Performance of Shear Wall Composed of LVL and Cement Fiber Board Sheathing

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Abstract
In this study, an experiment on shear walls has been carried out to determine structural reliability; this is necessary information for practitioners when constructing non-engineered houses or earthquake-resistant residential buildings. Analytical and numerical analyses have also been conducted, to establish an appropriate method to estimate the performance of this kind of structure that can be used in the future. A 3D specimen made of a Laminated Veneer Lumber (LVL) structural frame sheathed by Fiber Cement Board (CFB) with shear wall elements embedded in the wall without openings, termed Type 36 hereafter, was tested in the study. Static push and pull cyclic load was applied at the top of the specimen to simulate the seismic load.

The study found that the Non-Engineered earthquake resistant Type 36 house needs two shear wall panels without openings; these walls act as structural elements, to resist seismic force, at the zone with the highest risk of earthquake in Indonesia.

The structural system consisting of wood and cement-based building materials, shows sufficient resistance to earthquake, and so the shear wall panel can be used as a structural element in houses and earthquake-resistant residential buildings.

Keywords: earthquake-resistant; shear wall; LVL; CFB

1. Introduction
From recent damage, due to earthquakes in various places in Indonesia, it appears that residential houses made of concrete and/or masonry were insufficient and collapsed in severe earthquakes. More than ten years ago in Kobe, Japan, there was also a severe earthquake and huge damage was observed on many timber houses. Since then, not only the Japanese government but also universities and commercial companies have been paying effort to make timber residential houses stiffer, stronger and tougher. Following this good previous example, an attempt was initiated in Indonesia to make residential houses more capable of surviving severe earthquakes in the future.

This paper conducted shear wall reliability studies by using Laminated Veneer Lumber (LVL) engineered wood frame, sheathed with Cement Fiber Board (CFB), which we usually term Type 36 earthquake-resistant house in Indonesia.

The studies also carried out theoretical analysis, which includes analytical analysis based on Sugiyama model, and numerical analysis using non-linear structural analysis software SNAP V3. The theoretical study was compared with full-scale structural testing of a 3D-specimen in the laboratory.

2. Experimental Studies
The standard house design for low-income people in Indonesia is an earthquake-resistant Type 36, of which the floor plan is 6 x 6 m (Fig.1.). It is constructed with LVL walls and roof frames and walls, sheathed by CFB, with a corrugated metal roof tile at the highest earthquake risk zone (zone 6) in Indonesia (Ministry of Public Works of Indonesia, 2002). Because most of the places in Indonesia are earthquake-prone, buildings must withstand earthquakes. In order to avoid excessive concentration of force on a structural component, shear walls are installed to provide a uniformly distributed stiffness.

The shear wall panels examined are 2700 mm in height and 6000 mm in length. As two mutually parallel shear walls were used in this experiment, each shear wall panel should carry about 20 to 40 kN. The
seismic design load for Type 36 is equal to 68.37 kN (as shown in Table 1.) in accordance with the Indonesian Standard with maximum Peak Ground Acceleration (PGA) of 0.3g. (Ministry of Public Works of Indonesia, 2002)

Table 1. Seismic Design Load

| Weight of object                | (N)         |
|--------------------------------|-------------|
| Walls                          | 29991.62    |
| Roof tile, roof frame and ceiling | 82461.12   |
| Total house                    | 112452.74   |
| Seismic Design Load            | 68371.26    |

This shear wall uses two relatively new materials in construction in Indonesia i.e. LVL and CFB. LVL is made by Sengon wood (Paraserianthes Falcataria) and Rubber wood (Hevea Brasiliensis) taken from planted forest. The material properties of LVL are listed in Table 2.

Table 2. Mechanical and Physical Properties of LVL

| Properties                                      | Value   | Unit |
|------------------------------------------------|---------|------|
| Moisture content                               | 10.7    | (%)  |
| Density                                        | 540     | (kg/m³) |
| Modulus of Elasticity parallel to the grain; MOE | 7511    | (MPa) |
| Modulus of Rupture, parallel to the grain; MOR | 62.2    | (MPa) |
| Modulus of Elasticity perpendicular to the grain; MOE | 6174    | (MPa) |
| Modulus of Rupture, perpendicular to the grain; MOR | 51.4    | (MPa) |
| Tension parallel to the grain                  | 40.8    | (MPa) |
| Tension perpendicular to the grain             | 1.8     | (MPa) |
| Shear                                          | 5.4     | (MPa) |

Another material is CFB, made of cement mortar with bamboo fibers produced with size of 1800 x 900 x 18 mm. The material properties of CFB are given in Table 3.

Table 3. Mechanical and Physical Properties of CFB

| Property                                      | Value   | Unit   |
|-----------------------------------------------|---------|--------|
| Density                                       | 1220    | (kg/m³) |
| Modulus of Elasticity; MOE(1)                 | 31670   | (MPa)  |
| Modulus of Rupture; MOR(1)                    | 94,808  | (MPa)  |
| Shear Modulus; G(4)                           | 700     | (MPa)  |

(1)Subiyanto 2007 (not published)

3.1 Joint specimen

To determine the connection properties, several types of joint tests were conducted. The behaviour of the connection between LVL and CFB, which is fastened by nails with a diameter of 2.7 mm and a length of 50 mm, was estimated by a single shear monotonic test (Fig.2.). Because different behaviors in each direction were expected, the connection between LVL members, fastened by nails length of 100 mm, was estimated by tensile and compression monotonic loading tests (Fig.3.). The entire test was conducted on the Universal Testing Machine (UTM) with loading speed of 2 mm per minute for the tensile test and 0.5 mm per minute for the compression tests (Fig.2., Fig.3., Fig.4. and Fig.5.).

3.2 3D Specimen

A 3D full-scale specimen with a height of 2700 mm, a width of 3000 mm and a length of 6000 mm, was set-up on the reaction wall and strong floor. This test specimen was composed of 50 x 90 mm LVL for all framing members; all the main columns were fixed on the foundation, allowing no uplift for any columns. CFB sheathing boards of 18 mm thickness were nailed onto the shear wall system-framing members using smooth shank nails with a diameter of 2.7 mm and length of 50 mm, and spacings of 150 mm.

These test data were used for numerical analysis to clarify the analytical calculations and structural test results.
In addition to the sheathing boards, LVL bracing was also added at both ends of the longitudinal walls, for reinforcing the shear walls (Fig. 7.).

There are openings to model doors and windows in walls perpendicular to the longitudinal walls. Fig. 7.-a), b) and c) show details of specimen configuration and locations of transducers for measuring the displacements.

Fig. 6. A 3D-specimen for Destructive Test

Fig. 7 Specimen Configuration and Locations of Transducers

Fig. 7.b shows the braced shear wall element located at the left and right sides of the wall without openings. Fig. 7.c shows the installation of CFB, as a wall sheathing, on the LVL frame. Fig. 8. shows the sheathing nail pattern.

Fig. 8. Nail Pattern on CFB Sheathing Panel A

There are two panel sizes, panel A 1800 x 900 mm and panel B 600 x 900 mm. Installation of CFB on the LVL frame was fastened by nails.

Fig. 9. Nail Pattern on CFB Sheathing Panel B

Fig. 10. depicts the loading protocol adopted in this experiment.

4. Results and Discussions

4.1 Prediction Methods of Entire Structure

In order to calculate the behavior of the entire structure, it was assumed that the shear wall can be separated into two individual parts; one of which is the sheathing panel and another is the LVL frame. Behavior of the sheathing panel can be predicted by analytical method, whilst performance of the LVL frame can be estimated by FEM method. The combination of these two behaviors makes it possible to predict the entire behavior.

4.2 Analytical Methods

Analytical calculation of the shear wall was carried out based on the concept of Sugiyama's model. (Japan
2x4 Construction Association, 2007; Sugiyama and Matsumoto, 1993a; Sugiyama and Matsumoto, 1993b; Sugiyama and Matsumoto, 1994).

It should be noticed that the nails located at the corners of each panel were referenced by either horizontal number for \( n_a \) or \( n_b \) or vertical number for \( m_a \) or \( m_b \). This definition implies that corner nails are subjected to both directional shear forces at the same time, thus this location's nail has been considered as the most critical nail that might relate to the onset of yielding of shear wall.

Fig. 11. shows a mechanical model of the shear wall in which individual panels are assumed to share the same shear deformation angle with each other at least up to the instant of yielding.

From equilibrium condition of the external and internal moments, equation (1) is obtained

\[
P H = 9(g_{aA} g_{AB}) + 3(g_{bB} g_{BB})
\]  

...(1)

The compatibility condition that all panels should share the same deformation angle will lead to equation (2)

\[
\begin{bmatrix}
\gamma_{wall} \\
\gamma_A \\
\gamma_B
\end{bmatrix} =
\begin{bmatrix}
\delta_A \\
\delta_B
\end{bmatrix}
\begin{bmatrix}
H \\
G_CFB \\
G_CFB
\end{bmatrix}
\]

...(2)

In panel-A and panel-B, the following approximated shear force-shear deformation relationships can be assumed in accordance with the researches by Sugiyama and Matsumoto. (Japan 2x4 Construction Association, 2007; Sugiyama and Matsumoto, 1993a; Sugiyama and Matsumoto, 1993b; Sugiyama and Matsumoto, 1994)

For panel-A;

\[
\delta_A = \frac{1}{Q_A} = \frac{g_a}{K_{A}} = \frac{1}{G_{CFB} t A} + \left[ \frac{1}{n_A} + \frac{1}{m_A} \left( \frac{g_a}{L_A} \right)^2 \right] \left( \frac{2}{K_s} \right)
\]  

...(3)

\[
\text{for panel-B;}
\]

\[
\delta_B = \frac{1}{Q_B} = \frac{g_b}{K_{B}} = \frac{1}{G_{CFB} t B} + \left[ \frac{1}{n_B} + \frac{1}{m_B} \left( \frac{g_b}{L_B} \right)^2 \right] \left( \frac{2}{K_s} \right)
\]  

...(4)

where,

- \( G_{CFB} \): Shear rigidity of cement-fiber board (N/mm²).
- \( t \): Thickness of cement-fiber board (mm).
- \( K_s \): Slip modulus of nailed-on cement fiber board with LVL frame (N/mm).
- \( K_{A} \): Shear stiffness of panel-A (N/mm).
- \( K_{B} \): Shear stiffness of panel-B (N/mm).

Based upon Sugiyama and Matsumoto's assumption shown in Fig. 12, and Fig. 13., only the force component acting on the nail along the perimeter of the panel was considered and, for ease of design, it was also assumed to be constant within the panel.

Yielding of the shear wall will occur when the resultant shear force acting on the nail located at the corner of each panel achieves the ultimate value for the joint of CFB nailed on LVL.

For panel-A, the resultant force acting on the nail located at the corner of panel A is expressed in equation (5)

\[
q_{\text{res} \text{, panel-A}} = \sqrt{q_{HA}^2 + q_{VA}^2}
\]

\[
= P \left[ \frac{K_A g_A}{K_{Global n_A}} \right]^2 + \left[ \frac{K_A g_A^2}{K_{Global L_A m_A}} \right]^2
\]

...(5)

From equation (5) the yielding load of panel A is obtained by equation (6)

\[
P_A = \frac{f_{\text{yield}}} \sqrt{ \left( \frac{K_A g_A}{K_{Global n_A}} \right)^2 + \left( \frac{K_A g_A^2}{K_{Global L_A m_A}} \right)^2}
\]  

...(6)
where,

\[ f_{nail-u} \text{ (N)} : \text{Ultimate strength of CFB nailed on LVL frame. This value should be determined by the nailed single shear joint test.} \]

\[ K_{Global} = \frac{9K_A G_A^2 + 3K_B G_B^2}{H} \]

For panel-B, the resultant force acting on the nail located at the corner of panel B is expressed in equation (7)

\[ q_{resultant-B} = \sqrt{q_{HB}^2 + q_{FB}^2} \]

\[ = P \left( \frac{K_B g_B}{K_{Global} h_B} \right)^2 + \left( \frac{K_B g_B}{K_{Global} L_B m_B} \right)^2 \]...

(7)

From equation (7) yielding load of panel B is obtained by equation (8)

\[ P_{yB} = \frac{f_{nail-u}}{\sqrt{\left( \frac{K_B g_B}{K_{Global} h_B} \right)^2 + \left( \frac{K_B g_B}{K_{Global} L_B m_B} \right)^2}} \]...

(8)

Finally, the yielding load of the shear wall will be determined as the smaller value of both panels' yielding loads.

\[ P_{y-Wall} = \min \left\{ P_{yA}, P_{yB} \right\} \]...

(9)

4.3 FEM Analysis of LVL frame

The non-linear FEM program SNAP V3, developed by Kozo System/Kentiku Pivot Co., Ltd., which runs on the platform of Windows XP system, was used in this study.

The numerical studies were performed using SNAP V3 with modeling of the LVL frame as shown in Fig.14. The numerical study assumed the connections as elasto-plastic springs with stiffness obtained from the experiments of the connection described above. In the actual calculation procedure, the second stiffness of each spring was assumed as 0.01 of first stiffness to avoid non-convergence in calculation.

4.4 Experimental Results

Fig.15. shows test results of the CFB-LVL nailed joint. Table 7. shows individual characteristic values for each specimen (evaluated based on the perfect bi-linear approximation method assigned in Japanese Standard). (Japan 2x4 Construction Association, 2007) In Fig.15., the averaged perfect bi-linear curve was obtained by calculating the mean value of these characteristic values. The average ultimate strength \( P_u \) and stiffness \( K \) in Table 7. were used in equations (3), (4), (6) and (8) for predicting strength and stiffness of...
The CFB-LVL connection fastened by nails showed damage to the nails and LVL while the CFB was intact. The nail deformed extremely at the interface between CFB and LVL, and resulted in embedment in the LVL. The nail was pulled out at the late stage of the test. The test of the connection between LVL members, fastened by nails showed that damage occurred at both the nail and LVL. The nail deformed in the perpendicular direction, while LVL embedment and nail holes became larger, so that finally the nails were pulled out as shown in Fig.16 and Fig.17.

Fig.16. Angle Joint Condition After Test

Fig.17. Middle Joint Condition After Test

Fig.18. Load (P)-Relative to Displacement (S) and Relationship of LVL End-joint Member Fastened by Nail

Fig.19. Load (P)-Relative to Displacement (S) and Relationship of LVL Middle-joint Member Fastened by Nail

Fig.20. Load (P)-Relative to Displacement (S) and Relationship of LVL Angel-joint Member Fastened by Nail

Figs.18., 19. and 20. of the load (P)-relative to the displacement (S) show that, for the LVL, the compression performance was dominant compared with tensile. Fig.21. shows the load (P)-deformation to angle (γ) relationship of the 3D specimen. It appears from Fig.22. that yielding of the 3D specimen occurred at a deformation level of around $1/75 \text{ rad (0.0133)}$ and the maximum load was obtained at the deformation level of $1/30 \text{ rad (0.0333)}$, showing a sudden fatal load drop, leading to deformation increase to a level of $1/15 \text{ rad (0.0667)}$.

Fig.22.-a) shows that an initial failure occurred in the nailing between upper and lower panels and Fig.22.-b) shows the final stage of the destruction of the sheathing panels.

4.5 Discussions

Fig.23. shows a load (P)-deformation angle (γ) relationship of the LVL frame, in which the parameters shown in Table 6. were used for spring constants.
The trend for increasing strength after yielding seems to be due to the compression spring having a larger strength than the tension spring; hence even though the tension springs yields, the compression spring might remain elastic.

Fig.24. shows comparisons between the observed load-deformation angle relationship of the 3D specimen and that predicted by the theoretical models derived previously. The dot-dash line in Fig.24. indicates the calculated stiffness and yielding load of the sheathing panel predicted by equations (3), (4) and (9). The continuous line with circle ends indicates the predicted stiffness of the bracing system, which was brought from the 2D FEM analysis. The bold continuous line with triangle ends indicates the total predicted stiffness and the yielding load by summing up two individual components.

In Fig.24., the horizontal bold line indicates the design value calculated using the Indonesian standard. Comparing the ultimate strength with the required strength reveals that the safety factor is about 2, which is thought to be satisfactory for Indonesian standards.

5. Conclusion

In this study, a full-scale 3D specimen was tested and compared with theoretical predictions. The following conclusions can be drawn:

1. The calculation method based on the current design guideline, for the Japanese two by four system, could give a good prediction for the actual full-scale test specimen, composed of nailed CFB sheathing shear walls with LVL frame system.

2. The performance of the 3D full-scale test shows that the shear wall has enough strength to fulfill the requirements of the Indonesian standard.

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