Structural Performance and Constructional Phases of Rumah Gadang of West Sumatra, Indonesia

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Abstract

Considered as an ideal representation of the vernacular architecture of the South-East Asian region, 'rumah gadang' (big house) of West Sumatra, Indonesia, is regarded as a thoughtful indigenous design responsive to various contextual demands. One of these is structural aspects, particularly due to the widely known seismic activities of Indonesian lands. To ensure the fulfillment of certain procedures and technical standards required for the adequate structural performance, the constructional phases of 'rumah gadang' are traditionally systematized in specific manner, not only according to certain technical considerations bus also cultural requirements as well. In this regard, to evaluate the structural performance of this vernacular house, this paper presents structural analysis of 'rumah gadang' in different constructional phases, both under normal circumstance and under seismic activities, conducted by simulations. The results show that, under various loads including earthquake, the structure of the house experiences only minor deformations, particularly in the roof area, and that the structural stability increases along with the development of the construction phases. The research also give insight on how the society of West Sumatra incorporate spiritual values into the structural design and construction process of 'rumah gadang'.

Keywords: Indonesian vernacular architecture, rumah gadang, structural analysis, earthquake modelling, wooden house

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1. INTRODUCTION

Commonly found in the west region of the Island of Sumatra, Indonesia, South East Asia, 'rumah gadang' (the big house) is the vernacular house of the ethnic group of Minangkabau, who mostly inhabit the Province of West Sumatra. This house is particularly famous mostly for its strikingly curvilinear roof shape which resembles the buffalo horns (it is not a mere coincidence that the name 'Minangkabau' literally means 'the buffalo who won' (taken from an incident told in folk legend). Apart from the folk legend reason, the shape of this roof is also intended for an interior air-cooling system (Oliver, 2006a). Since the roof is the most important element in Indonesian vernacular building for its role of providing shade (Prijotomo, 2017), 'rumah gadang' becomes one of the timeless icons of Indonesian architecture. Beside that, among the major characteristics of the South East Asian vernacular house architecture, most of them (Example: the elevation of the structure upon stilts or piles) (Waterson, 1990), the elongated roof peak or the outward slanting gable (Waterson, 2002; Schefold, 2004), and the use of knock-down, non-rigid connections (Domenig, 2002; Prijotomo, 2010)—can be found in the house, establishing 'rumah gadang' as one of the ideal representation of the vernacular house architecture both in South East Asia and in Indonesia.

Vernacular architecture is widely known for its indigenous and apparently intuitive ways of problem-solving, an 'architecture without architect'. It has evolved over time in many ways when it is necessary to adapt to variable environments and the nature of family and social growth (Oliver, 2006b). The knowledge is developed to meet specific needs and relates directly to the environment, available resources, while using local technologies (Hărmănescu and Enache, 2016). Thus, as an example of vernacular architecture, 'rumah gadang' has to respond to its own challenges brought by the geographical context. One of these is creating earthquake-responsive structure and techniques due to its high-risked location at the Great Sumatran Fault Zone (Pemerintah Kabupaten Solok Selatan, 2012). Thus, it will be interesting and valuable to perform analyses on the structural performance of 'rumah gadang', both in the final form and the constructional phases of the house.

Therefore, this present paper focuses on the structural analysis of 'rumah gadang' in relation with its constructional phases using simulation of digital model, enriched with cultural analysis of the aspects which may affect or related to the structural system, construction techniques, and structural components of the house. It should also be noted that there are several types of 'rumah gadang' differing in size, formal complexity, and functional aspects, ranging from the simple, small domestic houses of common folks, to the large and aesthetically complex palace and ceremonial halls. In this regard, this paper focuses on a specimen of the simplest type: a domestic house for casual daily activities, considerably modest in size, and formally as well as structurally simple. Finally, in terms of the modelling and simulation, there are some considerations as well. Only the main structural elements of the house were modelled for the calculation: The posts, main beams, and the main structure of the roof in short, the main structural frame. Other elements, such as the secondary beams, floorboards, wooden walls, and roof coverings were not considered as structure; instead, such components are calculated as loads. It should also be noted that the construction of 'rumah gadang', not unlike those of other Indonesian and South-East Asian vernacular houses, is rather peculiar, in that the connections between structural members are mostly (if not all) non-rigid. Thus, to portray this non-rigidness as best as possible, a specific methodological strategy was applied in the simulations using SAP2000 program, whereby the 'rumah gadang' is represented in two

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types of structural models. This strategy, as well as the methodological settings and variables used in the simulations, are described in more detailed manner in Section 5 (Methodological Strategy).

2. RESEARCH METHODOLOGY

This paper addresses the key issues in three main sections which follow. First, the structural elements of 'rumah gadang' are described. The data presented in this section are obtained both from the primary source (direct observations) and the secondary source (literatures). While the literatures discuss the typo-morphological view of the house, the observations were conducted upon a specific, particular house. Afterwards, in the second section, the constructional phases of 'rumah gadang' are presented. Likewise, this section relies on both literatures and direct observations. Finally, in the third and final section, the structural performance of 'rumah gadang' is assessed through computer simulations. Thus, the following results and discussions mostly address these simulations. The general structure of the research methodology is depicted in Figure 1.

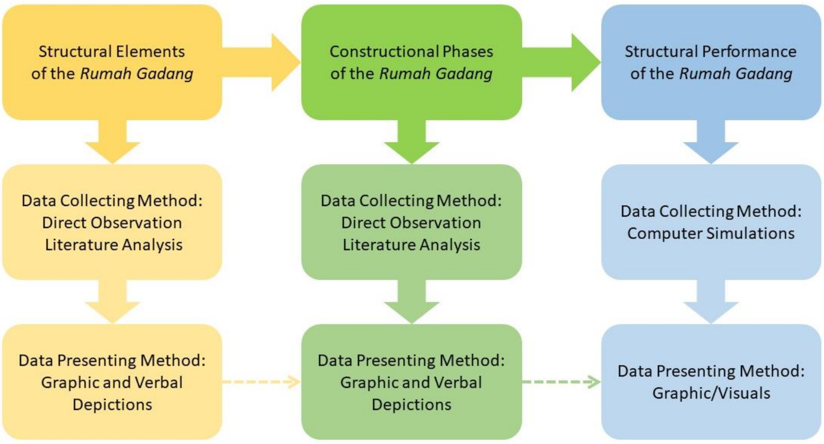

Figure 1. General structure of the research methodology (Johanita Anggia Rini, 2020)

Figure 2. A specimen of rumah gadang (Johanita Anggia Rini, 2020)

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3. STRUCTURAL ELEMENTS OF *RUMAH GADANG* AND ITS PHYSICAL CONTEXTS

3.1. Structural Elements of *Rumah Gadang*

'Rumah gadang' (Figure 2) is a post-and-beam house type, which is a major structural variation of vernacular dwellings in humid tropical climate (Lehner, 2016). The architectural characteristics of 'rumah gadang' vary depending on the 'luhak' (Minangkabau original regional unit) in which the house is located (Wongso, 2014). Apart form the location, the variations in term of forms and architectural pattern of 'rumah gadang' were also caused by the different traditional system (lareh) within Minangkabau society (Agus, 2006). The variations can be observed in the floor leveling (anjuang) and the positioning of the step ladder (Hasan, 2007). The size and complexity of the house also depend on the social position of the owner's ancestors. Located in the area of Alam Surambi Sungai Pagu, Solok Selatan District, the particular house investigated in this paper falls under the category of common folk house (Abdullah, Antariksa, and Suryasari, 2015). It has relatively small dimension with only 3 longitudinal structural module (lanjar) and it has no floor leveling (anjuang). It also has a considerably straight posts, unlike the posts of some larger houses which slant outward at the upper part.

According to the categorization of structural forms by Schodek (1991), the main structure of 'rumah gadang' is rigid frame consisting of both linear and curved structure. The linear elements are posts and beams, while the curved element is the ridge beam (balok parabuang) supporting the soaring curved roof. The main structural elements along with the traditional terminologies are depicted in Figure 3.

The most important post in the house, called 'tonggak tuo' or 'the elder post', is located at the outer side of a bedroom (bilik) called bilik limpapeh which is placed at the 'elder' end of the house (Hasan, 2007). Limpapeh itself is the great matriarch of the house (the Minangkabau society is matrilineal). Consequently, the tonggak tuo is the symbol of the ownership and leadership of the house. The other crucial structural elements are the supports, which can be described as the intersection between structural elements to transfer load between different systems (Schodek, 1991). Not unlike the other vernacular houses in Indonesia (and South East Asia), the supports in 'rumah gadang' are stone bases (sandi) placed under the wooden posts (Figure 4). These stones are bound to neither the posts nor the ground, thus small structural movements are still possible. This type of support is best categorized as 'pinned support', which can resist both vertical and horizontal forces, but not a rotating force or moment (Schodek, 1991).

Finally, the types of connections on the main structural frame of 'rumah gadang' are mortise-tenon and notch (Figure 5). Both of these connections are non-rigid, and are best categorized as 'pin joint', which allows rotating movement but resists translation in any direction, and is not resistant to the moment (Ching, Onouye and Zuberbuhler, 2014). Meanwhile, the other components of the house are non-structural elements: Wooden floorboards, wooden wallboards, wooden blinds to cover the underside of the house, and zincalume roof covering (originaly thatch).

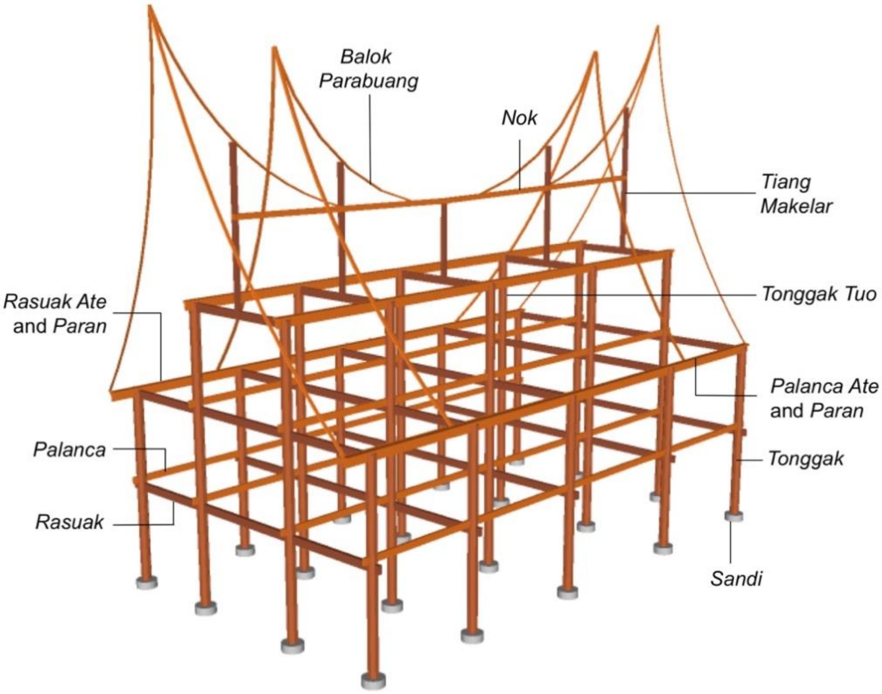

Figure 3. The main structural elements of 'rumah gadang' (Johanita Anggia Rini, 2020)

Figure 4. (left) The stone base (sandi) (Johanita Anggia Rini, 2020) Figure 5. (right) The structural connections (Johanita Anggia Rini, 2020)

3.2. Natural Settings

Due to its location at the at the Great Sumatran Fault Zone, the Minangkabau region is prone to the high risk of earthquakes and seismic activities. In this regard, some characteristics of 'rumah gadang' may be interpreted as intuitive solving for this issue: The regular form and structural configuration, the structural frame placed in a movable manner upon the stone bases, the non-rigid connections, and the lightweight materials. Besides, the area is also prone to the high humidity and flood risk, and thus the stilts system, in which the house is elevated from the ground, leaving a space under, is also quite reasonable. The natural settings of rumah gadang, summarized from Regional Plan of the District of Solok Selatan by Pemerintah Kabupaten Solok Selatan (2012), are described in a more detailed manner in Table 1.

Table 1. Natural settings of rumah gadang

Natural Condition		Consequences
Slope classification	69,19 % Very steep 30,81 % Steep-flat	Erosion, landslides, flood prone
Water condition	Abundant water flow through several large rivers, a lot of springs	ground water level close to the ground surface, moist soil
Seismicity	Located in the Great Sumatran Fault zone (*semangko*)	Earthquake prone
Soil type	Brown podsolik, latosol	Fertile land
Rainfall	1.600–4.000 mm/year	Medium-high rainfall, high humidity
Temperature	20°C – 33°C	High indoor temperature

4. CONSTRUCTIONAL PHASES OF RUMAH GADANG

4.1. Pre-Constructional Preparatory Stage

Prior to the construction process, a preparatory procession called meramu bahan (literally 'preparing the materials') is conducted. After a humble ritual, the adult men lead by the master carpenter (tukang tuo) go to the forest to gather the materials to build the house. In the gathering process, the materials are selected according to the physical as well as the cultural requirements (this is discussed in a more detailed manner in Section 7). Afterwards, in a procession called menarik kayu (literally 'dragging the wood'), the men broughts the materials to the location while singing accompanied by the sounds of gendang (drum beaten by hands). The materials are then soaked in mud for approximately one year, to enhance the durability; this process is called marandam (soaking). Finally, after the soaked materials are taken out and drained (tambun), the construction process can be started (Hasan, 2007).

4.2. Constructional Stage

The traditionally ideal construction process of 'rumah gadang' is started with a procession called mancacak paek (carving), during which time the master carpenter (tukang tuo) measures and marks the crucial points in the tonggak tuo to which the other structural members will be connected; in other words, this process will determine the basic proportion of the house (Wongso, 2020). The rest of the structural components are then measured and marked by other carpenters. The first assembling results in the very first of a series of basic structural frames of the house, called jarek. The metaphysically most crucial post in the house, called tonggak tuo (elder post), is included in the first jarek to be erected. However, preceding the erection is the reciting of the pepatah petitih (adage), a long proverb containing knowledge about the form, materials, functions, and inheritance system of the house.

Afterwards, the erection of the first jarek is performed in a special ceremony called batagak rumah (literally 'erecting the house') or batagak tonggak tuo (erecting the elder post), during which time two women from the family who will inhabit the house (two daughters of the house's owner, neither of them is married nor widowed (this custom is related to the matrilineal inheritance system of Minangkabau society) pull the rope (with the help from other men) to erect the jarek (Figure 6). Afterwards, the other structural components are placed consecutively (Hasan, 2007).

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Figure 6. The procession of batagak rumah or batagak tonggak tuo (Wongso, 2020: 62)

The whole constructional phases are depicted in Figure 7 and are outlined as followed:

Phase 1: The first set of structural frame or jarek, which had been assembled previously, is erected. This structural frame mainly consists of 4 posts or tonggak (one of them is the tonggak tuo) which are connected horizontally by the beams, or rasuak and rasuak ate. In the center of the upper beam (rasuak ate), a component called tiang makelar is placed to connect the roof frame vertically to the upper beam.

Phase 2: The rest of the structural frames (jareks) are erected to the both sides of the first jarek. The number of the frames depends on the structural-functional modules required in the house.

Phase 3: The erected structural frames (jareks) are connected using a set of longitudinal beams (palanca, palanca ate, and paran). The ridge beam (nok) is placed on the tops of the tiang makelars.

Phase 4: The stone bases (sandi) are placed under the posts (tonggaks), by slightly lifting the posts one at a time using lever system called kalang patiang.

Phase 5: The roof frames, consisted of curved ridge beams (balok parabuang), rafters (kasau), and slats (lae), are placed.

Phase 6: The roof coverings are placed. Originally the material was thatch, but nowadays the zincalume sheets are utilized.

Phase 7: The wooden floorboards are placed upon the supporting secondary wooden beams (jariau and sigitan).

Phase 8: The wooden wallboards, supporting wooden beams, and the various wooden blinds (terawang, salangko, and sasak) covering the underside of the house are erected.

Phase 9: The wooden step ladder is erected.

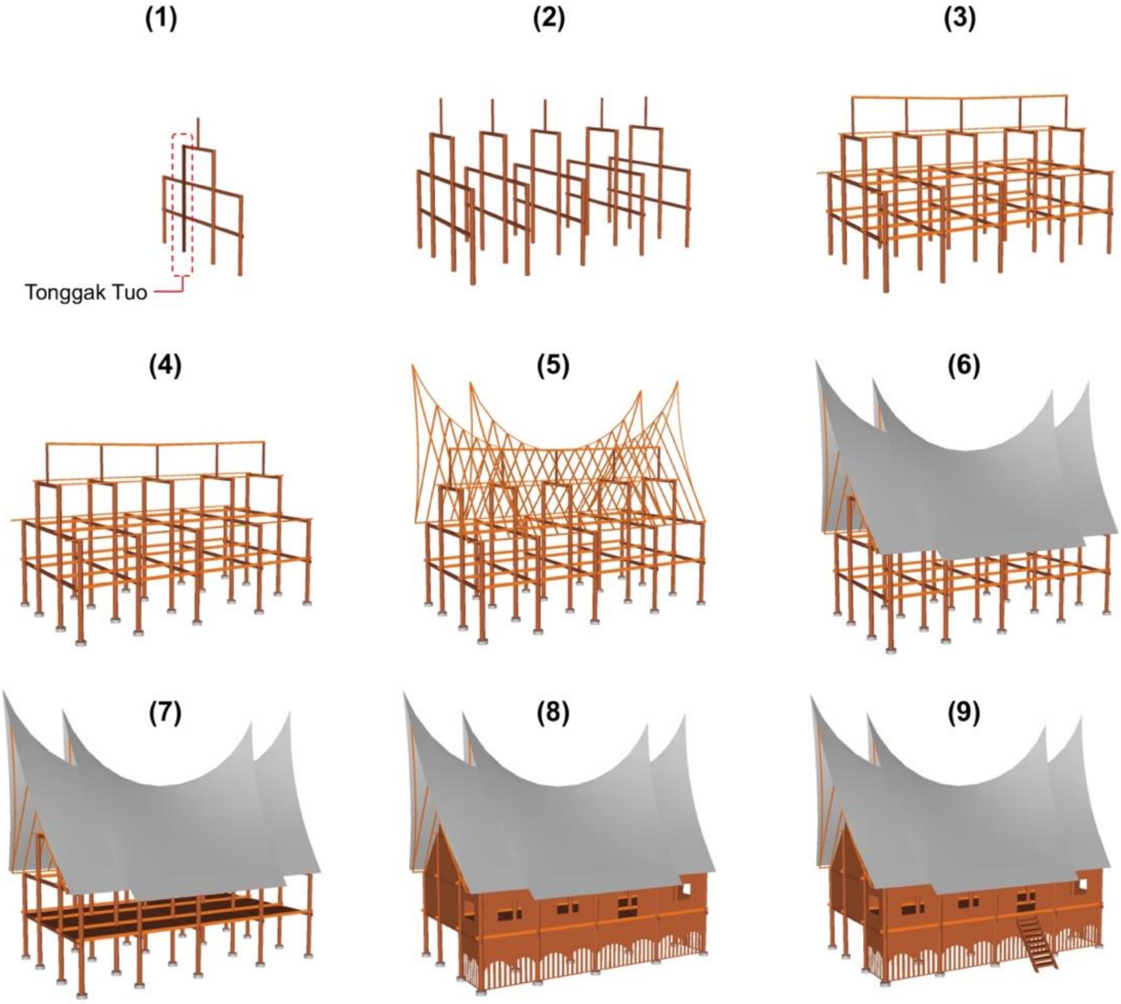

Figure 7. The constructional phases of ‘rumah gadang’ (Johanita Anggia Rini, 2020)

5. STRUCTURAL PERFORMANCE OF RUMAH GADANG

5.1. Methodological Variables

Computer simulations were conducted to measure the structural performance of the rumah gadang. The Structural Analysis Program (SAP) 2000 was utilized to run the simulations. The analysis were performed upon the main structural elements of the house: The posts, main beams, and the roof frame. Other elements, such as the secondary beams, floorboards, wooden walls, and roof coverings were considered as non-structural, and were calculated as loads. The main structural elements were modelled according to the real-life shapes and sizes, as can be observed in Table 2.

In the past, it is considered most ideal if a ‘rumah gadang’could be constructed wholly from a particular wood species called johar or juwar wood (Senna siamea), since it is the hardest wood that can be found in the region. Nevertheless, due to the increased scarcity of this type of wood, nowadays the houses are constructed by combining more than one type of wood. However, to portray the ideal or intended condition, for the simulations, the house was modelled as if it was constructed wholly from the johar wood, with the key properties, summarized from Meier (2015), presented in Table 3.

The simulations are performed at structurally crucial points in the constructional phases namely **Phase 2** (early phase) when all the structural frames (jareks) are erected, **Phase 3** (intermediate phase) when the structural frames (jareks) are connected using longitudinal beams (palanca, palanca ate, paran, and nok), and **Phase 8** (near-final phase) when all non-structural elements such as wall, floor, roof covering and live loads have been placed.

Three types of load were considered in the simulation: Dead load, live load, and earthquake, with the earthquake simulated in both x- and y-directions. Following the Indonesian National Standard, a combination of 1.2 dead load + 1 live load + 1 earthquake was used for the calculations. In the simulations for the early and intermediate construction phases, only dead load from the weight of juwar wood frame is considered, because the non-structural components and activities does not yet exist. Taking the data from the Regional Plan of Solok Selatan (Pemerintah Kabupaten Solok Selatan, 2012) into consideration, the simulations use the medium-type soil. The properties of the loads are presented in a more detailed manner in Table 4. These properties are formulated based on the standards by National Standardization Bureau (2013). The properties of zincalume roofing are considered to be the same as shingle roof (sirap) according to the Department of Public Works (1987).

The seismic spectrum for the Solok Selatan District required for the earthquake simulations are taken from the database of Desain Spektra Indonesia 2011 by the PUSKIM Department of Public Works of Indonesia (2011), which is depicted in Figure 8. The coordinate for the precise location is Lat: 1.4834534, Long: 101.0571535.

Table 2. Main structural elements of the rumah gadang analyzed in the simulations

Structural Frame	**Traditional Name**	**Cross Sectional Shape**	**Size (mm)**
Column	*Tonggak*	Octagonal	∅ 185
Long side lower beam	*Palanca*	Rectangular	150/40
Short side lower beam	*Rasuak*	Rectangular	210/70
Long side upper beam	*Palanca ate*	Rectangular	200/55
Long side upper beam	*Paran* (long side)	Rectangular	70/230
Short side upper beam	*Rasuak ate*	Rectangular	200/55
Short side upper beam	*Paran* (short side)	Rectangular	70/230
Vertical roof retaining frame	*Tiang makelar*	Rectangular	105/70
Rafter	*Kasau*	Rectangular	90/25
Ridge beam	*Nok*	Rectangular	105/70
Curved ridge beam	*Balok parabuang*	Rectangular	70/30

Table 3. Key properties of the johar wood

Local name	*johar* or *juwar*
Latin name	*Senna siamea*
Wood class	1
Weight per unit volume	800 kg/m^3
Elastic Modulus	11000 MPa
Poisson ratio	0,3

Table 4. Loads calculated in the simulations

Load Type	Origin	Amount	Explanation
Dead load	Wooden structure	800 kg/m^3	*Johar* wood's self-weight
Dead load	Wooden wall system	0,16 kN/m^2	2nd class wood, less supporting members
Dead load	Wooden floor system	0,31 kN/m^2	2nd class wood, more supporting members
Dead load	Zincalume roof with wooden rafters	0,40 kN/m^2	The weight of zincalume roof is assumed to be the same as *sirap* roof (wooden shingle) in Indonesian National Standard
Live load	Domestic activities	1,92 kN/m^2	Indonesian National Standard
Live load	Maintenance of sloped roof	0,96 kN/m^2	Indonesian National Standard
Earthquake	Response spectrum of Sungai Pagu District	S_S (g) 1,624 S_1 (g) 0,625 Site class D (medium soil)	Desain Spektra Indonesia 2011 (Ministry of Public Work of Indonesia)

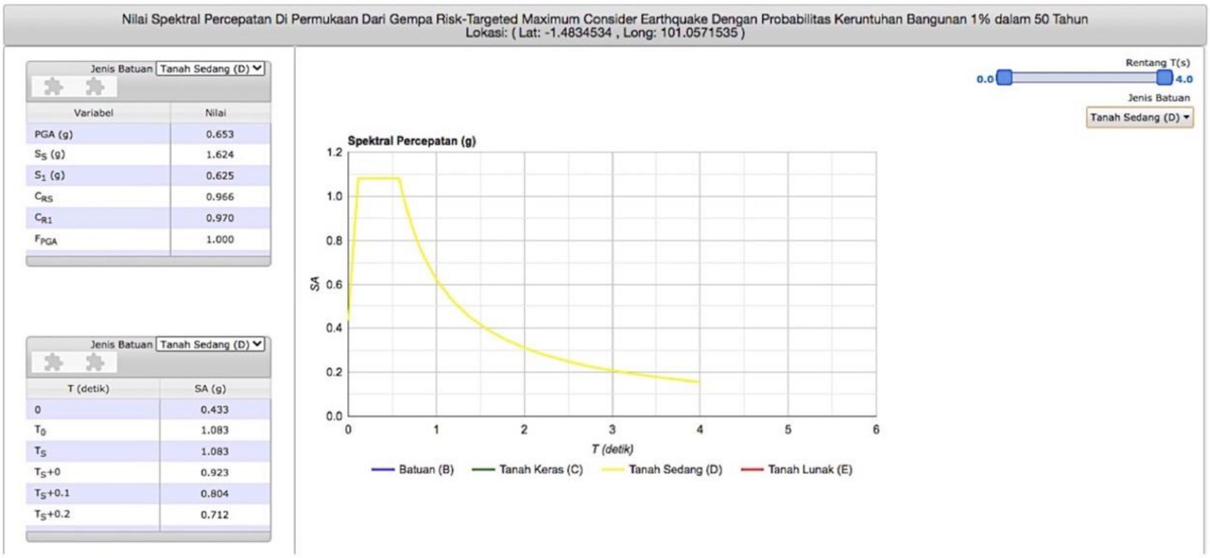

Figure 8. Seismic spectrum of Indonesia for Sungai Pagu District, Lat: -1.4834534, Long: 101.0571535 (PUSKIM Department of Public Works of Indonesia, 2011)

5.2. Metholodogical Strategy

One challenge in modelling and simulating vernacular house architecture for structural analysis is the peculiar construction techniques, in which the connections between the structural members are mostly non-rigid. Numerous researchers have formulated various strategies to address this particular issue. For example, Wasilah (2019) conducted simulations using the finite elements method to model and simulate the Ammatoan vernacular house; Taviana and Simbolon (2018) investigated traditional house of South Nias by modelling the supporting stone bases as link elements using the multilinear elastic kinematic system; Pranata and William (2013) modelled the supporting stone bases of the 'Ammu Hawu' traditional wooden house in East Nusa Tenggara as base-isolation system. Hartawan, Pradipto and Kusumawanto (2015) analysed the Bugis vernacular house in South Sulawesi by modelling the supporting stone bases as pinned supports and simulating the non-rigid connections between the posts and the beams as released moments. Prihatmaji, Kitamori and

Komatsu (2013) stated that the mortise and tenon connections between the wooden beams and columns allow rotation moments to be generated inside of the joints, caused by compression resistance between the beams and columns. 'Rumah gadang' itself possess this unorthodox constructional characteristic. Mantani and Fauzan (2019) decided to model the connections between posts and beams as partially fixed, while the supports are modelled as fixed; similar strategy has also been applied by Al Furqoni (2010).

Thus, learning from these previous researches, this paper applies a specific methodological strategy to model this unique constructional characteristic of the rumah gadang, in which two types of modelling were produced. In the first type, the connections between the wooden structural members (posts and beams) were modelled as non-rigid by releasing the major and minor moments at the ends of each member, while the supports (stone bases) were modelled as fixed. This type of model will be used in structural simulations at the early, intermediate and final phase of construction, because while the frame is not completely assembled, its non-rigidity will be more prominent. Conversely, in the second type, the connections between the wooden structural members were modelled as rigid, while the supports were modelled as pinned. This second type of model will be used to simulate the final constructional phase only. The frame structure model and the non-rigid representation of the frame with the moment released at the ends of each beam is depicted in Figure 9. The results of the simulations are presented in a visual/graphic manner. To depict the results clearly, the structural deformations were visualized in enlarged views, using the scale factor.

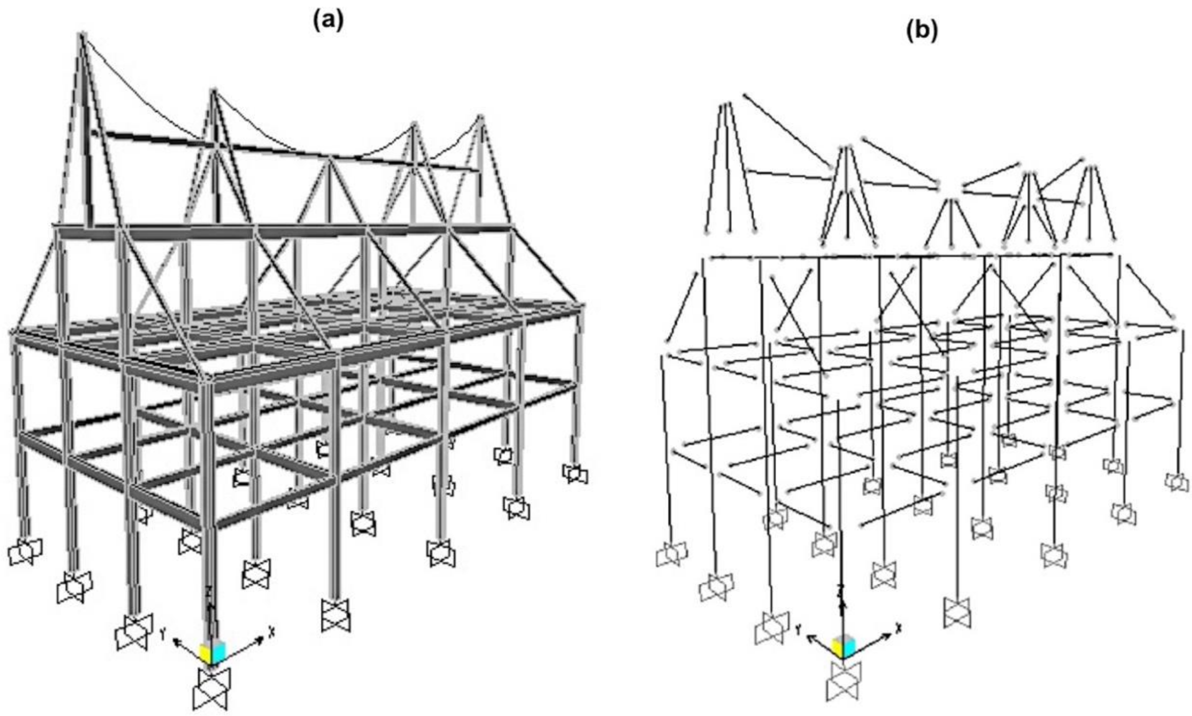

Figure 9. The frame structure model (a) and the non-rigid representation of the frame (b) used in the simulation (Johanita Anggia Rini, 2020)

6. RESULTS AND DISCUSSIONS

6.1. Structural Performance in Different Constructional Phases

In the simulation performed at the early constructional phase, the set of structural frames (jareks) are erected without being connected by the longitudinal beams. Since the real deformation is very small, the visualization has been enlarged with a scale factor of 6.000E-10. The results show that the set of structural frames (jareks) tends to collapse in longitudinal direction when hit by an earthquake from the X-direction or perpendicular to the plane of jareks. This deformation is caused by the absence of a longitudinal beams that bind the frames (the beams will be placed in the next phase). In the event of an earthquake from the Y-direction, almost no deformation is visible visually. This indicates that the stiffness of the jareks is good when subjected to a force parallel to the plane. The initial frame formation and post-loading deformations occuring in the structure can be observed in Figure 10.

The same simulation is performed for the intermediate constructional phase whereby the structural frames (jareks) are connected using a set of longitudinal beams (palanca, palanca ate, paran, and nok). The results show that, when the structure experiences earthquake from both X and Y direction, the deformation is very small visually. This deformation is visible on the roof, namely a very minor shift in the vertical roof retaining frame (tiang makelar) and the curved ridged beam (balok parabuang). These results indicate that the stability of the entire structure increases significantly after installation of the longitudinal beams. The initial frame formation and post-loading deformations occuring in the structure can be observed in Figure 11.

In the simulation for the end of construction phase when all the non-structural elements such as wall, floor, roof covering, and live loads are considered, no more deformations can be observed visually when the structure is subject to dead loads, live loads, and earthquakes from the X and Y direction. This result shows that in this final phase, even though the load is bigger, the structure becomes more stable after the spaces between the frames are filled with materials that increase the stiffness. The initial frame formation and post-loading deformations occuring in the structure can be observed in Figure 12.

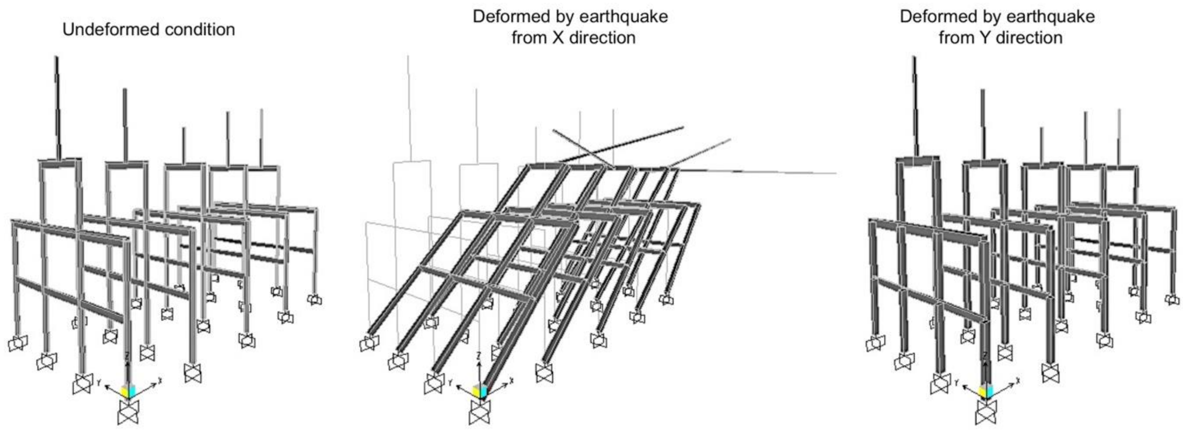

Figure 10. Initial frame formation and post-loading deformations in the early constructional phase model (Johanita Anggia Rini, 2020)

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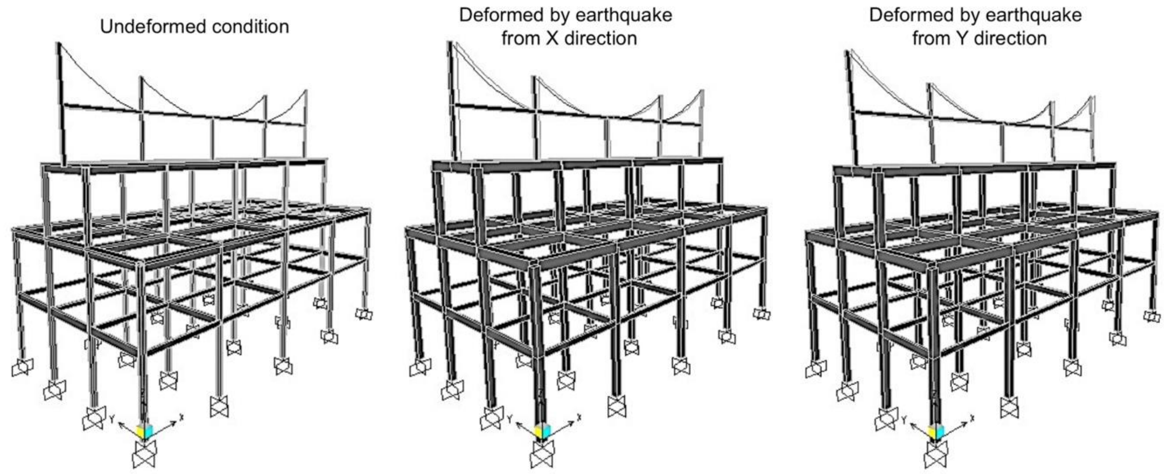

Figure 11. Initial frame formation and post-loading deformations in the intermediate constructional phase model (Johanita Anggia Rini, 2020)

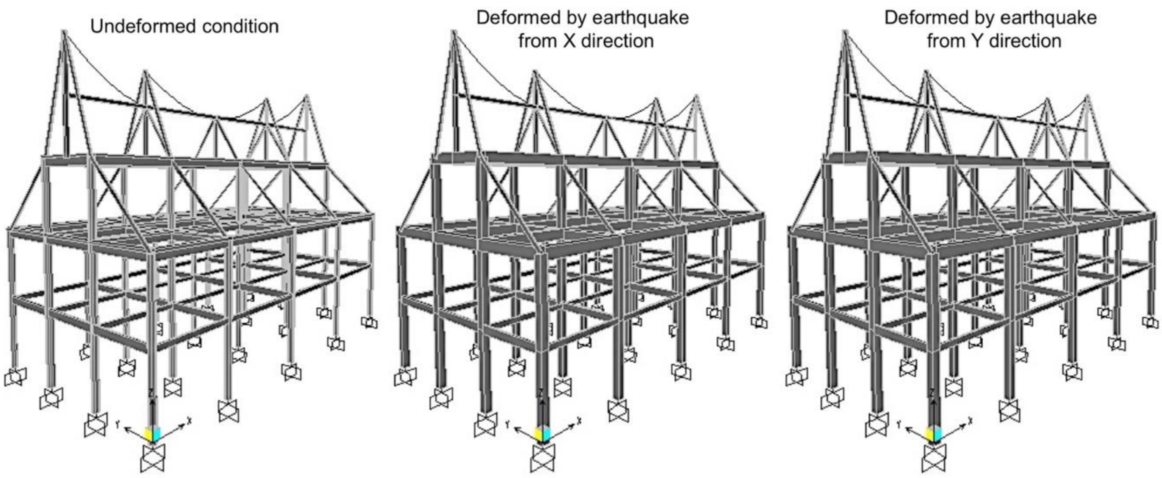

Figure 12. Initial frame formation and post-loading deformations in the end of constructional phase model (Johanita Anggia Rini, 2020)

6.2. Structural Performance in Final Configuration in Response to Dead Loads, Live Loads, and Earthquakes

In the previous discussion, we have seen that the final structure of 'rumah gadang'is already stable in withstanding dead, live, and earthquake loads. Nonetheless, we need to look at the possible damage and which parts of the structure are most vulnerable. Therefore, the factor scale in the simulation for the final structural configuration is enlarged to 2.000E-03 for better visualization. The simulation is then performed on both the model with fixed supports and non-rigid frames and the model with pinned support and rigid frames.

In the model with fixed supports and non-rigid frames, the deformations appear only very slightly. When exposed to dead, live, and earthquake loads on the x- and y-direction, the deformations are only visible in the roof frame, precisely in the curved ridge beam (balok parabuang) and the vertical retaining frame (tiang makelar). There is no visible deformation in the middle structure and the sub-structure. The initial frame formation and post-loading deformations that occur in plan and elevations can be observed in Figure 13.

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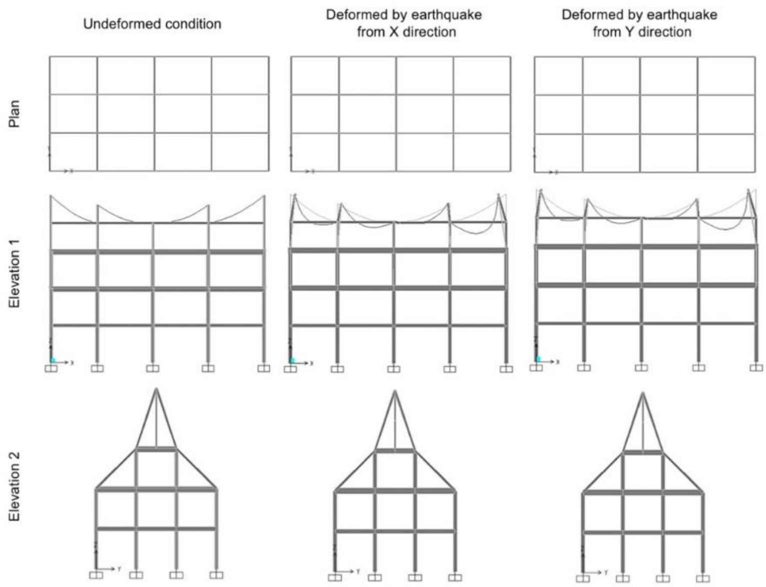

Figure 13. Initial frame formation and post-loading deformations in the model with fixed supports and non-rigid frames (Johanita Anggia Rini, 2020)

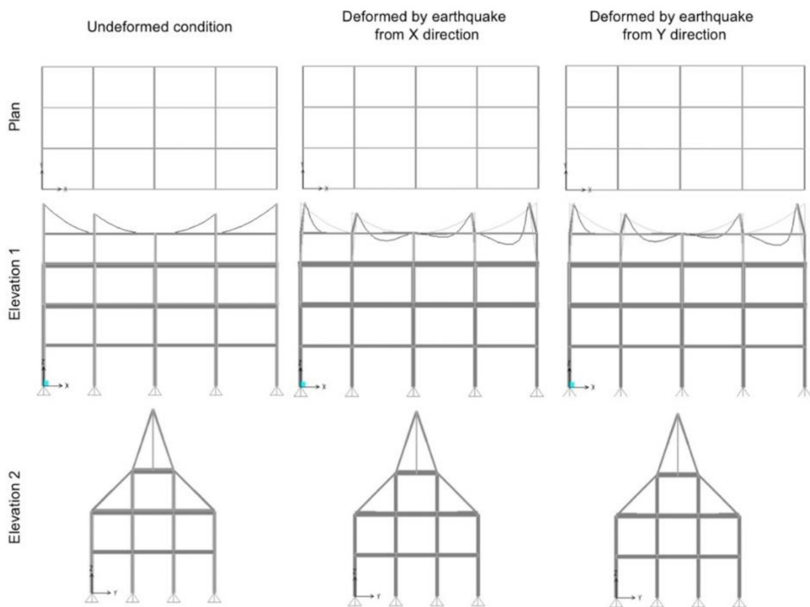

Figure 14. Initial frame formation and post loading deformations in the model with pinned supports and rigid frames (Johanita Anggia Rini, 2020)

Similar results presented in the second model with pinned supports and rigid connections: Despite the enlarged visualization, the deformations appear only very slightly. When exposed to dead, live, and earthquake loads on the x- and y-direction, the deformations are only visible in the roof frame, precisely in the curved ridge beam (balok parabuang) and the vertical retaining frame (tiang makelar), as in the previous first model. There is no visible deformation in the middle structure and the sub-structure. The initial frame formation and post-loading deformations that occur in plan and elevations can be seen in Figure 14.

It can be concluded that the main structure of 'rumah gadang' is able to withstand loads including earthquakes that are expected to occur in specific locations. Continuous wooden posts (tonggak) at 'rumah gadang' are very reliable. Minor deformations in the roof are caused

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by the fact that the type of 'rumah gadang' being analyzed has no dedicated roof truss, so that the entire roof load is channeled directly to the vertical retaining frame (tiang makelar) and the posts (tonggak). The tiang makelar is much smaller than the tonggak, as is the curved ridge beam (balok parabuang), so that both components are deformed. Continuous posts from the sub-structure to the roof with larger size play a major role in obtaining rigidity (Idham, 2019), while horizontal beams between posts affect the global behavior of the structure through the position, stiffness, and strength (Idham, Mohd and Numan, 2010). The deformations in the structural frame occuring in both models are depicted in the three-dimensional perspectives in comparison as illustrated in Figure 15.

From the scaled axial force diagram shown in Figure 16, it can be seen that the axial force in the posts is getting bigger in the substructure. The biggest axial force occurs at post number 66 and 65. Traditionaly, post number 66 is often chosen as tonggak tuo, the first erected post made from the materials with highest quality. This proves that the Minangkabau people have intuitively succeeded in predicting the consequences of the form of the 'rumah gadang' to the loading system, and which structural component will bear the largest load.

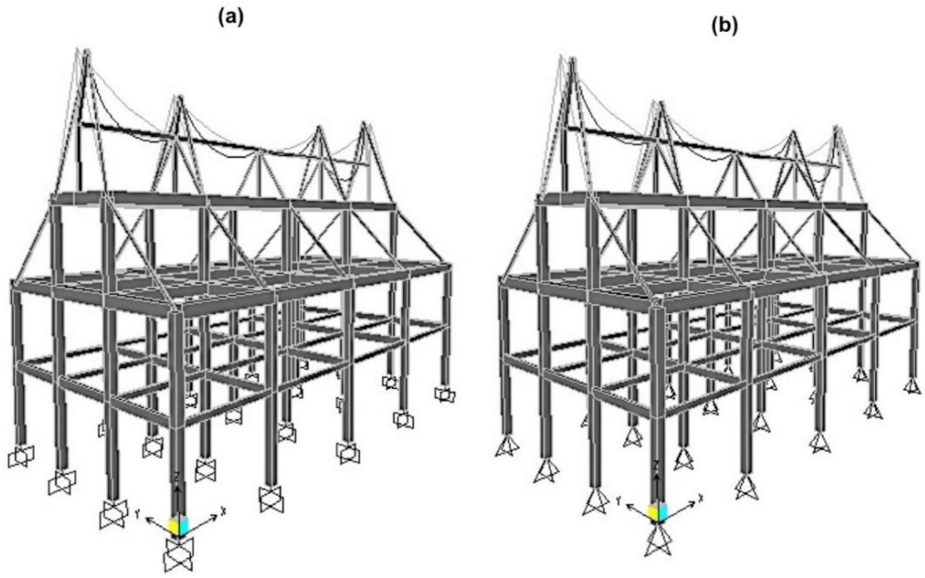

Figure 15. Deformations in model with fixed supports and non-rigid frame (a) and in model with pinned supports and rigid frame (b) (Johanita Anggia Rini, 2020)

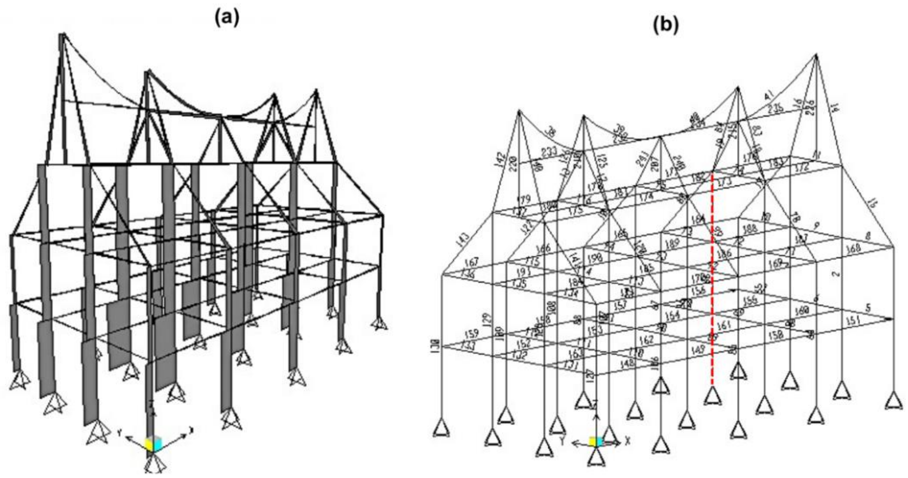

Figure 16. Scaled axial force diagram (a) and post with the biggest axial force (b) (Johanita Anggia Rini, 2020)

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6.3. Constructional Phase as Means for Guaranteeing Technical Quality and Transmitting Architectural Knowledge

It is a common knowledge that vernacular architecture can be discussed in two intertwined domains and elements, namely form and meaning (Mentayani, Ikaputra and Muthia, 2017); or, in other terms, the physical and metaphysical aspects. In the traditional society, it is common to incorporate intangible, metaphysical meanings into tangible, physical aspects of architecture such as building components or technical acts. Physically, through the simulations, we can conclude that the stability of the rumah gadang's structure increases at every phase of construction. However, the constructional phase of 'rumah gadang'also clearly contains metaphysical importance.

In general, the process of building a vernacular house involves two stages namely preparation and construction (Rapoport, 1969). In this regard, the process of building 'rumah gadang'consists of preparatory stages, such as meramu, menarik, mancacak paek, and the construction stages marked by the procession of batagak rumah or batagak tonggak tuo. During the preparatory stages, selecting the materials always involves not only the physical but also the cultural requirements such as choosing wood type that brings good luck, attention to the place where the tree grows, even attention to the tree figure while it is still growing (Frick, 1997). In the case of rumah gadang, the selected tree must not have vines twining, must not be sprouting, and must not be in bloom. From the metaphysical viewpoint, these things are believed to bring bad luck to the owner of the house; for example, that they will always be in debt. Yet, from the physical and technical viewpoint, such guidance are in considerations of material quality; e.g. sprouting trees contain a lot of gum that invites termites, and blooming trees contain a lot of glucose which attracts beetles (Hasan, 2007).

The construction stage of 'rumah gadang'involves social aspects as well. An example is the utilization of the prefabricated system, which is commonly involved in the construction of vernacular structures in Melanesia (Rapoport, 1969) and, in this case, is also applied in West Sumatra. In this process, the components of the structural frame (jarek) are assembled in the ground and then hoisted into place by cooperative effort. This act emphasizes togetherness and mutual assistance as one of the key values of the society. Another example is the reciting of a long proverb called pepatah petitih conveying knowledge about the form, material, function, and inheritance of the house in a ceremony prior to the construction of 'rumah gadang' (Hasan, 2007). This is an example of how a traditional community transmits architectural knowledge between generations through acting and activities (Prijotomo, 2017), in this case a traditional procession during the construction process. Other form of acts may be apprenticeships in woodworking, communal feasts, and festivals. The cooperative works between master carpenters and ordinary people has social implications as well, allowing the construction of complex or difficult techniques and forms to be feasible (Rapoport, 1969).

In conclusion, the constructional phase of 'rumah gadang'are designed to guarantee the quality of the technical aspects (materials, structure, stability) as well as to transmit the technical knowledge about building the house, both to the successive carpenters through the apprenticeship to the master carpenter (tukang tuo) and to the common people involved in the cooperative works.

7. CONCLUSION

Rumah gadang of the West Sumatra is an ideal representation of the major characteristics of the vernacular house architecture in South East Asian region in general and Indonesia in particular. As commonly acknowledged, vernacular architecture was intuitively designed, continuously modified and improved during a lengthy period in the past, in order to fulfill the demands of various aspects, structural consideration being one of those. By conducting structural analysis upon the house, this research provides insights about the house's structural performance in relation with the constructional phases. The simulations indicate that the structural stability increases as the construction phases develop, and the final structure and constructions of the house remain considerably stable even under relatively vigorous seismic forces. This implies that 'rumah gadang' was indeed designed with such structural considerations in mind even though the designers were unlikely to possess academic knowledge of such issues.

As commonly happens in Indonesia and other similar regions, to ensure that certain procedures were to be obeyed and maintained, and thus that the technical adequacy of the structural and constructional aspects of 'rumah gadang'is guaranteed, the Minangkabau society in West Sumatra often incorporate some spiritual and intangible values into the technical, tangible issues. This is mostly apparent in the phase of materials preparation, during which time not only the physical characteristics but also the metaphysical importance of the types of the wood used for the construction must also be taken into consideration, and the early phase of the construction process, during which time a particular ceremony was held to erect the tonggak tuo, the post traditionally regarded as the spiritually most important component of the house and is also the most crucial component of the structure.

This paper can be regarded as an example of how an Indonesian vernacular house is analyzed in terms of its structural performance. Nevertheless, considering the highly rich diversity of the vernacular architecture in Indonesia, more analyses upon a larger number of indigenous houses in different regions are recommended if we are to formulate a more comprehensive understanding of the structural performance of these houses, particularly in a comparative manner. Thus, it is possible and advisable to conduct similar analyses upon these other houses, as well as incorporating additional aspects such as the cultural importance, in the future works.

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Born in 1948 in Nicosia, Cyprus. After completing the formative education there, he was graduated from the High School of Antakya in 1967. He completed his bachelor (1973) and master's (1978) studies at the Department of Architecture at the Middle East Technical University and his doctoral (1982) at the Ankara University. He became lecturer in 1984, and professor in 1996. He practiced as freelance architect between 1973 and 1975. He did the duty as soldier in the 1974 Cyprus Peace Operation and was honored as veteran. After working as assistant lecturer at Ankara Academy of Engineering and Architecture (Ankara Devlet Mühendislik ve Mimarlık Akademisi or ADMMA) between 1976 and 1978 and at the Ankara University between 1978 and 1982, in 1982 he started working as Assistant Professor at the Department of Architecture, Gazi University. After working as lecturer in Saudi Arabia between 1984 and 1994, and as Dean Professor in Cyprus Eastern Mediterranean University between 1994 and 2003, he became Professor at Gazi University between 2003 and 2006. He worked as the Dean of the Faculty of Architecture in Cyprus Eastern Mediterranean University between 2006 and 2010 and as the Vice Rector in Istanbul Bilgi University between 2010 and 2011. Currently he is continuing to work as the Dean of the Faculty of Architecture and Design, Fatih Sultan Mehmet Vakıf University. Besides the educational activities, he also established the Faculty and Department of Architecture, initiated a new Architectural Education Model, participates in administrative positions such as the Head of the Department and the member of Diaconate Senate, as well as produces works, papers, and proceedings in the area of Architectural History and Theory. Besides his projects and patents, he also won and participated as juror in competitions. In addition to becoming the member of the Cultural Committee of Turkish Republic of Northern Cyprus as well as serving the public through various civil organizations, he also administered the Organization of Islam Conference (İslâm Konferansı Örgütü) Turkish Republic of Northern Cyprus as well as the Honorary Representative of Saudi Arabia between 1990 and 1994. For his contributions for the Turkish culture, he was awarded the Honorary Membership of Atatürk Cultural Center, Atatürk Turkish Supreme Council of Culture, Language, and History.

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