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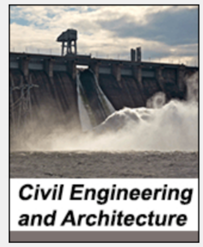

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Seismic Behavior of Joglo Traditional Wooden House Located in Special Region of Yogyakarta, Indonesia

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Abstract Joglo traditional wooden buildings are buildings that are still widely found in the city of Yogyakarta, Indonesia. These buildings were built in the sixteenth century and were not damaged during several earthquakes in the area in the years of 2001, 2004, 2006, and 2023. The purpose of this research is to study the stiffness and strength behaviors of Joglo wooden buildings due to seismic and gravity loads. The scope of the research is that the existing wooden building studied uses Teak wood (*Tectona grandis*) and it is located in Special Region of Yogyakarta, Indonesia. It was built in the sixteenth century. The behaviors studied are deformation and drift due to lateral loads in accordance with current Indonesian seismic code SNI 1726, and the capacities of the columns and the beams in accordance with current Indonesian timber code SNI 7973. The results obtained from this research show that the drift due to the design earthquake load is lower than the permitted limit. The results of modal analysis show that there is no twist in the first and second modes and the pattern of the first and second modes of the building are translated in each of the main directions. The strengths of the columns and the beams are much higher than the required strength. These results can be used as a reference for academics, practitioners, and the public that the Joglo wooden building structure system is safe against earthquake.

Keywords Joglo, Seismic, Drift, Strength, Tectona Grandis

1. Introduction

The seismic behavior of Joglo traditional wooden buildings against earthquake loads is important to be studied, because these types of buildings are often found in the Yogyakarta Special Region Province, Indonesia. The province is denoted as the area with moderate to severe earthquake intensity according to the earthquake map in the Indonesian earthquake code SNI 1726 [1]. In the last 25 years, there have been four earthquakes in the area, namely in 2001, 2004, 2006 and 2023. The structural members of wooden buildings of the Joglo houses did not experience any damage when the earthquakes occurred in those years.

Figure 1 shows an example of an existing Joglo wooden building which is the object of this research. The building has a type of structure whose stability is centered on the Sokoguru building structural system, namely the four main columns in the middle of the building. This structural part is intended to support gravity loads. These four main columns are connected to four beams called Blandar.

Figure 2 shows the condition of the existing main columns and main beams. All structural components and connections of the building were not damaged due to several earthquakes, including earthquakes that occurred in 2001, 2004, 2006 and 2023.

Figure 1. Joglo wooden house that is the object of research

(a). Main beam (Blandar) (b). Main Column (Sokoguru)

Figure 2. Existing main structural components of Joglo wooden house

The purpose of this research is to study the stiffness and strength behaviors of Joglo wooden buildings due to seismic and gravity loads.

The scope of the research is that the existing wooden building studied uses Teak wood (*Tectona grandis*) and it is located in Special Region of Yogyakarta, Indonesia with the GPS coordinates of -7.765015 and 110.336373. The behaviors studied were deformation and drift due to lateral loads in accordance with the Indonesian seismic code SNI 1726 [1] and the capacities of the structural members in accordance with the Indonesian timber code SNI 7973 [2]. This research uses structural analysis methods to determine the behavior of wooden buildings subjected to lateral earthquake load. Experimental research using a non-destructive method is supported to obtain the main parameters of the modulus of elasticity of the existing wood of the building.

In this research, the Joglo traditional wooden house is modeled as a frame structure. The joint behavior is modeled using rotational spring elements by taking into account rotational stiffness parameters similar to the joint behavior of the existing building. The spring model in the beam-to-column joint connection is an important factor affecting the load-carrying capacity and horizontal impact force of the wooden frame when the building is subjected to lateral load.

The analysis of the structure due to the earthquake load was carried out using the spectrum response analysis method. Data on the mechanical properties of the material, in this case the modulus of elasticity, was obtained from non-destructive testing in existing buildings, while compressive strength, bending strength, and specific gravity of Teak wood (*Tectona grandis*) were obtained from the results of previous studies [3, 4, 5].

2. Basic Theory

2.1. Response Spectrum Analysis

The response spectrum is an estimation of the peak responses, namely acceleration, displacement, and velocity responses of a single degree of freedom systems subjected to a prescribed ground motion [6].

The response spectrum method utilizes the response spectrum to set the possible deformations (stiffness) and forces (strength) that the building structure would experience under earthquake load. Response spectrum analysis is useful for the design of buildings due to earthquake load to predict the dynamic performance. Structures with longer fundamental periods experience greater displacements and structures of shorter fundamental periods experience greater accelerations [7].

2.2. Design Earthquake Load

In this research, the design earthquake load is calculated utilizing current Indonesian earthquake code SNI 1726 [1], which uses a spectrum response curve with $S_{Ds} = 0.31g$ and $S_{D1} = 0.77g$. S_{Ds} is the spectral response acceleration parameter at short periods, while S_{D1} is the spectral response acceleration parameter at long periods.

Calculation of the scale factor for the spectrum response design earthquake load refers to Chapter 7, Section 7.2.2 concerning the response coefficient of modification for seismic force-bearing systems [1]. In the Indonesian earthquake code Sections 7.8.6 and 7.12 [1], there is a provision that structural buildings must meet stiffness requirement, which is the requirement for the limit on drift due to lateral earthquake load, concerning the determination of inter-story drift, which can be calculated using Equation 1.

$$\Delta = 0.010\, h \quad (1)$$

where Δ is the permitted drift limit (mm) and h is the building height (mm).

2.3. Rotational Stiffness for Modeling of Beam-to-Column Timber Joint

As described previously, the beam-to-column joint system in Joglo traditional wooden building is not a rigid connection type, so it cannot fully withstand moments and there is some rotational behavior. Figure 3 shows the four main columns (Sokoguru) and the main beams (Blandar) as a frame structural system located in the middle of the building.

Figure 3. Four main columns (Sokoguru) and main beams (Blandar) as a frame system located in the center of building

Figure 4 shows a schematic of the beam (Blandar) to column (Sokoguru) joint connection system [8]. This type of structural system can perform as a moment resistant frame because the structural rigidity and stability are formed by the locking joint between the main column and the main beam [9].

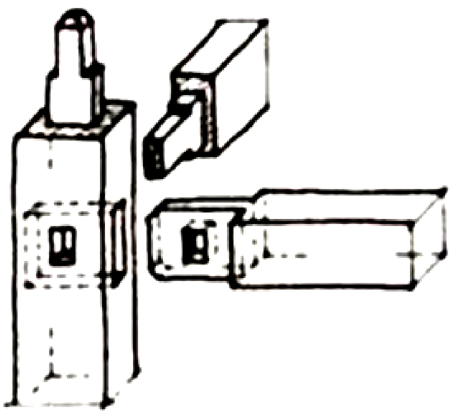


Figure 4. Schematic beam-to-column joint system of Joglo wooden house [8]

The beam-to-column timber joints are neither pinned nor rigid joint types, but are in the range of both [10]. Therefore, the rotational stiffness for the beam-to-column timber joints in modeling the Joglo building structures in this research is utilized, and the values of which are obtained from research by Polastri [11], that is 23103 kN.m/rad. This value is used as rotational stiffness for three main directions of x-, y-, and z-directions.

2.4. Column Support Modeling

The connection between the column and the base (called Umpak) is modeled as a pin joint [12], because this connection system does not withstand flexural moments. The wooden column is inserted into Umpak which has been made into a square hole of the same size as the column, with a depth of 100 mm. This connection system functions to prevent horizontal translation. Vertical translation does not occur due to the action of the self-weight of the building.

Figure 5. Timber column to the base of the existing building

2.5. Non-destructive Testing and Modulus of Elasticity Parameter

One of the non-destructive tests is the method [13] that utilizes two transducers; one transducer is the transmitter and the other is the receiver of ultrasonic wave signals, which are further measured and translated into the form of data. In this study, an indirect method is used, namely a measurement method by placing two transducers at a certain distance, and the position of each transducer forms an angle of 30 ^{o}with respect to the grain direction [13]. The data produced is the wave velocity parameter that is then converted into a dynamic modulus of elasticity (MoE_{dyn}) using Equation 2. It is based on the wave velocity parameter (m/s) according to the measurement time history.

Oliveira et al. [14], through their research, concluded a lot of important literature related to non-destructive testing, namely the dynamic modulus of elasticity and the results of destructive testing, namely the static modulus of elasticity. Research that has been conducted by Arriaga et al. [15] produces an empirical equation of the relationship between the static modulus of elasticity (MoE) and the dynamic modulus of elasticity, which is shown in Equation 3.

$$MoE_{dyn} = \rho.V^2.10^{-6} \quad (2)$$

$$MoE_{dyn} = 1.26 \text{ x } MoE \quad (3)$$

where MoE is the static modulus of elasticity (MPa), MoE_{dyn} is the dynamic modulus of elasticity (MPa), ρ is the specific gravity (kg/m^3), and V is the velocity of the ultrasonic waves (m/s).

Figure 6 shows the non-destructive testing to obtain the value of velocity with the Sylvatest 4 test equipment [13] using the indirect method. In this study, the test was carried out on four main columns in the Sokoguru section of the Joglo building, the four main beams of Blandar, as well as several edge columns and edge beams. This section is called *Rong-rongan*.

The full schematic of the components of the structure under test is shown in Figure 7. Cross-section's dimension of the four main columns (Sokoguru) is 150mm x 150mm, the main beam (Blandar) is 100mm x 150mm, the side column is 120mm x 120mm, the roof beam is 50mm x 100mm, and the side beams are 100mm x 150mm and 50mm x 150mm.

2.6. Seismic Behavior

Seismic behavior is the way a building interacts with seismic ground motion, with the results being drifts and stresses that occur within the building. Seismic behavior of the building depends on the parameters of the design. The wide variation in stiffness and strength around the perimeter will result in the center of mass not coinciding with the center of resistance.

Figure 6. Non-destructive testing to obtain the MoE_{dyn} of Joglo existing building

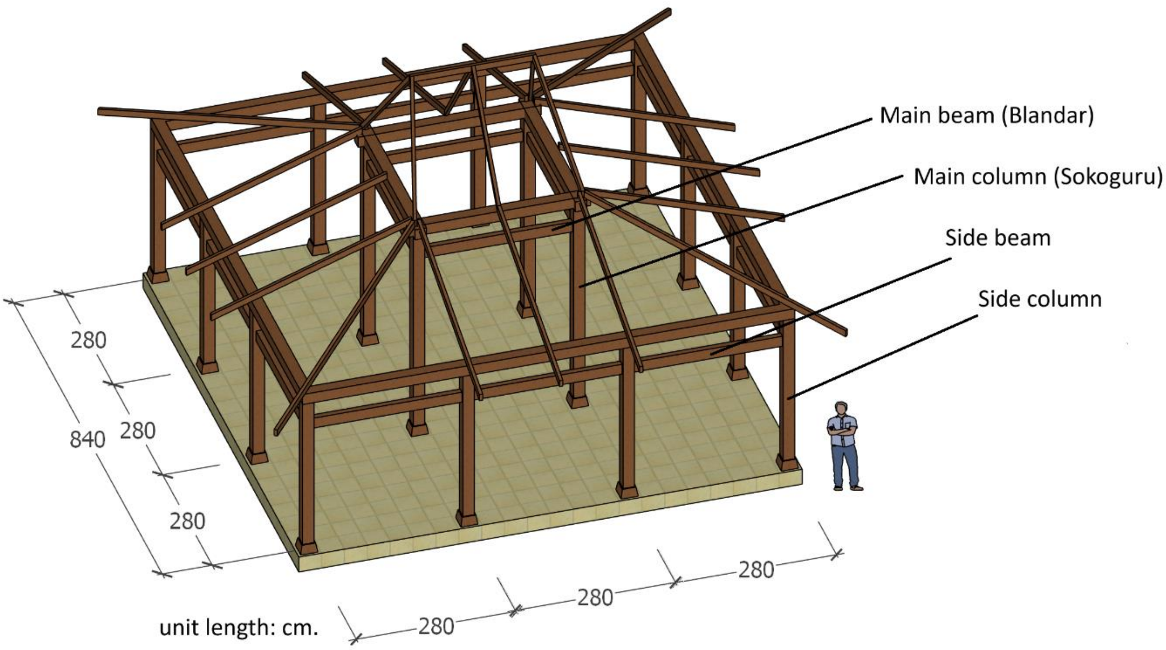


Figure 7. Columns and beams tested nondestructively

2.7. Design of Column and Beam Elements

The design of wooden columns and beams to determine the strength and capacity in this study is based on current Indonesian wood code SNI 7973 [2]. The design principle is to use the Load and Resistance Factor Design (LRFD) method. In this method, the effect of the factored load has to be lower than the capacity of the members.

Column strength capacity design refers to Sections 3.6 and 4.3 of SNI 7973 [2], where the adjusted design compression parallel to the grain (P') is influenced by compression strength parallel to the grain (F_c) and correction factors, which are wet service factor (C_M), temperature factor (C_t), size factor for sawn lumber (C_F), incising factor for dimension lumber (C_i), column stability factor (C_p), format conversion factor (KF), resistance factor (ϕ), and time effect factor (λ).

$$P_u \leq P' \quad (4.a)$$

$$P' = F_c \,.\, C_M \,.\, C_t \,.\, C_i \,.\, C_F \,.\, C_p \,.\, \text{KF} \,.\, \phi \,.\, \lambda \quad (4.b)$$

Beam strength capacity design refers to Sections 3.3, 3.4 3.5, and 4.3 of SNI 7973 [2], where the adjusted design bending moment (M') is influenced by flexural strength (F_b) and correction factors, which are wet service factor (C_M), temperature factor (C_t), size factor for sawn lumber (C_F), flat use factor (C_{fu}), incising factor for dimension lumber (C_i), beam stability factor (C_L), format conversion factor (KF), resistance factor (ϕ), and time effect factor (λ).

$$M_u \leq M' \quad (5.a)$$

$$M' = F_b . C_M \,.\, C_t \,.\, C_i \,.\, C_F \,.\, C_{fu} \,.\, C_L \,.\, \text{KF} \,.\, \phi \,.\, \lambda \quad (5.b)$$

Adjusted design shear (V') is influenced by shear strength (F_v) and adjustment factors, namely wet service factor (C_M), temperature factor (C_t), incising factor for dimension lumber (C_i), format conversion factor (KF), resistance factor (ϕ), and time effect factor (λ).

$$V_u \leq V' \quad (6.a)$$

$$V' = F_V \,.\, C_M \,.\, C_t \,.\, C_i \,.\, \text{KF} \,.\, \phi \,.\, \lambda \quad (6.b)$$

where P_u is the factored compressive load on the column, M_u is the factored bending moment on the beam, M' is the adjusted design bending moment, V_u is the factored shear force, and V' is the adjusted design shear [2], format conversion factor (KF), and resistance factor (ϕ).

In this study, the factored loads consist of dead, live, rain, and earthquake loads. The dead load consists of the self-weight of the building and the additional dead load, while the live load is the human load [16]. The rain load is 20 kg/m according to the rainfall conditions in the surrounding area. The combination of factored loads refers to the SNI 7973 code [2].

2.8. Mechanical Properties of Teak Wood (*Tectona grandis*)

Previous research to determine the physical and mechanical properties of Teak wood (*Tectona grandis*) has been carried out by several researches, namely by Forest Product Laboratory [3] to obtain specific gravity (physical properties), compressive strength, MoE, modulus of rupture (MoR), and shear strength, by Miranda et al. [4] to obtain compressive strength, MoE, and MoR, and by Seta et al. [5] to obtain specific gravity (physical properties), MoE, and MoR. Table 1 shows the reference data from the above-mentioned sources.

Table 1. References of mechanical properties of Teak wood (*Tectona grandis*)

Reference	SG	MoE (MPa)	MoR (MPa)	$F_{c//}$ (MPa)	F_v (MPa)
FPL [3]	0.55	10700	100.7	58.0	13.0
Miranda et al. [4]		10684	141.0	50.0	-
Seta et al. [5]	0.49	12000	80.0	-	-

3. Methodology

3.1. Non-Destructive Test of Existing Columns and Beams

Non-destructive tests were performed on four main columns, four main beams, four side columns, and four side beams as shown in Figure 8. In each of these structural members, tests were carried out ranging from 15 to 18 points on the pedestal at each end and mid-span of the element. The total points tested were 268 points. Figure 8 shows one of the points in the side column under testing.

Figure 8. Non-destructive test on one of the side columns using the indirect method

The non-destructive tests are carried out by taking data on the speed of longitudinal wave propagation on each side of the wood member. For the beam component, data collection is carried out at the ends and mid-span. Meanwhile, for the column component, data collection is carried out in the lower support and mid-span.

Figure 9 shows an example of a non-destructive testing result, which is velocity. The test results show the velocity parameter of the ultrasonic waves, which is then converted into a dynamic modulus of elasticity using Equation 2. The relationship between the static modulus of elasticity and the dynamic modulus of elasticity can be calculated using Equation 3.

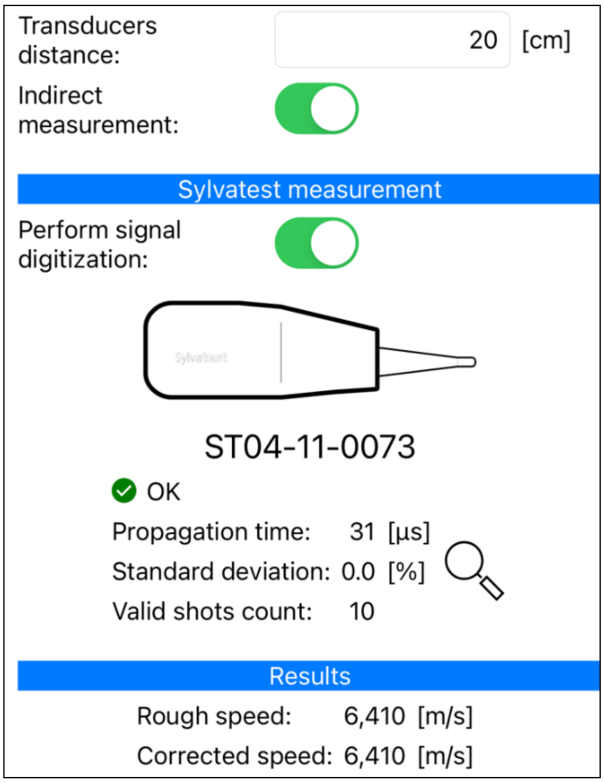


Figure 9. The example of a non-destructive testing result: velocity (m/s)

The calculation results are shown in Figure 10, with an average static Modulus of the value of 24182.98 MPa, the standard deviation of 4605.47 MPa and the coefficient of variation of 19.04%. These results indicate that the data can be accepted based on the code of the maximum coefficient of variation limit of 25% [2].

The results of this non-destructive test show that the modulus of elasticity of the existing wood that used in this existing Joglo building has a value that is much higher than the modulus of elasticity of the existing wood in general [3,4,5]. This is because the existing building is very old wood. The joglo building itself was built in the sixteenth century. Based on information from the owner of the building, the wood used is more than one hundred years old.

3.2. Modeling and Analysis

Structural modeling is carried out with a finite element computer software named SAP2000 version 16 [18]. SAP2000 software can be used for modeling wooden building structures. Previous research on the behavior of wooden buildings due to earthquake loads was done by Saptaningtyas et al. [19] to study the behavior of earthquake-resistant Sasak traditional wooden buildings in Sade Village, Lombok, Indonesia.

Columns and beams are modeled as frame elements, and the beams of the roof are also modeled as frame elements. The supports are modeled as pinned, assuming that the bottom of the column cannot translate in any directions and cannot resist the bending moment. In the joints between the elements, a spring-joint model is placed with the consideration that the connection system is neither pinned nor rigid, and the spring stiffness value is 23103 kN.m/rad [11].

The design spectrum response is taken from the earthquake map according to SNI 1726 code [1] with coordinates according to the location of the existing building, which uses a spectrum response curve with S_{Ds} = 0.31g and S_{D1} = 0.77g.

Figure 11 shows the spectrum response curve. In calculating the design earthquake load with this method, a scale factor of 2.8 is used with the consideration that the structural system is an ordinary moment-resisting frame system with an R value of 3.5 [1].

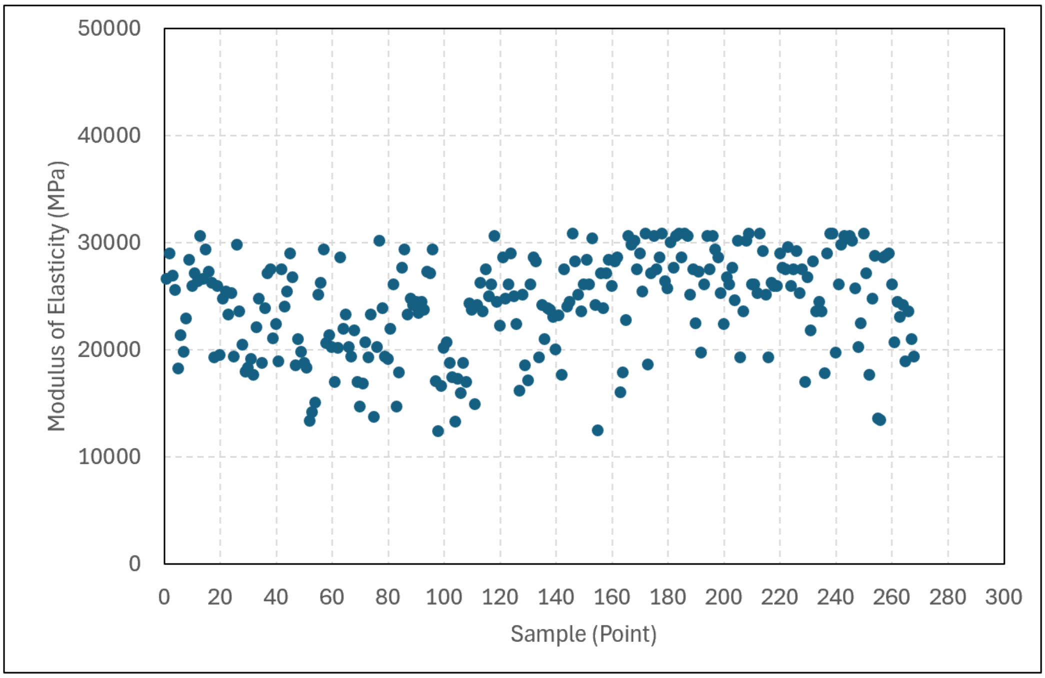


Figure 10. Results obtained from non-destructive testing: Modulus of Elasticity [17]

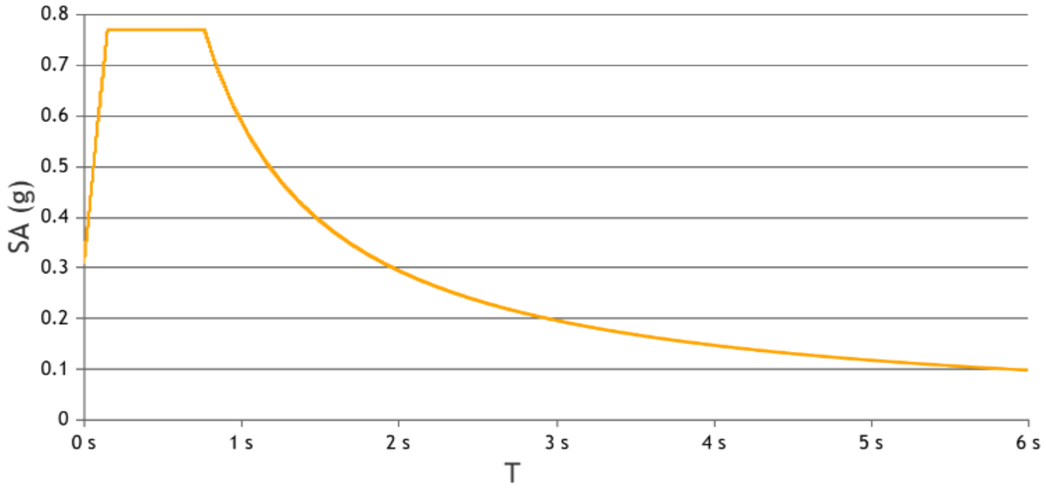


Figure 11. Response spectrum curve for response spectrum analysis [1]

4. Results and Discussion

4.1. Structural Analysis and Results

The existing Joglo wooden building is modeled as a 3D frame structure system. Springs are assigned in all three rotational directions of each joint with rotational stiffness in accordance to the data references [11]. All bottom ends of the timber columns, both the main and the side columns use the pin support models.

Structural analysis was carried out to determine the stiffness and strength performance of the building due to gravity loads and earthquake loads. The earthquake load was calculated using spectrum response analysis, so that in structural modeling, a diaphragm model was made at an elevation of +3000 mm.

Figure 12 shows the results of modeling the existing Joglo wooden building. The gravity loads are calculated using tributary area and modeled as uniform loads on the roof beams.

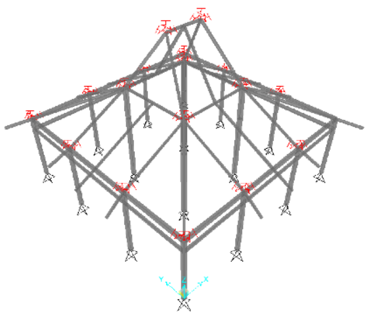
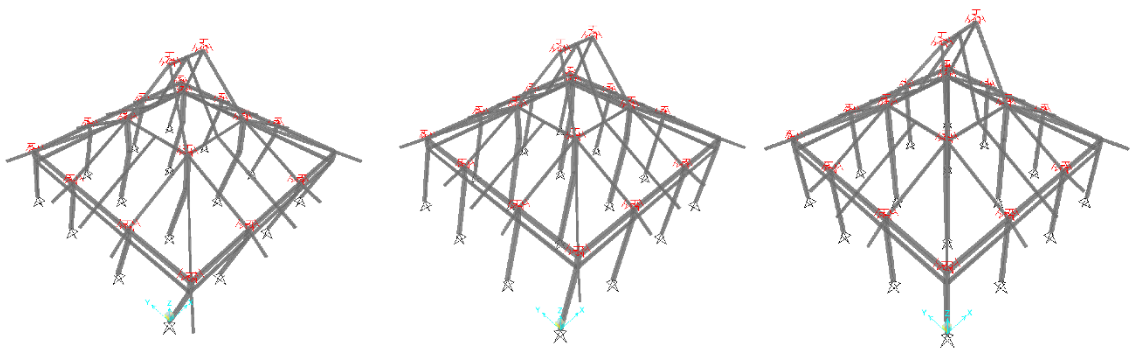


Figure 12. Schematic 3D model of the existing Joglo wooden building

Figure 13 shows the modal analysis results, which are the translation in y-direction (1st mode), translation in x-direction (2nd mode), and rotation in z-direction (3rd mode). The results obtained from the modal analysis indicate that the first and second modes are translational and not rotational, so this condition meets the provisions in the SNI 1726 earthquake code [1].

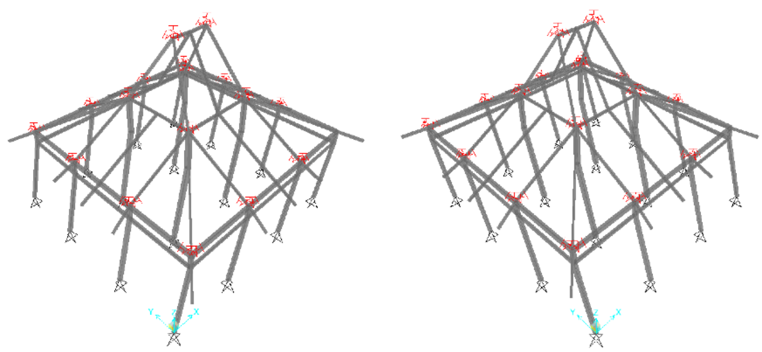
Figure 14 shows the deformation of the building due to the x-direction (Ex) and y-direction earthquakes (Ey). Table 2 shows the results of the drift calculation based on SNI 1726 code [1]. The results of the analysis generally show that the drifts in both the x-direction and the y-direction do not exceed the allowable limit.

Figure 15 shows the internal forces due to the maximum combination of factored loads. Table 3 further shows the results of the calculation of column and beam capacities using Equation 4, Equation 5, and Equation 6 according to SNI 7973 code [2]. The modulus of elasticity that is used in the structural modeling using SAP2000 and for calculation is obtained from non-destructive testing, while the references of specific gravity, compression strength parallel to the grain, MoR, and shear strength that are used in the calculation are from the reference [3] as seen in Table 1.



(a). Mode 1: T = 0.21 sec. (b). Mode 2: T = 0.22 sec. (c). Mode 3: T = 0.05 sec.

Figure 13. Results of modal analysis

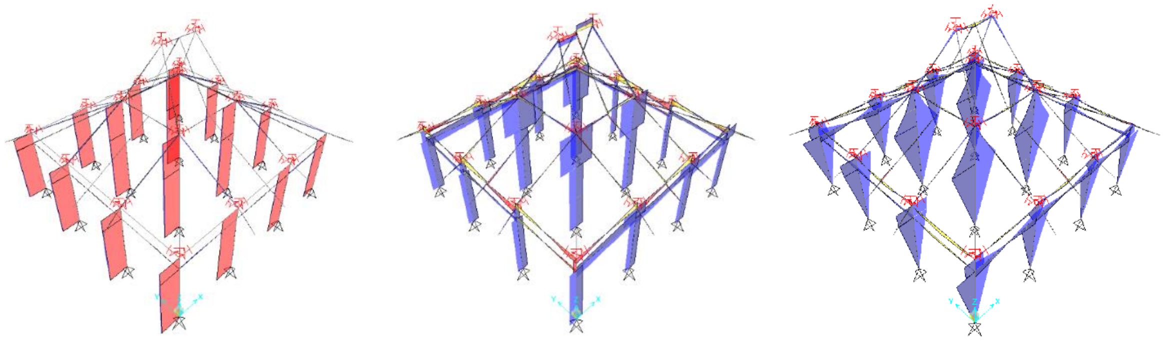


(a). Deformation in x-direction (b). Deformation in y-direction

Figure 14. Results of deformation due to earthquake loads

Table 2. Results of drift calculation

Load	Deformation (mm)	Drift (mm//mm)	Limit (mm/mm)	Status
Ex	6.02	0.002	0.010	Ok
Ey	6.19	0.002	0.010	Ok



(a). Axial forces (b). Shear forces (c). Bending moments

Figure 15. Results of internal forces due to maximum factored loads combination

Table 3. Results of calculation of the capacity of column and beam elements

Element	Factored load	Capacity	Status
Main Column (Sokoguru)	Pu = 2.79 kN	P' = 1626.52 kN	Ok
	Vu = 1.05 kN	V' = 196.11 kN	Ok
	Mu = 1.21 kN.m	M' = 74.98 kN.m	Ok
Side-Column	Pu = 19.31 kN	P' = 1040.97 kN	Ok
	Vu = 0.24 kN	V' = 38.39 kN	Ok
	Mu = 0.71 kN.m	M' = 125.51 kN.m	Ok
Main Beam (Blandar)	Mu = 0.13 kN.m	M' = 74.98 kN.m	Ok
	Vu = 0.40 kN	V' = 87.16 kN	Ok
Side-Beam	Mu = 0.39 kN.m	M' = 74.98 kN.m	Ok
	Vu = 0.36 kN	V' = 87.16 kN	Ok
Roof-Beam	Mu = 0.31 kN.m	M' = 74.98 kN.m	Ok
	Vu = 0.29 kN	V' = 87.16 kN	Ok

4.2. Discussion

There are several assumptions in the calculation of the adjusted design values. The condition of dry timber is assumed because the building is protected against wet conditions. The temperature of the area ranges from 28-30 ℃. The building functions as a residential building. The calculation results show that the capacities of all columns and beams are much higher than the load effects. Therefore, the building is safe in accordance to the current Indonesian codes mentioned above.

The strength and stiffness of the Joglo structure are influenced by factors such as the type of the connection, the roof system as a superimposed dead load, quality or wood species, and maintenance [20].

However, there is an important aspect that has been studied, which is the structural system of Joglo building. The essence of the wooden building lies in the section of *Rong-rongan*, which is the main construction that supports the Blandar beams. The four main Sokoguru columns and the Blandar main beams which are the center of stiffness of the building, have a symmetrical building plan shape in both directions of the main axis of the building. This supports resistance to lateral earthquake loads.

Beam-to-column joints that behave in a non-rigid manner contribute to the earthquake energy dissipation that occurs in the connection system.

5. Conclusions

The results obtained from this research show that the drift due to the design earthquake load is lower than the permitted limit. The results of modal analysis show that there is no twist in the first and second modes and the pattern of the first and second modes of the building are translated on each of the main directions.

By comparing internal forces of the columns and the beams obtained from structural analysis with the design strengths in accordance to the Indonesia timber code SNI 7973, it can be seen that all columns and beams of the existing Joglo building can withstand both the design vertical gravity loads and lateral earthquake loads. These results can be a reference for academics, practitioners, and the public that the Joglo wooden building structure system is safe against earthquake.

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