Strength and Stiffness of Wooden Building using Static Equivalent Analysis

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Abstract

Wooden buildings can be used to support tourism infrastructure in the West Java region including to enhance resilience to disasters, especially earthquakes. This research aimed to study the behavior of wooden buildings due to designed earthquake loads. Three dimensional structural analysis were applied to obtain parameters of the strength and stiffness behavior of the building against lateral loads. The scopes of the research were: the building functions as part of the tourism support infrastructure in Stamplat, Indragiri Village, Bandung Regency, West Java, as a lodging building. The building uses a frame system concept with the main components being beams and columns of yellow Meranti wood (*Shorea faguatiana*). The size of the building is 30 m^2. All cross-sections of beams and columns are rectangles. The static-based shear load is calculated using equivalent static analysis. The stiffness (drift) is calculated according to Indonesian earthquake code SNI 1726:2019. Design the capacity of columns and beams (strength) using reference to Indonesian National Standard SNI 7973:2013. Results of this research indicated that the nominal capacities of bending moment and shear forces of the columns and beams meet the requirements according to Indonesian timber code SNI 7973:2013. The drift of the building due to the equivalent static earthquake load in the main direction of the building does not exceed the permit limits; the stiffness of the building meets the requirements according to Indonesian seismic code SNI 1726:2019. Mechanically laminated technology provides benefits, even though the quality (class strength) of the wood is limited. If designed properly, it can be used as an earthquake-resistant building.

Keywords: Strength, stiffness, wooden bulding, static equivalent, based shear.

Introduction

Wood, in terms of strength class II-III, generally has a limited cross-sectional size. In designing of buildings in earthquake-prone locations, the placement of columns and main beams are the major concern, so that the capacity of the cross-sectional components can function optimally to distribute internal forces due to dead loads, live loads, rain loads, and lateral loads (earthquakes).

Innovation in engineered wood is the choice in this study, based on the consideration of the need to form wood with the dimensions and cross-sectional sizes as needed, using medium-grade wood. The goal is to produce earthquake-resistant buildings with a frame system, with the main components being columns and beams using mechanical lamination technology.

Analysis of building structures against lateral loads is essential to determine the strength and stiffness behavior of building structures. The goal is that when the building is used during its service life and if an earthquake occurs, there will be no structural damage that can result in loss of life or damage to the structural components of the building.

This research focuses on the use of wood as a main member of buildings to support tourism infrastructure in Stamplat, Indragiri Village, Bandung Regency, West Java.

Figure 1. Location of wooden house construction in this research (Pranata *et al*., 2022).

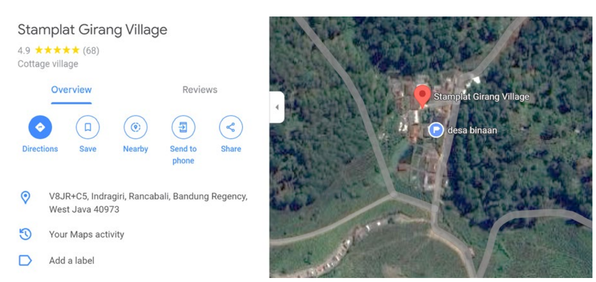

Figure 2. Google maps location of the wooden building in Stamplat, Bandung Regency, West Java.

This research aimed to study the behavior of wooden buildings which is designed for earthquake loads. The function of the building is as a guest house.

The scope used in the research is that the building functions as part of the tourism support infrastructure, located at Stamplat, Indragiri Village, Bandung Regency, West Java, as a lodging building. Figure 1 shows the planned location of the wooden building, which is near the Rancabali tea plantation. Meanwhile, Figure 2 shows the location of Google Maps coordinates, namely -7.1189 and 107.3404.

Previous research, namely studying the behavior of wooden buildings, both one-story and multi-storey, was carried out, among others, by Furqoni (2010), namely researching elevated houses against earthquakes. Manthani and Fauzan (2019) conducted research to study the behavior of the traditional West Sumatran building structures under earthquake loadings. Diredja *et al*. (2019) conducted research to study the structural performance of residential buildings using Mahogany Glulam wood. Research regarding the performance evaluation of low-rise buildings has also been carried out by Pranata *et al*. (Pranata *et al*., 2021). Mahapatni *et al*. (Mahapatni *et al*., 2023) have also carried out research on the analysis and design of traditional Balinese buildings.

Mechanical laminated wood is made by combining two or more wood laminae to obtain a larger cross-sectional size. Potential horizontal shear due to internal force mechanisms can be prevented by fasteners installed at certain intervals. This product is used as a structural component for wide-span buildings. Beams are joined mechanically using fasteners (Fraserwood, 2024; Pranata *et al*., 2013).

Materials and Methods

The building uses a frame system concept (Pranata et al., 2022) with the main components being beams and columns of yellow Meranti wood (*Shorea faguatiana*). The size of the building is 30 m^2 or 6m x 5m. All cross-sections of beams and columns are rectangles. The dimension of the column is 100mm x 200mm, the main beam dimension is 100mm x 200mm, the secondary beams and roof ring beams dimensions are 100mm x 100mm, and the roof beam dimension is 100mm x 100mm.

The Designed Earthquake Load

The lateral or designed earthquake load was calculated using equivalent static analysis according to Indonesian earthquake SNI 1726:2019 (BSN, 2019), with S_{DS} parameters of 0.92g and S_{D1} of 0.51g (PusGen, 2021). The stiffness (drift) was calculated according to Indonesian earthquake SNI 1726:2019 (BSN, 2019).

The design of the capacity (strength) of columns and beams implemented SNI 7973:2013 (BSN, 2013). References to residential building live loads refered to the Indonesian loading code SNI 1727:2020 (BSN, 2020). The three-dimensional structure analysis using the equivalent static method was carried out using SAP2000 software (CSI, 2013).

Physical and Mechanical Properties of yellow Meranti (*Shorea faguatiana*)

In this research, data on the physical properties (specific gravity) and mechanical properties of wood (modulus of elasticity, modulus of rupture, compressive strength, and shear strength) of yellow Meranti (*Shorea faguatiana*) wood species using references from the Wood Handbook (FPL, 2021) as shown in Table 1.

Table 1. Physical and mechanical properties of yellow Meranti (*Shorea faguatiana*) species (FPL, 2021).

References	MoE (MPa)	MoR (MPa)	F_c (MPa)	F_v (MPa)	SG
FPL., 2021	9000	55.2	40.7	10.5	0.46

MoE is the elastic moduli of timber that used as main beams, main columns, secondary beams, and roof-beams. MoR is the modulus of rupture of timber. Fc is the compression strength of timber. Fv is the shear strength of the timber. SG is the specific gravity ot the timber.

Equivalent Static Analysis

The equivalent static analysis is a simplified technique to substitute the effect of earthquake for a static force distributed laterally on a structure. The total applied-based forces (V) are evaluated in the two main axes of the building (Beer *et al*., 2018).

Equivalent static analysis can be used as a method of analysis to estimate the force on the structures due to lateral or earthquake load. This analysis can be used on low-rise buildings (Faiz and Kumar, 2023).

Table 2. Parameter of design spectra (PusGen, 2021).

Parameters	Value
PGA MCEG	0.5137g
S_S MCEr	1.1467g
S_1 MCEr	0.5160g
T_L	20 sec.
T_o	0.11
T_s	0.55
S_{DS}	0.92
S_{D1}	0.51

In this research, the equivalent static earthquake load was calculated based on procedures in accordance with Indonesian earthquake code SNI 1726:2019 (BSN, 2019). The parameters required for calculating the static base shear force using design spectra data obtained from the Indonesian earthquake map (PusGen, 2021) are shown in Table 2. Peak Ground Acceleration (PGA) is the surface acceleration of the mapped Maximum Considered Earthquake Ground Motion (MCEG) peak, S_s is the acceleration parameter of the Maximum Considered Earthquake (MCE) spectral response of the earthquake map in the short period, 5 percent attenuation, S_1 is the acceleration parameter of the MCE spectral response of the earthquake map in the period of 1 second, T_L is a long period transition map, T_0 is 0.2 S_{D1}/S_{DS}, T_S is S_{D1}/S_{DS}, and S_{Ds} is the acceleration parameter of the spectral response for short periods (attenuation 5 percent), S_{D1} is the acceleration parameter of the spectral response for a period of 1 second (attenuation 5 percent) (BSN, 2019).

Provisions for Strength of Building Components

Column and beam as a structural members of the wooden buildings can be designed by referring to Load and Resistance Factor (LRFD) method in the Indonesian timber code SNI 7973:2013 (BSN, 2013).

The design for factored compressive load on the column member can be calculated using Equation 1. The design for factored bending moment for column and beam members can be calculated using Equation 2. Furthermore, the design for factored shear force for column and beam members can be calculated using Equation 3. The stiffness behavior of the beam, namely deflection due to live load, can be calculated using Equation 4, the value of which must not exceed the allowable limit.

$$P_u \le P' \quad (1.a$$

$$P' = F_c'.A \quad (1.b)$$

$$F_C' = F_c.C_M.C_t.C_F.C_i.C_p.K_F.\phi.\lambda \quad (1.c)$$

$$M_u \le M' \quad (2.a)$$

$$M' = F_b'.S_x \quad (2.b)$$

$$F_b' = F_b.C_M.C_t.C_L.C_F.C_{fu}.C_i.K_F.j.\lambda \quad (2.c)$$

$$S = I_x / y \quad (2.d)$$

$$V_u \le V' \quad (3.a)$$

$$V' = F_v'.\frac{2.b.d}{3} \quad (3.b)$$

$$F_v' = F_v.C_M.C_t.C_i.K_F.j.\lambda \quad (3.c)$$

$$\delta_{max} = L/400 \quad (4)$$

where:

P_u = factored compression load of column (N)
P' = the value of adjusted compression force (N)
F_c' = value of adjusted compression strength (MPa)
A = bruto cross-section of the column (mm^2)
M_U = factored bending moment (N.mm)
M' = value of adjusted bending moment (N.mm)
F_b' = value of adjusted bending strength (MPa)
S_x = elastic section moduli (Hibbeler, 2023) (mm^3)
V_U = factored shear force (N)
V' = value of adjusted shear force (N)
F_v' = value of adjusted shear strength (MPa)
I_x = moment of inertia (Goodno, 2021; Hibbeler, 2023) (mm^4)
b = width of beam (mm)
Q = moment of static of beam cross-section (mm^3)
δ_{max} = maximum permitted deflection of beam (mm)
L = length of beam (mm).

Provisions for Stiffness of Building

Guest houses with functions for the tourism support infrastructure are included in the risk category IV based on the Indonesian earthquake code (BSN, 2019). In the design of earthquake-resistant buildings, the deformation limit (Δ_{max}) for wooden buildings is categorized as other buildings can be calculated using Equation 5.

$$\Delta_{max} = 0.01 \times h_{sx} \quad (5)$$

where:
h_{sx} = the story height.

Results and Discussion

Structural Analysis of Wooden Building

In this research, the building has dimensions of 6m x 5m, with the function being a guest house. Figure 3 shows a schematic 3D model including beams, columns, and roof structure (Pranata et al., 2022; Pranata *et al.*, 2023). Analysis of the 3D structure was carried out with SAP2000 software (CSI, 2013).

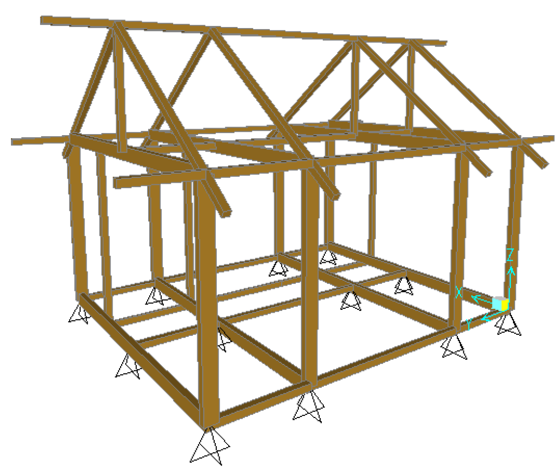

Figure 3. 3D model of the guest house in this research.

Indonesian loading codes (BSN, 2020) are used to determine live loads and superimposed dead loads that act during the service life of the guest house. The weight of the wooden curtain, batten structure, and rain loads were modeled and calculated based on the tributary area, which were acting on the roof beams. The height of the main column is 3 meters. The total height of the building at the top of the roof is 4.8 meters.

Table 3. Results obtained from modal analysis.

Mode	Period (sec.)	Status
1	0.23	Translation x-direction
2	0.22	Translation y-direction
3	0.19	Rotation z-direction

Results obtained from model analysis using SAP2000 software are shown in Table 3, with the result that the first two modes are translations, and the third mode is rotation.

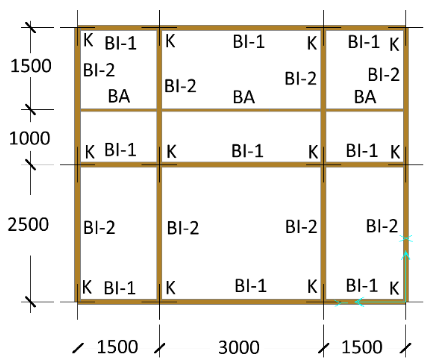

Figure 4. Numbering of main columns, main beams and secondary beams (unit length: mm).

Table 4. Results obtained from analysis: Deflection of beams.

Beam	Length (mm)	Deflection (mm)	Permission limits (mm)	Check
BI-1	1500	0.97	3.75	Ok
BI-1	3000	2.67	7.50	Ok
BI-2	2500	1.37	6.25	Ok
BA	1500	1.70	3.75	Ok
BA	3000	5.12	7.50	Ok

Figure 4 shows the numbering of main and secondary beams. Table 4 shows the results of structural analysis, which are the deformation of the building due to factored loads. Permission limit is calculated using Equation 4. Considering that this is an elevated building, it is very important to study the deflections in the floor elevation beams, so that the building meets the comfort requirements during its service life.

Table 5. Results obtained from analysis: Drift due to designed earthquake on x-direction.

Direction	Displ. (mm)	Drift (mm/mm)	Permission limits	Status
X	4.78	0.0016	0.010	Ok
Y	3.72	0.0013	0.010	Ok

Table 5 shows results of drift of the building due to design-equivalent static loads in the main direction, which are x-direction and y-direction. These results indicate that the drift that occurs at an elevation of +3 meters of the building does not exceed this limit according to SNI 1726:2019 (BSN, 2019). Permission limit is calculated using Equation 5. Ductility of the structure is identified as a requirement in the structural design of wooden buildings [Jorissen and Massimo, 2011].

Table 6. Results of column and beam members capacity check.

Member	Design Type	Factored Load	Capacity	Status
Column (K)	Axial	11.66 kN	436.6 kN	Ok
	Moment	0.35 kN.m	36.8 kN.m	Ok
	Shear	0.23 kN	140.0 kN	Ok
Main Beam (B1)	Moment	0.38 kN.m	36.8 kN.m	Ok
	Shear	0.41 kN	140.0 kN	Ok
Main Beam (B2)	Moment	0.59 kN.m	36.8 kN.m	Ok
	Shear	0.45 kN	140.0 kN	Ok
Sec. Beam (BA)	Moment	0.07 kN.m	73.6 kN.m	Ok
	Shear	0.06 kN	56.0 kN	Ok
Roof-Beam	Moment	0.34 kN.m	73.6 kN.m	Ok
	Shear	0.82 kN	56.0 kN	Ok

Table 6 shows the results of column and beam capacity calculations. The factored loads are obtained from the results of structural analysis under maximum load combination. Calculation of compression capacities were carried out using Equation 1a, capacities due to flexural moments were carried out using Equation 2a, and shear capacities were carried out using Equation 3a.

Figure 6. Construction process of the wooden guest house (Pranata *et al*., 2022).

Figure 7. The wooden guest house after completion (Pranata *et al*., 2022).

The results of this calculation indicate that the main beams, secondary beams, and columns have a higher capacity than the working loads, so that the structure is safe during its service life. Figure 6 shows the construction process of a wooden building. Figure 7 shows a wooden building with a function for a guest house that has been completed.

Structural analysis considers the beam stiffness aspect, which is deformation due to gravity load, the strength aspect, which is the capacity of both beams and columns, and the building stiffness aspect due to earthquake load. The study in this research shows that beam deflection as shown in Table 4 needs to be a concern so that the building meets the design requirements according to SNI 7973:2013 (BSN, 2013), even though the beam and column capacity analysis (Table 6) shows results that appear to be over capacity.

There are basic assumptions in the calculation of the adjusted design values, according to the condition where the building was built. The temperature of the area ranges from 5° to 25° C. The function of the building meets the criteria for a residential house.

Since the wooden building has a low mass that which means it is equivalent to reduced horizontal base shear load even during strong earthquakes, wooden buildings might be a good choice in high seismic zone regions (Porcu, 2017). A general earthquake diagnosis method can be used to evaluate the lateral performance of wooden houses using the calculation of lateral load-carrying capacity (Mitani et al., 2022). The calculation of the response and limit strength of the building is used to evaluate the performance of wooden houses due to lateral or earthquake load.

Conclusions

The behavior of wooden buildings studied in this research is strength and stiffness. The nominal capacities of bending moment and shear forces of the columns and beams meet the requirements and the value is lower than the maximum factored load combination. These results indicated that the strength of the building met the requirements according to Indonesian timber code SNI 7973:2013. The research results show that the drift of the building due to the equivalent static earthquake load in the main direction of the building does not exceed the permit limits. These results indicated that the stiffness of the building meets the requirements according to Indonesian seismic code SNI 1726:2019.

Mechanically laminated technology used in the main beam of a wooden house affects the results of deflection of beams. Results indicated that the deflection of beams does not exceed the permitted limits.

Overall, analysis of timber structures based on three dimensional structural analysis provides benefits, namely predicting the strength and stiffness behavior of wooden buildings. Even though the quality (class strength) of the wood is limited, if designed properly, it can be used as an earthquake-resistant building.

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