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A Simple Stilt Structure Technique for Earthquake Resistance of Wooden Vernacular Houses in Bima, Sumbawa Island, Indonesia

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***Abstract*—The existence of local building structures in Bima vernacular architecture is the research object in this study. The condition of the Bima Regency, which is prone to tectonic and volcanic earthquakes, is the context that influences the structure of the wooden stilt houses. This vulnerability occurs because of two earthquake fault lines flanking the Sumbawa island and an active volcano, Mount Tambora. Identification of Bima vernacular houses' structures and their effectiveness in reducing deformation due to earthquakes become the aims of this study. Data collection uses field observation methods to identify local building structures and construction systems. It also uses digital simulation to determine diagonal bar elements' effectiveness on the stage structure in reducing deformation due to an earthquake. The results showed that the stilt structure consisting of post components with corbels to support the beams, double beams arranged in a cross, diagonal bars, and wooden pegs were structures that maintained their existence. The existence of this stilt structure technique is part of the local seismic culture of the Bima community. The simulation result shows that diagonal bars' presence reduces deformation in structural elements due to earthquake loads. The synergy between structural components occurs in the construction of the Bima vernacular house structure. Thus, the system, form, and material of the Bima stilt structure can reference the development of earthquake-resistant houses in Indonesia.**

***Keywords*—Stilt structure; earthquake resistant; vernacular architecture; Bima.**

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I. INTRODUCTION

Bima Regency is on Sumbawa Island, which is prone to earthquakes. This vulnerability occurs because of two earthquake fault lines flanking the island [1]. The earthquake fault line in the north is the active Flores Back Arc Thrust fault, and in the south is the meeting of the tectonic plates of the Indonesian Ocean–Eurasia [2]. Besides, there is an active volcano, Mount Tambora. So, both tectonic earthquakes and volcanic earthquakes can be a disaster threat. The geological conditions of a specific area and natural disasters that often occur in the past can affect buildings' typology and construction [3].

Vernacular architecture's character results from human relations with the environment, enabling people to live in harmony with natural conditions by utilizing local materials and adapting to the local climate [4], [5]. Local communities in earthquake-prone areas strive to adapt to environmental conditions and preserve their built environment [6]. With their knowledge and skills, Indigenous people try to protect life's safety and the built environment when a disaster occurs. Vernacular architecture in Bima Regency, which is the object of this study, consists of wooden stilt houses and granaries. Buildings structure with timber material and wood frame construction have an excellent response to seismic in various parts of the world, for example, in Turkey [7]–[10], the Himalayan region of India [11] [12], Nepal [13], Kaikoura in New Zealand [14], Japan [15], and Korea [16]. Traditional wooden frame constructions have better durability from past earthquake events than unreinforced masonry wall construction [17]. It also has a large deformation capacity with little damage during an earthquake, especially on the traditional infill timber walls [18], [19]. For example, a traditional Chinese structure of a timber frame with a wood panel (infill wall) shows a higher load carrying capacity, stiffness, and better energy dissipation capacity than a frame without a wood panel [20].

So, vernacular architecture in Bima has the character of a built environment adapted to local conditions prone to earthquakes. In Bima Regency, most people living in villages still use stilt houses to live.

The average number of dwellings with wood material still dominates around 64% compared to brick or bamboo material of residential buildings in each district [21]. The existence of wooden stilt houses proves that they are adaptive to their natural conditions, prone to earthquakes. Bima vernacular architecture typology is *uma lengge*, *uma mbolo*, *uma jompa*, and *uma panggu* (figure 1). *Uma lengge* and *uma mbolo* still exist with a minimal amount. Meanwhile, the granaries called uma jompa only live in a few villages. For this reason, the scope of the discussion focused on residential buildings called *uma panggu*, which referred to wooden stilt houses. There are four types of wooden stilt dwellings in Bima: six-post house, nine-post house, twelve-post house, and sixteen-post house.

Fig. 1 Typology of Bima vernacular architecture: *uma lengge* (A), *uma mbolo* (B), *uma jompa* (C), *uma panggu* (D)

Local seismic culture (LSC) is local people's knowledge about earthquakes' effect on buildings and how they consistently apply it to strengthen building structures [22]. The people then pass on this knowledge to the next generations, and they make improvements. They make repairs or reinforcements following the needs of the building to anticipate the next earthquake. The structure system and buildings' elements show their effectiveness in resisting earthquakes in the past [23]. The community has maintained the existence of the building from generation to generation. They also believe that it still be useful in resisting earthquakes in the future. Besides, maintenance and reinforcement aspects of a damaged building after the earthquake also became part of the LSC. Local seismic culture is part of the practice or application of vernacular architecture. Therefore, local seismic culture has the following characteristics: local materials, local community skills, and other local resources [6]. The more essential features are the subsequent local culture in traditional building techniques, which effectively resist earthquakes [6]. This local seismic culture arises from the community's need to react to earthquakes and survive in anticipation of the next earthquake [24]. The structure and construction of vernacular architecture in Bima are closely related to local seismic culture (LSC) because it is prone to earthquake disasters. It has simple construction details but supports the performance of the structural system.

Vernacular houses' construction uses local technology and a simple structure that involves the local community, materials, and knowledge [25], [26]. In the seismic prone area, the vernacular dwellings usually have a simple floor plan geometry, with a low ratio between the floor plan's length and width so that it has the same resistance in each direction [23]. The techniques in traditional structures that play a role in reducing the risk of structural failure due to earthquakes are usually in three structural parts, namely the lower structure (foundation), middle structure (floor and walls), and the upper structure (roof). Wooden poles placed on flat stones exist in the lower structure of stilt houses in traditional Omahada houses in Nias and Uma Lengge in Bima, which considered this system more responsive to an earthquake [27]. The bracing component (diagonal bar) in the wall structure (middle structure) has succeeded in increasing resistance to lateral forces, for example, the wall frame of a traditional house in Anatolia, Turkey [8], [9].

The first objective of this research is to identify the traditional earthquake-resistant techniques in Bima vernacular architecture in the context of local seismic culture (LSC). The second one is to prove the diagonal bar's effectiveness, the components on the stilt structure in reducing deformation due to earthquakes.

II. Materials and Method

A. Location of Research Object

To determine the location of the study, we developed a sampling framework with three criteria. The first is a map of the area and sub-district data in Bima Regency, which has experienced an earthquake. Second, villages in each selected sub-district have wooden houses on stilts of at least 65%. Finally, communities still have four types of wooden stilt dwellings: six-post house, nine-post house, twelve-post house, and sixteen-post house. Based on the criteria, we determined the research object's location, as shown in figure 2.

The research locations were Mbawa Village, Maria Village, Sambori Village, and Kole Village (figure 2). The case in this study consisted of 16 houses on stilts. The object studied in each village was four houses on stilts with different types, namely six-posts, nine-posts, twelve-posts, and sixteen-posts houses on stilts. Mbawa Village is located in Donggo Sub-district. Maria Village is located in Wawo Sub-district. Sambori Village is situated in Lambitu Sub-district, and Kole Village is located in Ambalawi Sub-district.

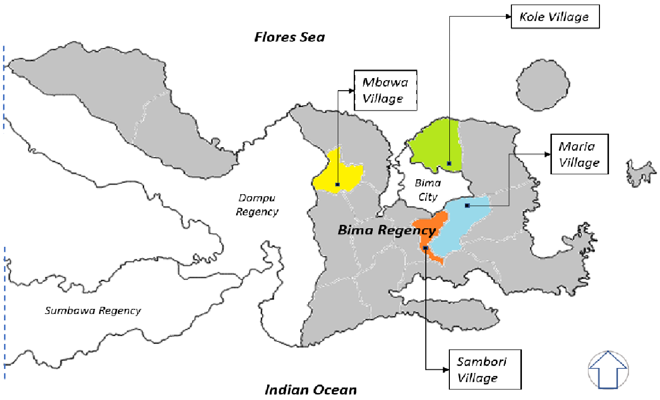

Fig. 2 Location of research objects: Mbawa, Maria, Sambori, and Kole Village

B. *Research Method*

This study uses a deductive framework, namely quantitative research, with several stages. In the initial stage, we conducted a literature review to develop a theoretical framework and a hypothesis. The next step is data collection, data analysis, and discussion of research results.

C. *Method of Data Collection*

This study uses field observations and interviews with local building experts to collect 16 empirical data on *uma panggu* (stilt houses) in Bima Regency, precisely in Mbawa, Maria, Sambori, and Kole Village. Field observation and measurement results are floor plan, elevation, and section drawing of the houses. Besides, we also documented the structural system's schematic, construction detail of the stilt structure, the designation of structural components in the local language, and the construction process. As a comparison, we also collected empirical data about *uma lengge*, *uma jompa*, and *uma mbolo*.

D. *Method of Data Analysis*

To achieve the first objective, we analyzed data from field observations by comparing the research objects and describing the structure parts of the stilt house in terms of traditional technique construction in response to seismic load. To achieve the second objective, we conducted experiments through model simulations with Autodesk Robot Structural Analysis software. This simulation starts first with the preparation stage, including gathering earthquake acceleration spectral data of the research locations. Second, based on the research object's field measurement, we develop the building structure's geometry model, including setting the property material. Third, we compile the building structure loads, input parameters for analysis and running simulation using modal analysis and response spectrum analysis. The last one is getting simulation results. The results are then analyzed to find the effect of diagonal bars in reducing the deformation and stresses of the stilt house structure caused by earthquake loads from the X and Y directions.

To examine the stilt structure's performance, we made two types of models based on 16 data of the research objects. The first type is 16 models without diagonal bars and the second, 16 models with diagonal bars (existing model). The models using material properties followed the results of field observations and meet Indonesian National Standards: SNI 7973-2013 [28] and SNI 03-3233-1998 [29]. The wood material input in the model adjusts to the field observations results.

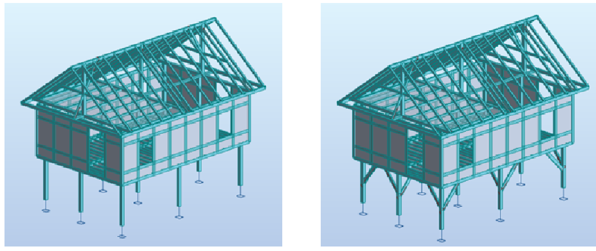

Fig. 3 The example model for simulation: model without diagonal bars (A) and existing model (B) for the case of a nine-post stilt house in Mbawa Village

Figure 3 shows the model of a nine-post stilt house in Mbawa Village: model without diagonal bars (A) and existing model (B). The building load data follows the regulations for dead loads, live loads, and earthquake loads. Data on the earthquake acceleration spectral values match the Mbawa, Maria, Sambora, and Kole Village values. Other parameters for earthquake loads following the Indonesian National Standard is SNI 1726-2012 [30]. Using the simulation with modal analysis and response spectrum analysis, we produce maximum deformation and stress data on the structure due to earthquake loads. The comparison among the models without diagonal bars and existing models for all empirical data provides information on the effectiveness of diagonal bar components in minimizing maximum deformation and stress in the structure of stilt houses.

III. Results and Discussion

A. *Local Timber for Building Material*

People in Bima use local wood, namely *monggo* (*Eugenia Polyanta*), *mengi* (*Dysoxylum rufum*), and *luhu* (*Schoutenia ovata*) for structural elements of their stilt houses. The woods have an average specific gravity of 0.64, 0.64, and 0.98, respectively [29]. Besides, teak wood (*Tectona grandis*) with an average specific gravity of 0.67 [29] is also used extensively, especially in Kole Village. In addition to lightweight, timber also has excellent tensile and compressive properties that support the house's resistance to earthquakes. Thus, the stilt houses have an outstanding response to seismic in Bima Regency due to their mechanical wooden properties of the structural elements. The wooden stilt houses have better durability from past earthquake events than unreinforced masonry construction [17].

B. *The Characteristics of The Floor Plan and Elevation*

The floor plan's basic form on the stilt houses is square (figure 4, table 1). This simple form has the potentiality to withstand earthquakes when compared to the irregular form [23]. Among the four types of research objects, the stilt houses with twelve-poles and sixteen-poles are more prone to earthquakes than the dwellings with six-poles and nine-poles. Apart from the ratio of the larger floor plan's length and width, they have a weightier building mass due to greater floor area (table 1).

TABLE I
FIELD MEASUREMENT RESULTS OF WOODEN STILT HOUSES FOR THE RESEARCH OBJECT

Object	Location (Village)	Number of poles	Floor plan width (cm)	Floor plan length (cm)	Floor area (m²)
A	Mbawa	6	340	530	18.02
B	Mbawa	9	410	610	25.01
C	Mbawa	12	520	820	42.64
D	Mbawa	16	650	890	57.85
E	Maria	6	320	580	18.56
F	Maria	9	450	700	31.50
G	Maria	12	480	760	36.48
H	Maria	16	670	1010	67.67
I	Sambori	6	340	450	15.30
J	Sambori	9	410	600	24.60
K	Sambori	12	750	900	67.50
L	Sambori	16	590	900	53.10
M	Kole	6	340	650	22.10
N	Kole	9	480	770	36.96
O	Kole	12	590	980	57.82
P	Kole	16	670	960	64.32

In contrast with the simple floor plan, the elevation of the stilt houses in the category is unsimple. When viewed vertically, the middle (floor and wall) and top (roof) of the houses are supported only by slim pillars (figure 4). This form of elevation is prone because it results in significant stress on the post structure during shaking due to the earthquake.

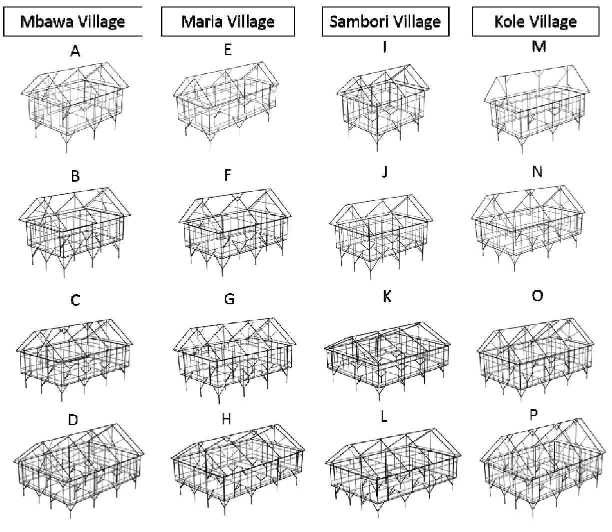

Fig. 4 Structural frame of the six-poles (A, E, I, M), nine-poles (B, F, J, N), twelve-poles (C, G, K, O), and sixteen-poles stilt houses (D, H, L, P) in Mbawa Village, Maria Village, Sambori Village, and Kole Village

C. Structural Configurations

The lower structure configurations exist in the form of a slender wooden post. The number of poles is according to the type of stilt house. These wood columns are unique because they have useful protrusions (corbel) to support the double beams connecting the poles (figure 7). The configuration is a vulnerable part of seismic loads. In Bima, the carpenters solved this problem by installing a diagonal bar (bracing) of wood that connected poles with double beams to a joint in the form of wooden pegs. This diagonal bar is called *ceko* in a local language, an integral part of the stilt structure in the wooden house of Bima vernacular architecture. This stilt structure is part of the local seismic culture (LSC) related to the traditional building structures in the Bima indigenous community. Expert local carpenters added the bracing component to the stilt structure to increase rigidity during an earthquake.

The structure model using *ceko* still exists in the typology of *uma lengge* (figure 5A), *uma jompa* (figure 5C), and *uma panggu* (figure 5D). But there is a stilt structure model without *ceko*, namely *uma mbolo* (figure 5B). The type of *uma mbolo* only exists in Mbawa Village. The number is currently less than 10. The community does not build this type anymore. The traditional technique of stilt structure, called *ceko*, still exists and continues to be utilized to construct wooden stilt houses in Bima. Figure 5 shows the diagonal bar (*ceko*) at the lower structure (LS). The traditional wood construction technique is part of local seismic culture [22], [23]. The existing sketches of the structure and stilt construction in figure 5 show similarities in the three typologies. The similarity is in the stilt structure of *uma lengge* (figure 5A), *uma jompa* (figure 5C), and *uma panggu* (figure 5D). It appears in four structural components. These components are the poles, double beams, diagonal bars, and cylindrical wooden pegs. But the stage structure on *uma mbolo* (figure 5B) is different from the others because the connecting beam is a single beam, a square peg, and no bracing or diagonal bar.

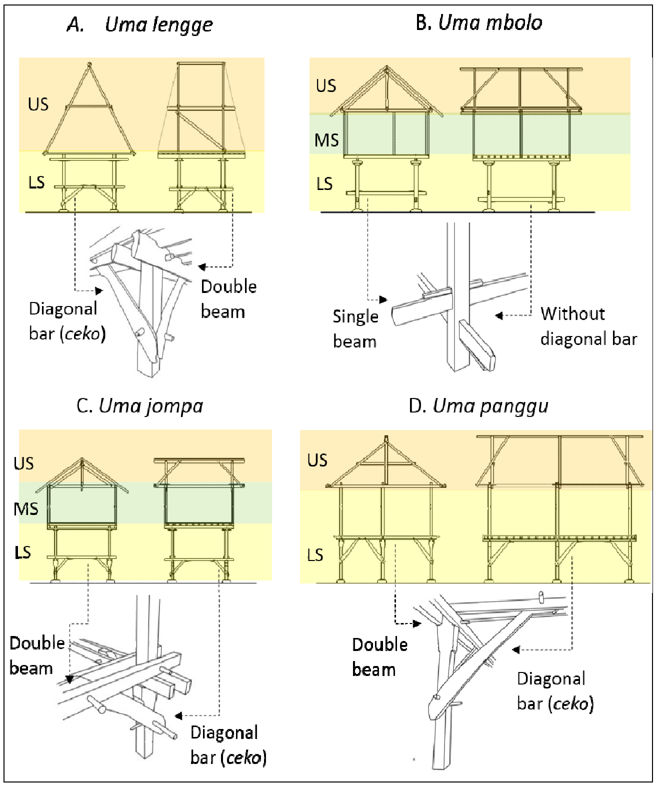

Fig. 5 Sections of *uma lengge* (A), *uma mbolo* (B), *uma jompa* (C), and *uma panggu* (D), which has some level: lower structure (LS), middle structure (MS), and upper structure (US), and also the comparison of their stilt structure.

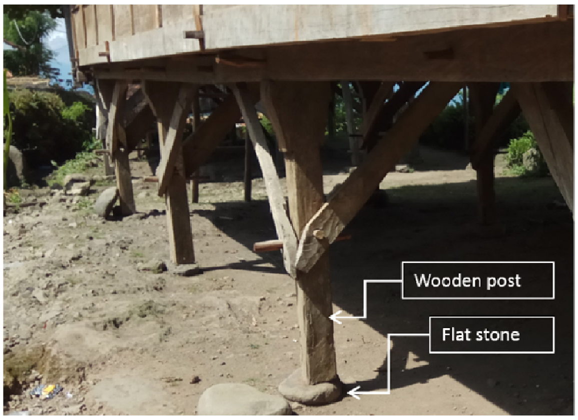

Fig. 6 The foundation structure of stilt house: a wooden post placed on a flat stone

Foundation and stilt structures are an essential part of the structure of the vernacular architecture in Bima in response to lateral loads due to earthquakes. The friction damper character belongs to the foundation in a wooden post placed on a flat stone (figure 6). This type of foundation allows for a shift between the pillar and the flat stone during an earthquake, reducing internal forces. It likes the friction damper or base isolation character [27]. The stone's surface area has a greater area than the pole cross-section so that if an earthquake occurs, the pole shift over the flat stone. This foundation type also allows the energy dissipation [22] to reduce the impact of earthquake vibrations on the poles.

To resist the lateral force due to earthquakes, the stage structure at *uma panggu* has four components that synergize with each other, namely pole with useful corbels, double beams arranged crosswise, wooden pegs, and diagonal bars that strengthen the relationship between double beams and poles. Figure 7 shows the assembly of these components.

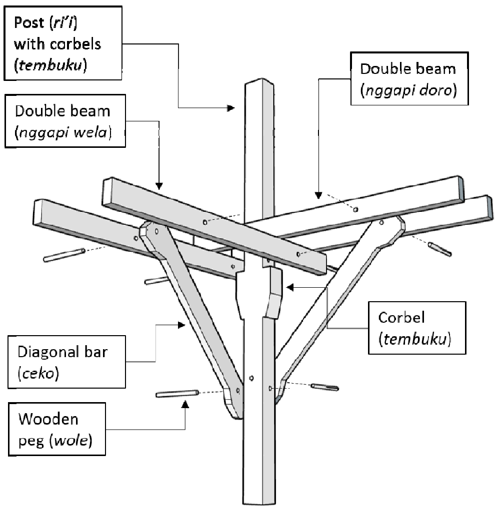

Fig. 7 Assembly of the stilt structure components: post with corbels, double beams, diagonal bars, and wooden pegs

The relationship between pole, beams, and diagonal bars is the pin connection with a connecting tool in the form of a wooden peg. Corbel and diagonal bars have a function as structural stability elements. This structural stability system can resist lateral loads in two directions without reducing the pile's strength. The connection relies on the contact area with the post's corbel and the pegs as a connection tool. The aspect of improving the stilt structure in Bima after the earthquake occurred when the post loosened. The carpenter then tightens the pegs again. The post that allows friction and then loosens on the part of the connection with the pegs can also have the potential of a 'fuse' that can dissipate energy when an earthquake occurs [20], [22]. The local people's traditions to make repairs and strengthen their homes after an earthquake are also part of the local seismic culture. This improvement and strengthening aspect is part of local seismic culture [22], [23].

D. *The effectiveness of the diagonal bar*

Quantitatively we conducted experiments with digital simulations to determine the stilt structure's effectiveness with diagonal rod components. We derive data from sixteen houses on stilts (*uma panggu*) from four villages to build digital simulation models. Figures 8 and 9 show the comparison of simulation results between existing models and models without diagonal bars.

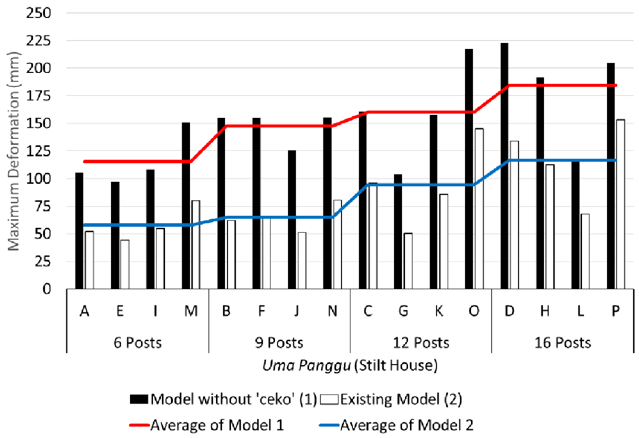

Fig. 8 Comparison of the maximum deformation (mm) between the models without diagonal bars (*ceko*) and existing models in each type of stage house (*uma panggu*)

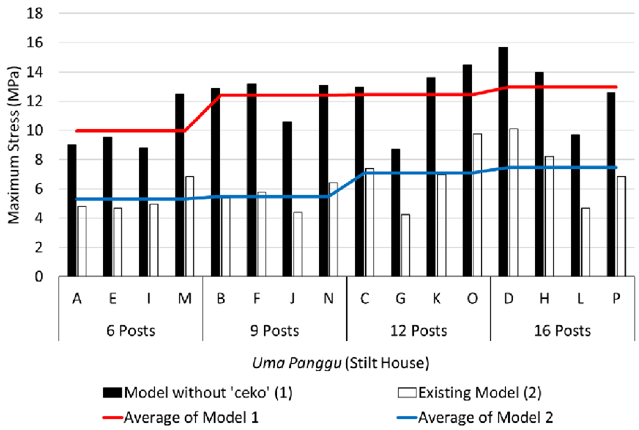

Fig. 9 Comparison of the maximum stress (MPa) between the models without diagonal bars (*ceko*) and existing models in each type of stage house (*uma panggu*)

The simulation results with response spectrum analysis on 16 models indicate the maximum deformation (figure 8) and the stress (figure 9) due to X and Y-axis's seismic direction.

Based on the simulation results, the existing model (model with diagonal bar) performs better in all types of stilt houses. The average of maximum deformation for the type of stilt houses of six posts, nine posts, twelve posts, and sixteen posts is 115.41 mm, 147.79 mm, 160.03 mm, and 184.39 mm, respectively, in the model without diagonal bars. This average is higher than the maximum deformation average in the existing model (model with diagonal bars), namely 57.86 mm for the six posts type, 64.74 mm for the nine posts type, 94.33 mm type twelve posts type, and 116.93 mm for the type 16 poles. Uma panggu model with diagonal bars can reduce deformation by 45%. The average maximum stress on the house type on stilts of six posts, nine posts, twelve posts, and sixteen posts is 9.95 MPa, 12.40 MPa, 12.45 MPa, and 12.96 MPa, respectively in the model without diagonal bars. This average is higher than the average maximum stress on the existing model (model with diagonal bars), namely 5.32 MPa for the six pile type, 5.50 MPa for the nine pile type, 7.09 MPa for the type of twelve posts, and 7.46 MPa for the type of 16 posts. The model with diagonal bars can reduce stress on the structure by up to 47%. So, the diagonal bar's role is very significant because it reduces the deformation and stress by 45% and 47%. These results strengthen the evidence that the diagonal rod component plays an essential role in reducing buildings' vulnerability due to the earthquake [8]. This component is part of the solution to the unsimple configuration on the elevation of the vernacular houses on stilt. The sixteen posts type has the highest average of deformation and stress. These results prove that the model with a heavier load is more prone to earthquakes.

IV. Conclusion

This study has proved that the wooden stilt structure of Bima vernacular architecture is part of the local seismic culture, which includes the aspects of structural existence, simple traditional techniques, and maintenance. The structural components' similarities are found in the three types of stilt houses: *uma lengge*, *uma jompa*, and *uma panggu*. They are wooden poles, double beams, diagonal bars, and wooden pegs. It is strong evidence that local people still apply this traditional technique to their vernacular architecture. The components and applying the techniques prove that they effectively responded to the earthquake in Bima Regency. Besides, the use of wooden pegs in the joints between components allows energy dissipation when an earthquake occurs. The foundation technique in the form of wooden poles placed on the flat stone is similar to the base isolation technique in modern buildings for seismic control. This base isolation function is to "separate" the building structure from the ground's horizontal forces when an earthquake occurs. So, two kinds of seismic control concepts applied to the Bima vernacular stilt structure: the seismic isolation system applied to the foundation and the building structure components' energy dissipation.

Moreover, there are synergies between the stage structure components: posts with protrusions for supporting the beams, double beams arranged in a cross, diagonal bars, and wooden pegs. Diagonal bars on the simple stilt structure have proven to be effective in increasing their structures' performance. The diagonal bar's role is very significant because it can reduce the maximum deformation and stress by 45% and 47%. The simulation results reinforce the evidence that the diagonal bar component of vernacular architecture in Bima plays a significant role in reducing vulnerability due to earthquakes. This research contributes to the awareness to maintain the local seismic culture as part of earthquake disaster mitigation aspects. The system, form, and material of the stilt structure in Bima's vernacular architecture can reference the development of earthquake-resistant houses in Indonesia. Some parts related to digital simulations in the structure's parts in detail, including the foundation system, are an opportunity for further research.

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