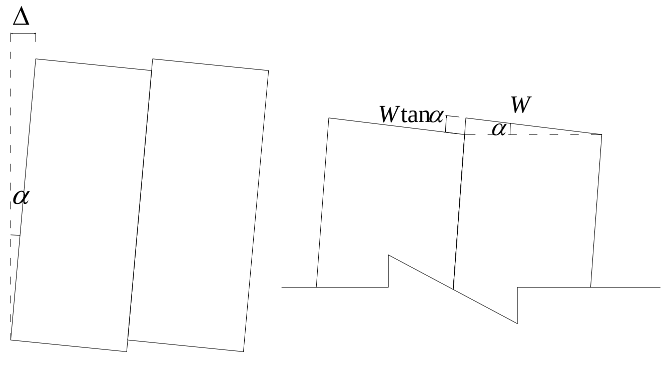

Figure 12. The shear deformation of bamboo nails

For the dowel action of bamboo nail , Chang(2007) conducted a double shear test for the bamboo nails (Fig.13). According to this test , the dowel force F_N can be simplified as following:

$$F_N = \begin{cases} 241.6 \times A_N \times \Delta_N \ \ kgf & 0 \leq \Delta_N \leq 1.32cm \\ 318.2 \times A_N \ \ kgf & 1.32cm < \Delta_N \leq 4cm \end{cases} \quad (3.19)$$

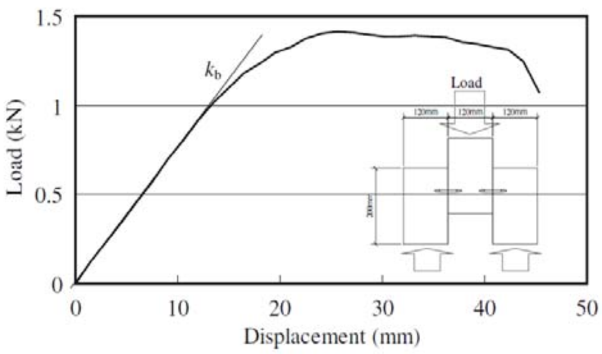

Figure 13. Loading–displacement relation of bamboo nail(Chang ,2007)

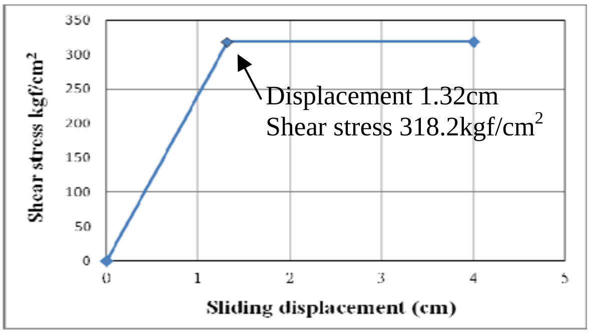

Figure 14. The stress-displacement relationship of bamboo nail adopted for analysis

4. THE COMPRESSSIVE BRACE MODEL OF THE WOODEN WALL

Fig.15 shows the load and deformation of the wooden wall. The compressive force and deformation of the compressive brace can be written with P and Δ by using Eqn. 4.1 and Eqn.4.2. Here φ is the angle from diagonal line to vertical line.

$$\Delta_d = \Delta \times \sin\varphi \tag{4.1}$$

$$P_d = \frac{P}{\sin\varphi} \tag{4.2}$$

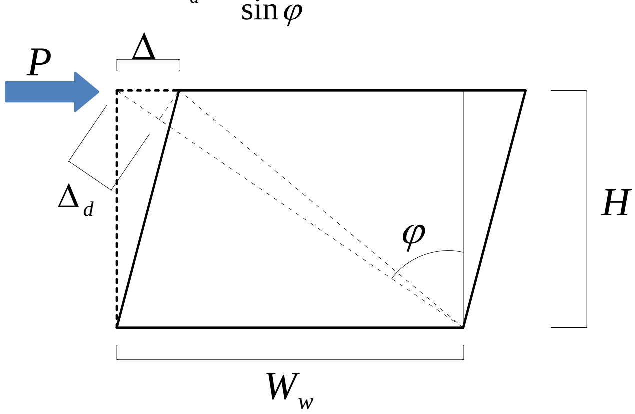

Figure 15. The force and deformation relationship between wall and compressive brace

After getting the loading-displacement relationship of the wooden wall , the performance stages of the wall can be defined further. Fig.16 is the adopted loading-displacement curve of the compressive brace. This curve was defined by three damage behavior of the wall , which are

(1) The maximum compressive stress F_{HB} of the beam reaches the strength F_{BY} , and the loading and deformation of the brace is defined as P_y and Δ_y. According to the stiffness of the compressive brace at first stage , the effective width W_d of the compressive brace can be define as

$$W_d = \frac{P_y \times \sqrt{W_w^2 + H^2}}{\Delta_y \times t \times E_d \times \sin^2\varphi} = \frac{P_y \times L_d}{\Delta_y \times t \times E_d \times \sin^2\varphi} \tag{4.3}$$

$$L_d = \sqrt{W_w^{\ 2} + H^2} \tag{4.4}$$

$$E_d = \frac{E_{//} \times E_{\perp}}{E_{//} \times \sin^{3.1}\varphi + E_{\perp} \times \cos^{3.1}\varphi} \tag{4.5}$$

(2) The bamboo nail reaches ultimate shear strength and the wall usually performs the ultimate strength P_u at the same time.

(3) The maximum compressive stress F_{HB} of the beam reaches the strength F_{BU} , and the deformation

of the brace is defined as Δ_{bd} .

Then , as shown in Fig.17, four plastic hinge properties of the compressive brace could be set for nonlinear analysis.

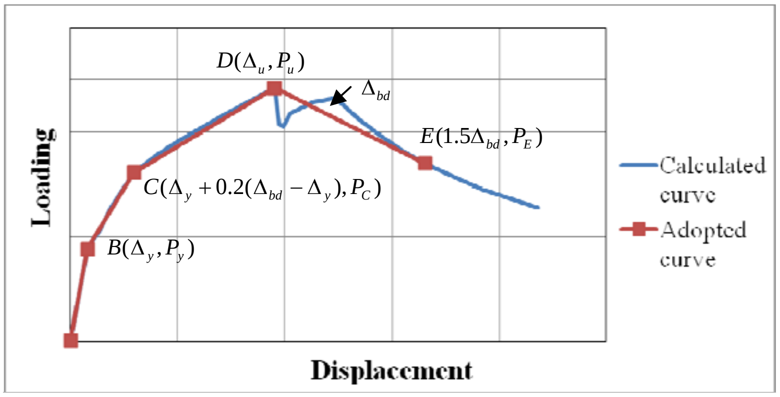

Figure 16. The adopted loading-displacement relationship curve of the modeling compressive brace

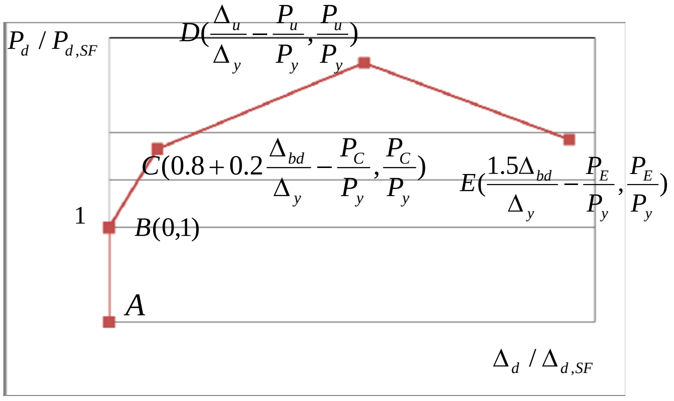

Figure 17. The plastic hinge properties setting of the modeling compressive brace

5. SEISMIC ASSESSMENT APPLICATION

The bracing model developed for the traditional wooden wall has been practiced in the seismic assessment of Yan-shuei Octagonal Hall which is a registered heritage architecture of Tainan City. The Hall is two-storeys wooden building. Fig.18 , Fig.19 and Fig.20 show the construction arrangement of wooden panel wall.

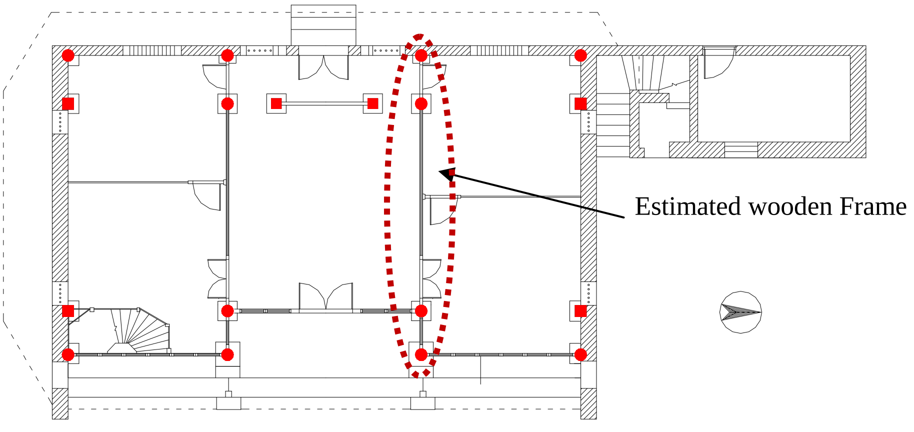

Figure 18. The first floor plan of Yanshuei Octagonal Display Hall (Chang ,2004)

Figure 19. The partition wall on 1st floor plan

Figure 20. The partition wall on 2nd floor plan

5.1 The analysis model of the wooden frame

Table 5.1 lists the material properties of wood and bamboo nail used in the seismic assessment. Fig.21 is the analysis model of the wooden frame. In the model , the equivalent compressive bracing of wooden panel walls were given corresponding axial force plastic hinge setting. Besides , all beam-column joints also has been assigned with different moment plastic hinge by the method given in the reference (Chang et.al,2011).

Table 5.1 The material property

The density of the wood	0.43	
MOE parallel to wood grain	70000	kgf/cm^2
Compressive strength parallel to wood grain	120	kgf/cm^2
MOE perpendicular to wood grain	2800	kgf/cm^2
Compressive strength perpendicular to wood grain	40	kgf/cm^2
The shear stiffness of the bamboo nail(Chang ,2007)	38.57	kgf/cm

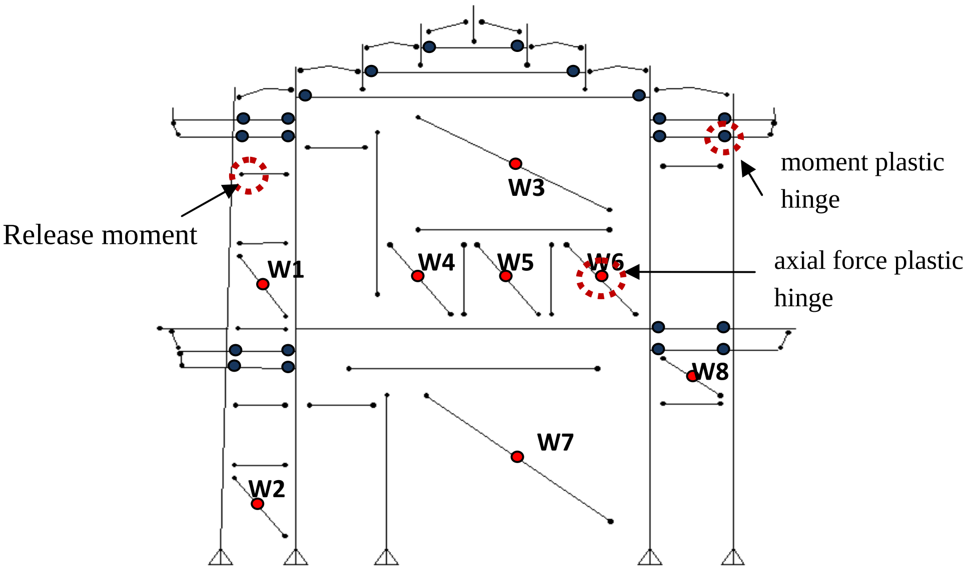

Figure 21. Analysis model of the wooden frame

5.2 The pushover analysis result and discussion

5.2.1 The damage mode

Fig.22 is the distribution of plastic hinges as drift angle of the roof reached 0.171. The circled plastic hinges of the member exceeds the ultimate strength (stage D). Under the in-plane push load , the joints in the porch area damaged first , and then the wooden wall brace in the porch area exceeded the ultimate strength . The main wooden wall in the first floor damaged until the drift angle of the building reached 16.65% , which is much later than the damage of beam-column joint. Obviously , during earthquake excitation , this wooden panel wall will help avoiding the building collapse , even the wood frame has performed considerable large deformation. This phenomena also has been observed very often in the 1999 Chi-Chi earthquake.

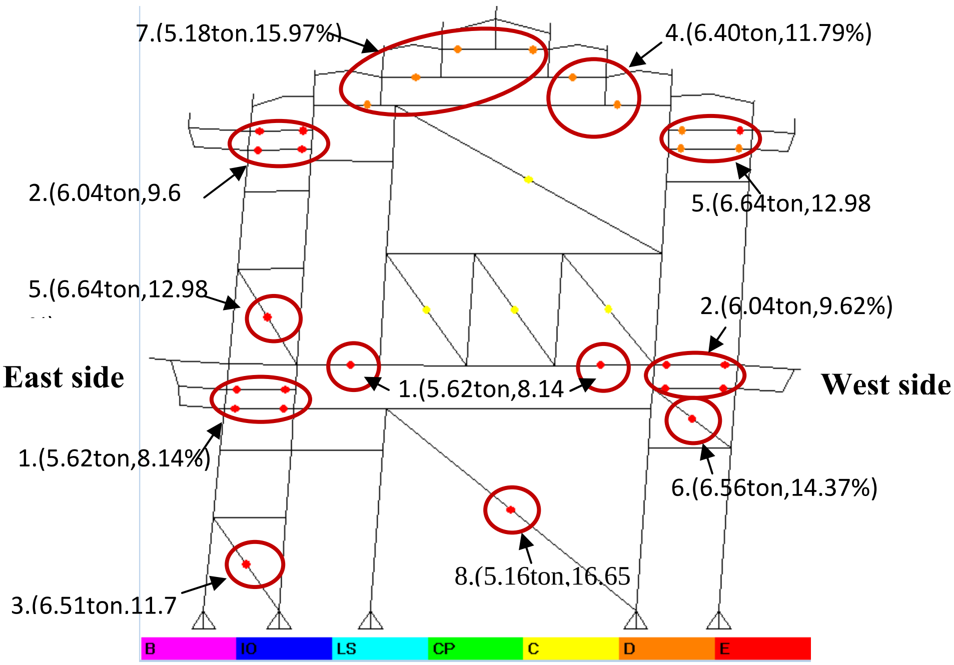

Figure 22. The damage mode of the frame when the drift angle on the roof reach 0.171

5.2.2 Discussion

Fig.23 shows the comparison of the wooden panel walls under in-plane loading. The ultimate resistant loading and the stiffness of the frame with wooden panel wall is much higher than that without wooden panel wall. The ultimate resistant loading of the frame with wooden panel wall is 1.74 times of the pure frame. This result explains that the wooden panel wall is indeed an important element to resist the seismic loading and needs to be considered in the seismic assessment of traditional wooden building.

Besides, as shown in Fig.24 , the storey stiffness of the second floor is higher than that of the first floor. At maximum load , the storey drift angle of second floor is only 83% of the first floor. This is because some secondary wooden beams and columns are arranged in the wooden wall of second floor. The wall is divided into four small parts(W1~W4) , and for each part(W1~W4) , the height/width ratio becomes smaller. This result also means that changing the construction of the wall , especially reduce height/width ratio of the panel , can effectively improve the stiffness of the traditional wooden frame.

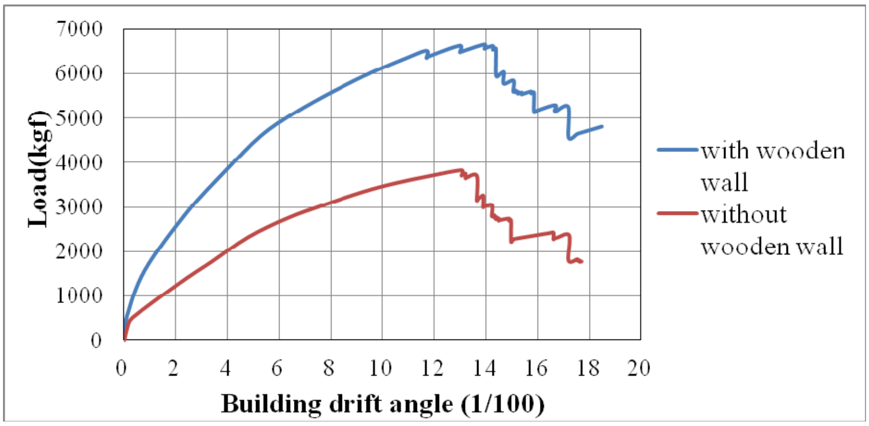

Figure 23. The contribution of the wooden panel wall

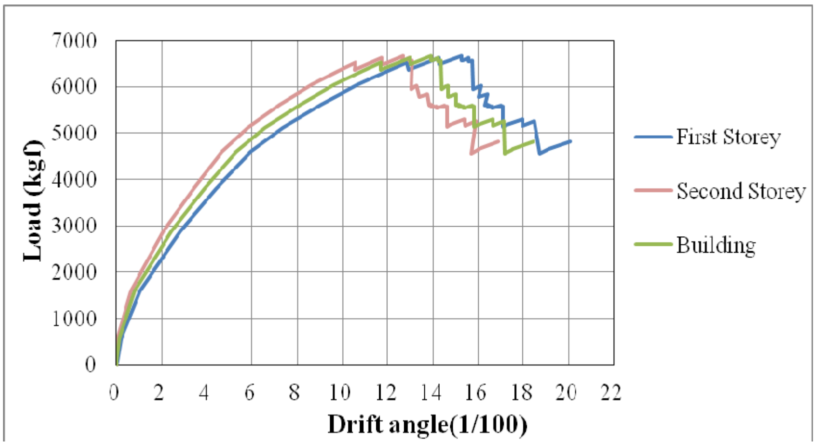

Figure 24. The comparison of the drift angle of different storey

6. CONCLUSIONS

In this study , the panel wall used to infill the wooden frame of traditional building is modeled as an equivalent compressive bracing , which is based upon the detail behavior of unit panel. The plastic hinge properties of the bracing are defined for nonlinear analysis , which is related to the compressive damage of the wooden beam and the dowel action of bamboo nails. The developed bracing model has been used in the seismic assessment of Yan-shuei Octagonal Hall in Tainan City. The analysis shows the panel walls will increase the structure stiffness and the ultimate resistant load. In addition , the panel wall is helpful to avoid the frame totally collapse after the beam-column joints of the frame has suffered seriously damage. This phenomena also has been observed very often in the 1999 Chi-Chi earthquake.

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