Seismic Performance Analysis of Meru (Bali Pagoda): Preliminary Study

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Abstract. This study evaluates the earthquake-resistant performance of Meru, specifically level eleven, located in the Ulun Danu Batur Kintamani Temple Area, Bali Province. Despite the upper layer's construction with wooden frames and panels, and the base layer's masonry walls, Meru has remained remarkably undamaged by earthquakes since its establishment in 1968. The analysis encompasses Meru's architectural forms, structural systems, building materials, and dynamic response to seismic activity. A 3-D finite element model and nonlinear time history dynamic analysis methods were employed to investigate its earthquake resistance. The findings indicate that Meru can withstand credible maximum seismicity for a return period of 2500 years, and the natural period and modes of Meru have been determined. This study serves as an initial investigation into predicting and monitoring the behavior of Meru structures during earthquakes. Future research could involve experimental analysis of individual components and the overall structure to further validate the analytical model. As a result, this study offers significant insights into the upkeep and preservation of traditional Balinese historic buildings in an earthquake-prone area.

1 Introduction

Meru is a sacred building of worship for Hindu communities in Bali, serving as a place of reverence for both deities and ancestors. This building keeps history from the surrounding community since the era where the building was built. Sometimes this building also becomes a symbol of the journey and struggle of the surrounding community [1]. The architectural model of this place of worship was initially introduced in Bali by a priest around the 11th century. The measurement process, selection of building materials, and construction stages are carried out by traditional Balinese architects (*undagi*) in accordance with the traditional references outlined in the *Lontar Asta Kosali* [2].

Due to its uniqueness, Meru has been the subject of study by many researchers. Some aspects of Meru that have been previously studied include the various variations of Meru found throughout Bali, the philosophical background of Meru's structural foundation, the

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layout, proportions, and symbolism of Meru buildings [3], the typology of its form and developmental roots, and Lansing (J.S., 1991) who studied the 5-tiered Meru regarding the dimensional ratios of its horizontal, vertical, and diagonal components [4]. Previous research has largely focused on design philosophy and dimensional ratios of the buildings, while in-depth studies on the seismic behavior of Meru structures are scarce. However, by studying the structure of Meru and its performance, local craftsmen (*undagi*), and even the general public can understand and consider how Meru can withstand earthquakes. Meru structures can be categorized as unique structures with traditional local materials and different framework geometries compared to standard buildings, resulting in distinct combinations and ultimately exhibiting different seismic response behaviors..

Therefore, studying the factors that enable Meru structures to withstand seismic vibrations is a highly interesting endeavor. The primary scope of this paper is to outline the analysis results for the unique structure possessed by Meru. By understanding the seismic resilience characteristics of Meru, future monitoring, maintenance, and reinforcement can be easily implemented. Furthermore, upon completion of experimental validation, design recommendations for more effective Meru constructions can be shared with architectural designers. This paper can serve as an additional scholarly reference that discusses how the uniqueness of traditional structures in the past had good seismic resilience capabilities. The explanations regarding the seismic resilience characteristics of traditional buildings, as explained based on civil engineering principles, can serve as inspiration for the fundamentals of designing other unique architectural structures.

2 Methods

Among the many variations of forms and structures, for this study, the Meru Ulun Danu Batur structure located in the Kintamani area, as shown in Figure 1, has been chosen. This Meru was selected because it is one of the highest number of levels, towering at a height of 14.52 meters with 11 levels. Compare to other Meru in Bali, and due to its height, this structure is the most vulnerable to the effect of the earthquakes.

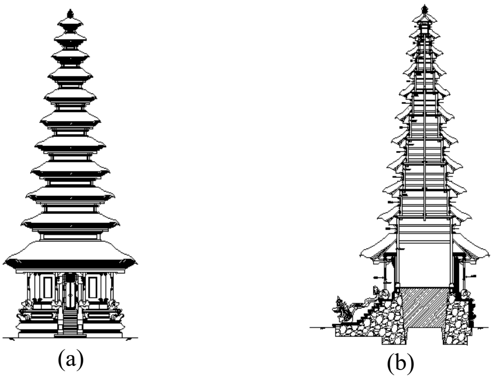

(a) (b)

Fig. 1. Meru Ulun Danu Batur (a) Front view (b) Side view.

To interpret the dynamic behavior of the structure, a numerical model has been developed. Based on the observation, the foundation of the Meru structure is using rubble stone, which sufficiently rigid to carry the Meru self-weight. Furthermore, the rigidity is relatively higher compared to the Meru's upper structure, therefore in this study the foundation is assumed as hinge support.

Modal analysis is employed to investigate the structural mode shapes and its natural period. Subsequently, linear time history analysis is caried out to assess the structure's performance under seismic events. Furthermore, the results are compared trough material and deformation capacity.

2.1 Material and structural characteristics

In Bali, traditional construction is primarily based on wood and stone, especially for monumental architecture. In the case of sacred building remnants like Meru, a combination of wooden frame structures, wooden panels, and brick walls can be found. Regarding the brick walls, various types of clay are used, locally produced. Generally, the compressive strength ranges around 5 MPa, and this strength level is sufficient to meet the minimum strength requirement of 2.5 MPa for structural purposes. Brick has a density of 1700 kg/m^3 and an elasticity modulus, E, of 240 MPa with a Poisson's ratio of 0.15 [5]. The type of wood known as majegau is extensively used in structural elements due to its long lifespan and aesthetic qualities. It falls under the category of first-class wood, with an axial strength, σ, of 11 MPa, an elasticity modulus, E, of 12500 MPa, and a density of 670 kg/m^3 [6]. The roof is made from ijuk, with a wet density of 285 kg/m^3 [7]

2.2 Structural model

The seismic performance of the wooden structure installed with wooden panels is evaluated using the analysis model shown in Figure 2. The structural model employed in this analysis is a 3D frame model, considering the influence of brick walls and wooden panels, with columns and beams assumed to be elastic. The frame element in ETABS with 0.2 stiffness factor is used to represent the traditional wooden frame system with semi-rigid connection [8]. Similarly, the stiffness factor for brick wall connections is 0.35 according to SNI 2847:2019 [9]. The damping ratio is assumed based on the energy absorbed at several connections to be 5%.

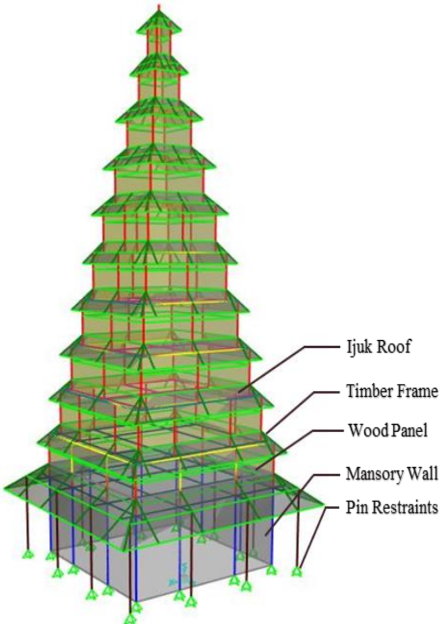


Fig. 2. Meru structural model.

Table 1. Height dimensions of each level of meru.

Level	Height (mm)
11	930
10	980
9	1030
8	1030
7	1080
6	1080
5	1080
4	1080
3	1080
2	1080
1	1870

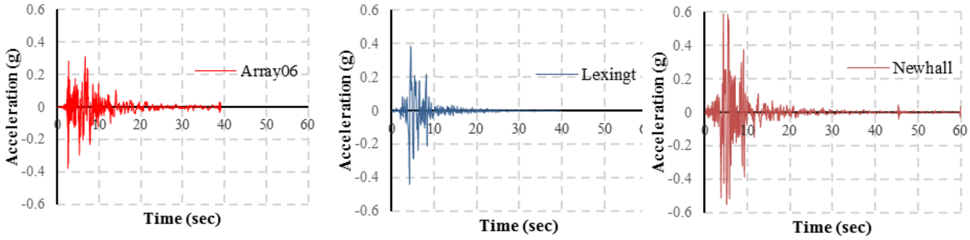
The dead load used in the structural design is conceptualized by idealizing the roof load, as listed in Table 2. This load is then converted into gravitational load during linear dynamic analysis based on the structural modes. The live load used is 20 kg/m^2 due to rainfall in accordance with SNI 1727:2020 [10].

Table 2. Idealized floor gravity loading in Meru.

Tier	Roof		
	Height (m)	Weight Per Unit Volume (kg/m^3)	Weight Per Area (Kg/m^2)
1	0.35	285	99.75
2	0.35	285	99.75
3	0.35	285	99.75
4	0.35	285	99.75
5	0.35	285	99.75
6	0.35	285	99.75
7	0.35	285	99.75
8	0.35	285	99.75
9	0.35	285	99.75
10	0.35	285	99.75
11	0.24	285	68.40

2.3 Seismic load selection

To investigate the seismic response behavior of the Meru structural system, time history analysis was conducted using 3 earthquake records. Earthquakes with magnitudes greater than 5 on the Richter scale were chosen, with characteristics categorized as destructive. The earthquake records used for analysis are shown in Figure 3.

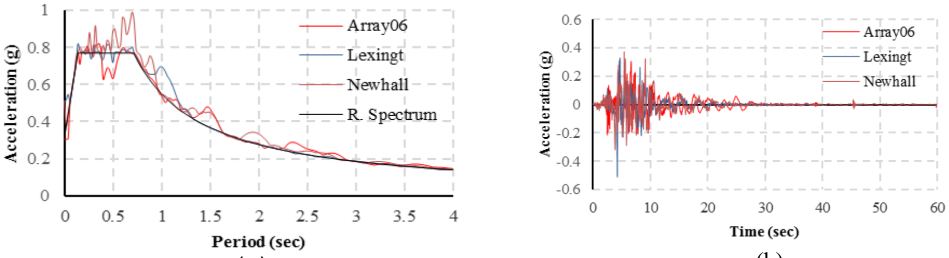


(a) (b) (c)

Fig. 3. (a) Acceleration Time History of ARRAY 06, (b) Acceleration Time History of Lexingt, (c) Acceleration Time History of Newhall.

The structural model is assumed to be a seismic force-resisting system with seismic category IV (monumental buildings) and an importance factor (I) of 1.5. Therefore, the response modification factor (R) value is 1.5, the over-strength factor (Ω_0) is 1.5, and the lateral deformation amplification factor (Cd) is 1.5, as taken from SNI 1726:2019 [11].

The structure is loaded with spectral acceleration parameters for short period (SDS) and at 1 second (SD1), which are 0.73 and 0.51, respectively. These values are the spectral parameters for the Kintamani area, Bali. The response spectrum represents of the maximum response of a structure to ground motion at different frequencies. This includes both short and long periods. The earthquake records are scaled to the design base earthquake level, which is estimated to occur at least once in the building's lifetime, every 250 years, or with a 10% probability within 50 years. This is illustrated in Figure 4. The earthquake records are scaled in such a way that the average SRSS (Square Root of Sum of Squares) spectrum over the period range of 0.2T to 1.5T, where T is the fundamental period, does not fall below 71% of the target response spectrum, as recommended by ASCE.



(a) (b)

Fig. 4. (a) Target response spectrum and scaled earthquake spectrum.

Each of the scaled earthquakes, referred to as earthquake 1, earthquake 2, and earthquake 3.

3 Result and discussion

The analysis results are divided into three sections: modal analysis results, time history analysis results, and limit equilibrium analysis results.

Modal analysis of the Meru structure has been conducted. This analysis is based on the mass and stiffness of the structure. From the analysis results, an estimated weight of the building is around 133 kN or approximately 13 tons. The structural shape tendencies during seismic vibrations result from the accumulation of mass participation and deformation shapes at specific frequencies (periods). As shown in Figure 5, the majority of contributions come from relatively short periods (on the response spectrum scale, refer to Figure 4). This indicates that the Meru structure will be sensitive or more responsive to vibrations with shorter periods, or in other words, higher earthquake frequencies. These shorter periods also suggest that the ratio of the Meru building's mass to its structural stiffness categorizes it as a rigid or inflexible structure.

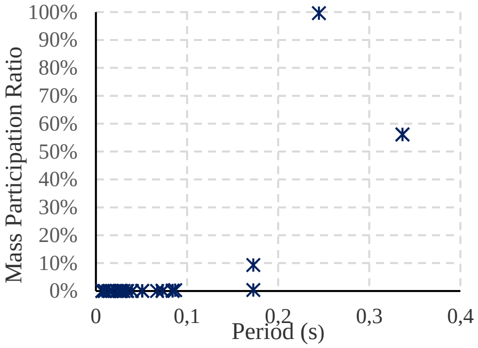


Fig. 5. Modal participation factor and period range influence on the meru structure.

It can also be observed in Figure 5 that there are 3 prominent peaks where the mass participation factor is above 15%. This indicates the largest contributions to the movement of the Meru structure that influence its shape during earthquakes. Figure 6 displays the first three significant structural modes affecting the structure - mode 1 and mode 2 with a combined contribution of 56% at a vibration period of 0.336 seconds, as well as mode 3 with a contribution of 99% at a vibration period of 0.244 seconds.

Although the movement of the Meru structure will result from the superposition of responses from all contributing modes, these three shapes are the most dominant in influencing the structure during seismic shaking. Figure 6 is the visualization of the first three mode shape.

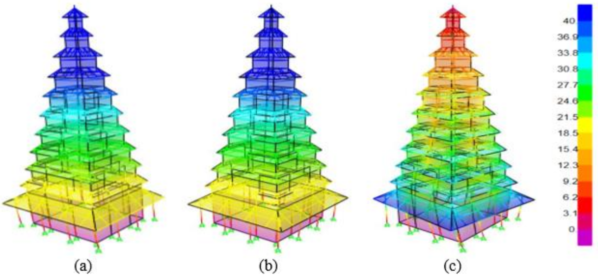


Fig. 6. Mode shapes (a) Mode 1, (b) Mode 2, (c) Mode 3.

Entering into the dynamic analysis, namely time history analysis, results are obtained for the structural response forces and accelerations, complete with displacements and drifts at each level.

In Figure 7, the relationship between base shear and base acceleration is depicted. It can be observed that the maximum base shear force (around 80 kN) is obtained when the maximum acceleration response is reached (approximately 1.2g). In simple terms, it can be stated that the shear force response generated by the Meru structure is about 60% of the total weight of Meru, which is caused by the 1.2g acceleration. Referring to the response spectrum, this 1.2g acceleration response (refer to Figure 4) is a result of the structural characteristics of Meru, which has a relatively small natural vibration period. This period even corresponds to over 75% of the structure's response to vibration periods less than 0.244 seconds (refer to Figure 5).

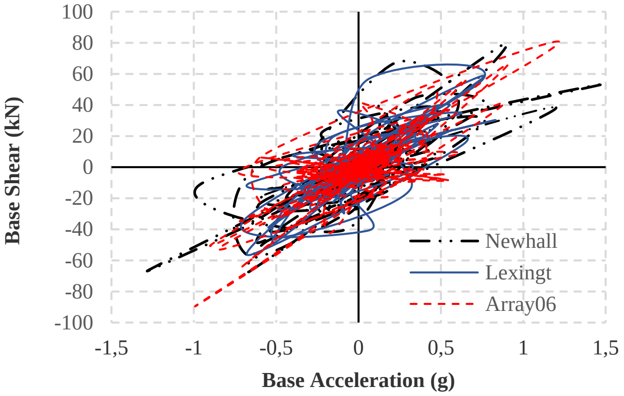


Fig. 7. Relationship between base shear-acceleration within the structure during an earthquake.

Generally, flexible structures or those with longer periods are expected to have smaller acceleration responses compared to rigid structures. However, with longer periods, structures are prone to experiencing larger deformations. These substantial movements need to be supported by good material ductility. It is advantageous for the Meru structure to have a very short natural period, as this allows it to experience relatively small accelerations and deformation responses that are also not insignificant.

For more detailed information on acceleration and deformation responses during earthquakes, refer to Figure 8, where the maximum deformation response at the roof's end or peak level reaches 38 mm.

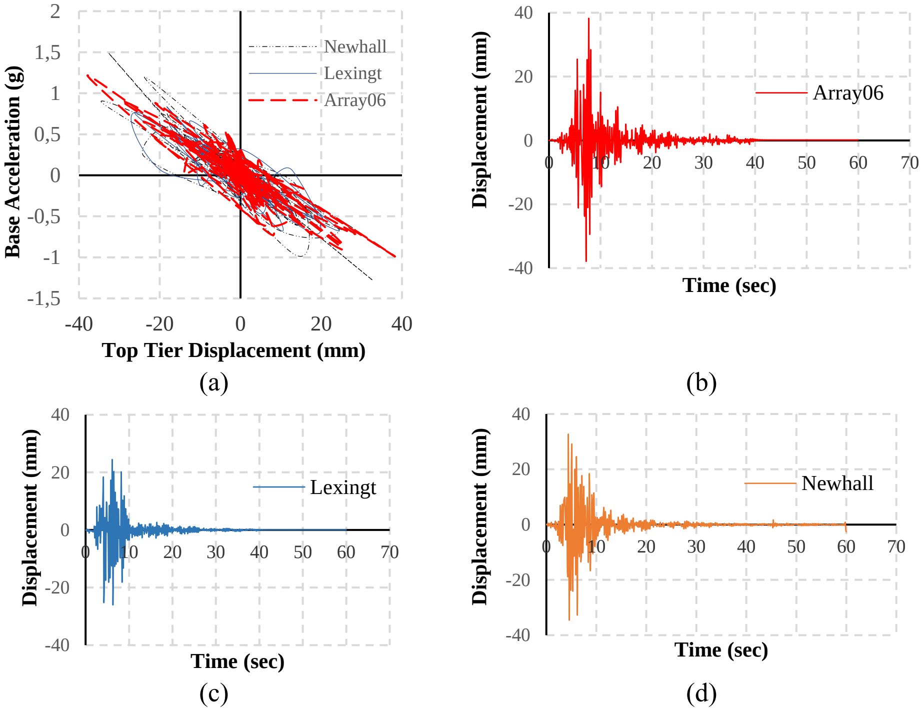
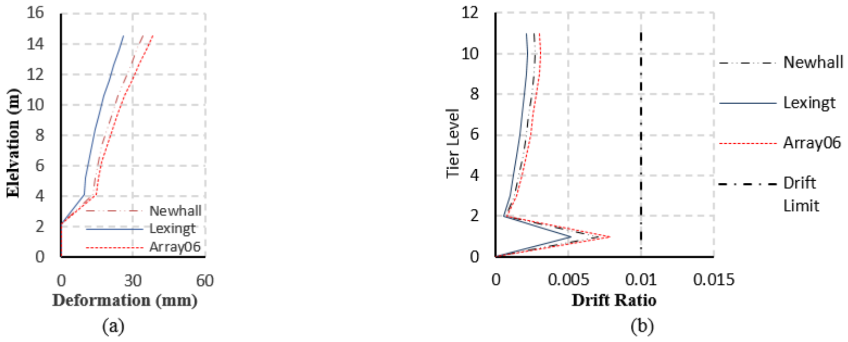


Fig. 8. (a) Acceleration-displacement relation in the structure during earthquakes (b) Displacement of the top tier during earthquake 1 (c) Earthquake 2, and (d) Earthquake 3.

The clearer comparison among the three earthquakes used can be observed in Figure 9(a), which illustrates the overall deformation of Meru up to its elevation. Figure 9(b) presents the comparison of drift ratios at each level of the Meru structure. From the observation of drift ratios, the results indicate that the maximum inter-story displacement is around 0.0079 or 1/125. This small drift ratio indicates a good seismic performance of a wooden structure, as it is sufficient to fulfill the safety level of traditional wooden structures, which has a maximum allowable safety limit of 1% according to SNI 1726:2019.



(a) (b)

Fig. 9. (a) Absolute maximum displacements and (b) Drift response of the structure during earthquakes.

The result of stress field analysis resulting from deformation during the earthquake are presented in Figure 10. During an earthquake event, stress and strain will naturally vary according to the deformation, influenced by the material's strength. The maximum stress obtained from the three earthquakes is 2.9 MPa. This value is still lower than the material's strength limits for both wood and brick walls, which are 11 MPa and 5 MPa, respectively. With a capacity greater than the occurring stress, the components composing the Meru will remain safe at this seismic level. It is evident that the beneficial effects of Meru's seismic response characteristics, with relatively small deformations, are highly conducive and compatible with the material's capacity. Therefore, it is reasonable that the 11-tier Meru is still standing well until now.

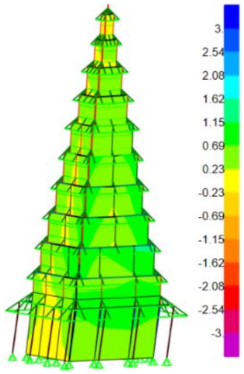


Fig. 10. The maximum stress acting on the brick wall and wooden panel (max = 2.9 Mpa).

4 Conclusion

Meru possesses a unique structural configuration that influences its dynamic behavior and, consequently, its seismic resilience. Such a configuration, in addition to relying on geometry and mass distribution, is also influenced by the mechanical properties of its elements. Modal analysis, linear time history, deformation limits, and capacity equilibrium analyses have been conducted. From the discussion of the analysis results, it is concluded that:

1. The Meru structure is considered rigid, as observed from the comparison of its mass and stiffness.
2. The rigidity characteristics of the Meru can lead to a point where the response of acceleration and deformation to earthquake vibrations becomes relatively small.
3. During earthquakes, the majority of deformation shapes correspond to mode 1 and mode 2, or simply put, similar to cantilever beam deformation.
4. The drift that occurs at each level of Meru remains within safe limits, in accordance with the SNI 1726:2019 guidelines.
5. Similarly, the stress that occurs does not exceed its capacity.

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