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Learning from timber folded grid structure for Mosque in Indonesia

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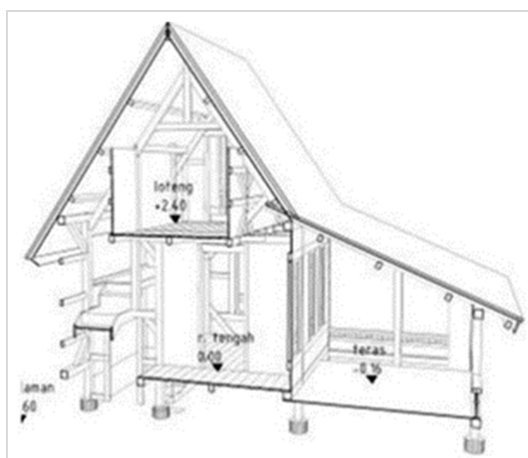
ABSTRACT

Timber has been used in traditional Indonesia short-span roof structure. This short span timber structure still depended on the maximum length and thickness of the timber. Despite the introduction of the trusses system, timber constructions are still limited to short span roofs. Steel and concrete are still more popular to be used as long span roof structure material. This phenomenon was also shown in mosque roof structure development. The timber roof structure was replaced by steel and concrete long span roof, especially in form of dome structure.
This paper presents the complexity of design to construction process of Nurul Hasanah Aceh Mosque in Palu City which pioneers the long-span single-layer folded grid timber roof structure in Indonesia. This article discusses design exploration of the mosque which showed the inseparable structural, construction, and architectural aspect in design process. The construction could serve as milestone for the development of long-span timber roof construction in Indonesia. This article also recommends several technical and computational improvement to further develop complex long-span timber structures in Indonesia.

Introduction

Timber has been used as roof structure in Indonesia traditionally. Unique structural system is used in traditional and vernacular buildings in Indonesia which also differs from one region to another. Some of the well-known examples are traditional Sundanese housing in Kampung Naga, Tongkonan house in Toraja, and Joglo in East Java (figure 1) (Larasati Z.R., Primasetra, and Suhendri 2017; Luritzhofer 2019; Mochsen et al. 2015). Even though their structural principle is different with each other and could not be simply categorized as post-lintel or rafter structure, they have one same characteristic: its span depends on the maximum length and thickness of the timber.



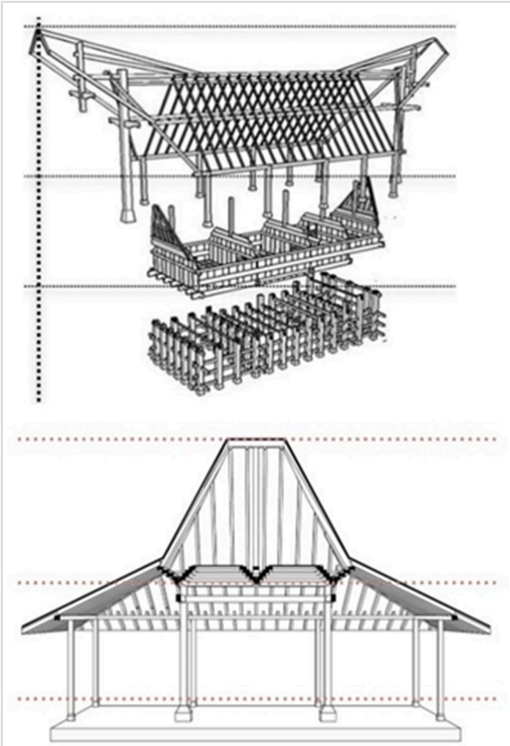
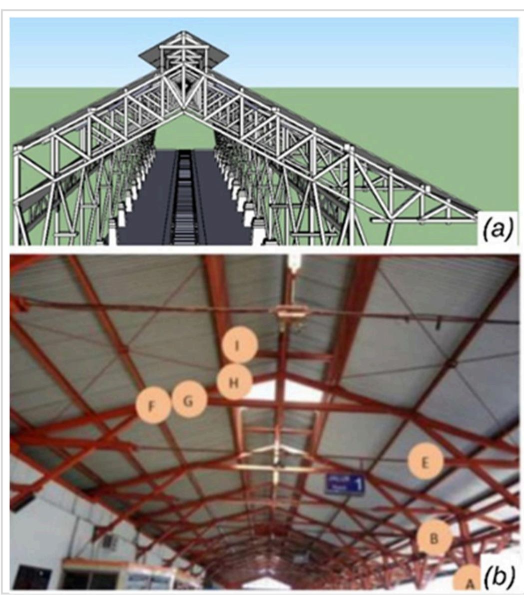


Figure 1. Roof structure schematic of traditional Indonesian timber structure: Naga village (top), Tongkonan house (middle), and Joglo (bottom) (Larasati Z. R., Primasetra, and Suhendri 2017; Luritzhofer 2019; Mochsen et al. 2015)



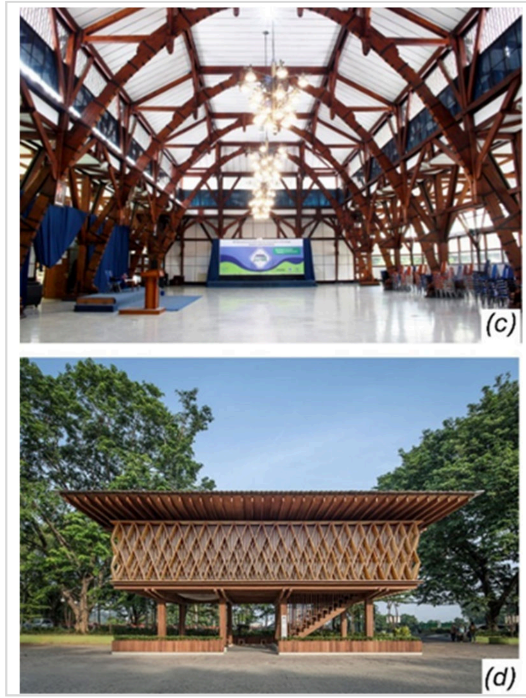


Figure 2. Indonesian timber roof construction during colonialisation and contemporary: Stasiun kota lama (a), and Pasar Turi (b) in Surabaya, ITB twin Aulas in Bandung (c), and Microlibrary Warak Kayu (d) (Sujudwijono 2013; Chandra et al. 2018; SHAU Indonesia 2020)

During the Dutch occupancy period, the trusses system was introduced and have been used as roof structure in Indonesia (figure 2). It enables a longer span than the timber length. Three of the old examples are Stasiun kota lama (Old city station), Stasiun Pasar Turi in Surabaya, and West and East Aula of Institut Teknologi Bandung (Chandra et al. 2018; Sujudwijono 2013). The later was built using combination of trusses and arc. These aulas could be the most well-known long span timber roof constructed in Indonesia, even though it was built in 1920. The newer timber roof structure is still emerging in Indonesia, especially with the introduction of engineered wood. For example, the Microlibrary Warak Kayu (SHAU Indonesia 2020). But these newer timber constructions are still limited to short span roof. The steel and concrete are still more popular to be used as long span roof structure material.

In some regions in Indonesia, there are traditional mosques with a post and lintel structure using pillars and wooden beams grouped based on the number of posts with rafters span between beams. The first is a mosque with four main pillars (figure 3 bottom). The second is a mosque with one central pillar, called the saka tunggal mosque (figure 3 top). Compared to a mosque with four main pillars (saka guru), a one-central post (*tunggal*) has a prayer space that allows more flexible movement during congregational prayers (Wibowo and Sasano 2016). In addition, a mosque with one central pillar can represent the intention of cultural symbols and structural efficiency (Husni et al. 2021). Both types of mosques have pyramidal tiered roofs or tajug roofs. Mosques with single wooden pillars are only found in some regions of Java Island, such as in Cirebon, Banyumas, Kebumen, and Yogyakarta. However, mosques with four wooden pillars are still found in various places in Indonesia, both in Java and outside Java Island. Five Grand Mosques in Java with a tiered pyramidal roof supported by four main wooden pillars are in Demak, Cirebon, Banten, Surakarta, and Yogyakarta (Bambang Setia Budi 2006; Bambang Setia Budi 2004; Wiryomartono 2009). They were built between the fifteenth and seventeenth centuries. Timber roof structures of mosques then stalled since the development of dome structures of roof mosques in Indonesia.

During the post-colonial period, mosques with reinforced concrete structures and domed roofs were more developed (Fawaid, Zamroni, and Baharun 2019; Wiryomartono 2009). The Muslim community in Yogyakarta built the Syuhada Mosque in 1950 with a dome roof and four minarets (Safitri 2020). The arch dominates the mosque building, both in structural and non-structural elements with reinforced concrete material. Only the doors and windows elements still use wood. Likewise, the Al Azhar Mosque in Jakarta, built-in 1953, also has a dome roof with reinforced concrete material (Wiryomartono 2009). It adopted middle eastern mosque characteristic. The peak of the presence of mosques with domed roofs in Indonesia and even in Southeast Asia is the Istiqlal Mosque in Jakarta, completed in 1978 (Setiadi 2015). The presence of the Syuhada, Al Azhar, and Istiqlal mosques has become a trendsetter for mosques with domed roofs using reinforced concrete structures. One of the advantages of a mosque structure with a reinforced concrete structure is the wide span capability that is difficult to achieve by conventional wooden roof structures.

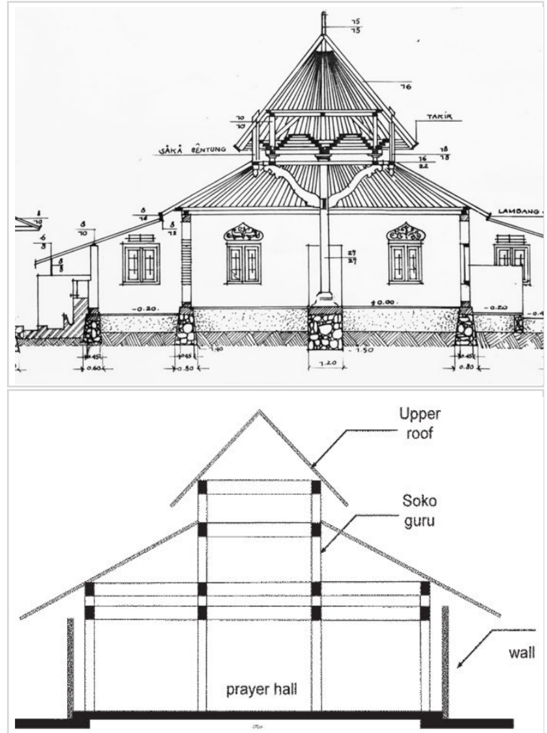


Figure 3. Example of *saka tunggal* (top) and *saka guru* (bottom) cross-section in Indonesian traditional Mosque(Bambang Setia Budi 2006; Wibowo and Sasano 2016)

After 2000, contemporary mosque with new design were began to sprout in Indonesia. Some of it are Al-Irsyad mosque in Bandung, West Sumatera Raya Mosque, and 99 Light Tubaba Mosque in Lampung (figure 4). The shape of those mosque does not have any dome in it. Instead, they incorporated other design aspect such as locality, and simplicity. Nevertheless, in all those example, long span is still used to provide large non-disrupted space. Unfortunately, timber long span structure is not used.

Timber post and lintel structures, relatively have short spans, so columns are still needed to continue the gravity and lateral loads. However, mosques need a great interior space character so that a column-free worship space with wide spans and high floor-to-ceiling distances can answer these needs. Conventional wooden structures and constructions with short spans cannot answer these challenges. The wide-span structure system with wood material has developed rapidly, one of which is the folded-plate structure system (Stitic and Weinand 2015).

Figure 4. Indonesian contemporary Mosque: Al-Irsyad Mosque (top), West Sumatra Raya Mosque (bottom left), 99 Light Tubaba Mosque (bottom right) (ArchDaily 2010; Mosqpedia 2022; Andramatin 2022)

This paper presents an innovative single-layer folded grid timber structure to realize a long-span mosque roof design of Nurul Hasanah Mosque Aceh in Palu City. It gives a great impression of its shape and interior space using local timber. The novelty of the single-layer folded grid timber structure, compared to other wooden-structured mosques in Indonesia, is that it provides a solution to the needs of wide spans, free of columns in the interior, and an immense monumental space. In addition, the selection of the system also considers technological efficiency. Technological efficiency is the efficiency achieved through simple and inexpensive construction methods while still meeting building requirement (Sandaker 2007). The folded-plate structure that utilizes the wooden plank plane demands a sufficient board thickness. The wider the plate, the greater the thickness of the board (Li and Knippers 2015). This condition can impact increasing the volume of material so that the structure becomes less efficient. For this reason, the wooden plane was replaced with a single-layer grid with wood material. This development is more advantageous because the structure becomes stiffer and lighter, making the system more efficient than the conventional folded plates.

This article aims to learn from the experience of the design to construction of Nurul Hasanah Aceh Mosque. First, the context, design option, and construction of the mosque were discussed. Then the design options were analysed and compared. Lastly, the technological and computational tools were proposed for advancing long-span single-layer grid timber structures.

Design to Construction of Nurul Hasanah Aceh Mosque

Context

Palu City is an earthquake-prone area in Central Sulawesi. Palu City sits on Palu-Karo faults, which the second largest fault in Indonesia. The devastating earthquake with a magnitude of 7.4 on the Richter scale in September 2018 (Tim Pusat Studi Gempa Nasional 2018) destroyed many buildings, including mosque. Nurulhasanah Pengawu Mosque suffered huge damage after the earthquake (figure 5). In the name of solidarity, Government of Aceh Province funded the rebuilding of Nurulhasanah Pengawu Mosque and rename it into Nurul Hasanah Aceh Mosque. Aceh Province also suffered large tsunami in 2004.

Figure 5. Nurulhasanah Pengawu Mosque condition after earthquake

Sulawesi Island has local timber material that has potential to be used in construction. Some of it is also already well known in local communities and have its own local name. Some of it are summarised in table 1. The local use of timber construction could also be seen in its traditional construction, such as Tambi and Lobo house. But this tradition was started to disappear (Samad and Sahide 2019).

Tabel 1. Sulawesi Island timber potentials

No.	Species	Some local name in Sulawesi	Source in Sulawesi	Strength class	Construction use
1	Elmerrillia *ovalis*	Cempaka hutan kasar	Muna, Sulawesi	III	Beam, floor, panel.
2	Gordonia *amboinensis*	Ulo, reik	North Sulawesi	-	Non-expose construction
3	Mangifera *altissima*	Lumisi, mandi	Sulawesi	III	Non-expose construction
4	Neonauclea *schlechteri*	Anggerit	Sulawesi	II	Building and bridge
5	Parkia *timoriana*	Rampah, Petai	Sulawesi	III	Non-permanent construction
6	Planchonia *valida*	Nambu, Putat	Sulawesi	-	Column, beam, rafter, etc
7	Polyalthia *glauca*	Tepis	Sulawesi	II – III	Non-permanent construction, and house
8	Santiria *laevigata*	Topi-topi, Kenari	Central Sulawesi	III	Light construction
9	Serianthes *minahassae*	Terhus, terkuseh	North Sulawesi	III	Light construction
10	Sonneratia *caseolaris*	Perapat	South Sulawesi	-	House construction
11	Terminalia *bellirica*	Layoli, Ketapang	Central Sulawesi	II – III	Light construction
12	Macadamia *hildebrandii*	Tomaku, perande	South, Southeast and Central Sulawesi	II – III	Non-expose construction
13	Cocos *nucifera*	Kayuku	Central Sulawesi	-	Building material
14	Ceiba *pentandra*	Kafu	Central Sulawesi	-	Building material
15	Cananga *odorata*	Andolia	Central Sulawesi	-	Building material
16	Neolamarckia cadamba	Kaumama	Central Sulawesi	-	Building material
17	Manilkara fasciculata	Nantu	Central Sulawesi	-	Building material
18.	Manilkara merrilliana	Kumea Batu	Central, South Sulawesi	II	Non-expose construction

Source: (Abdurrohim, Y. I. Mandang, and Uhaedi Sutisna 2004; Asdar 2020; Lempang and Asdar 2008; Pitopang et al. 2021)

Figure 6. Visual representation of the first alternative

The initial concept of roof Mosque building design

First alternative came out first during the design process and became the base for the space configuration and characteristic. The geometry of the roof mosque was also initiated in this step (figure 6). The roof design was inspired by the two traditional timber building from Sulawesi and Aceh: Tambi and Rumoh Aceh (figure 7). The silhouette of both buildings, which has different roof pitch angle, was combined to create a multi-angle pitched roof.

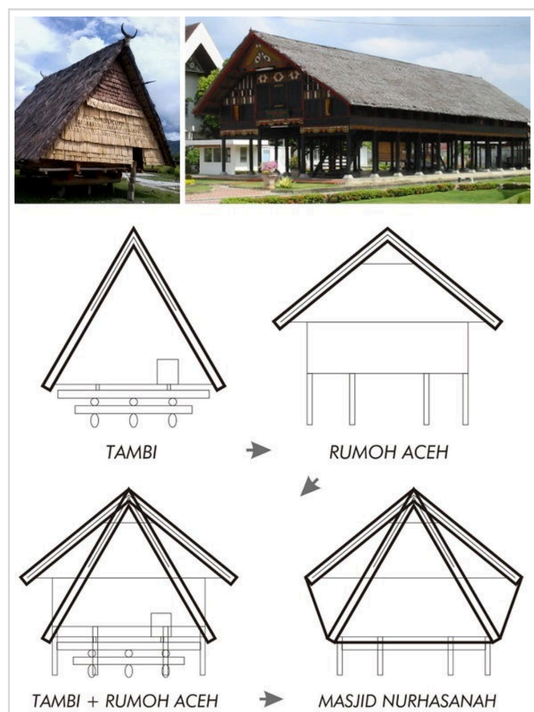


Figure 7. Top: Tambi house and Rumoh Aceh (Kevin 2020; Wikipedia 2022) Bottom: Roof geometry concept

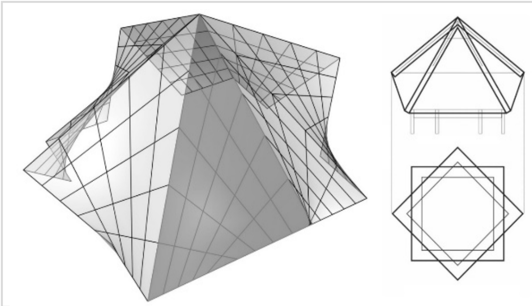
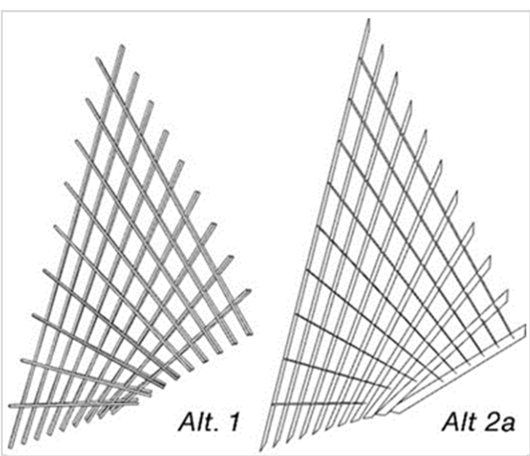


Figure 8. Initial roof geometry

This design has the basic shape of a hyperbolic paraboloid surface that is mirrored and combined into a single pyramid with a squared octagonal star roof plan, a prominent Islamic geometry (figure 8). The rectangular room spans 20 metres. The Hyperbolic paraboloid surface has its inherent rigidity due to its double curvature. It consists of straight members, creating a single layer grid structure. By combining the hyperbolic paraboloid surfaces into a pyramid, folding ridge lines were created, which became the stiffener of the whole roof. The pyramid geometry also gives a monumental exterior shape and interior space, which are both important in mosque architecture.

Design development

This chapter would describe the major design development alternative that affected the selection of structure and construction. It mainly focuses on the roof design which affects the remaining surfaces. The advantages and disadvantages of each alternative will be explained, and why it was or was not chosen.



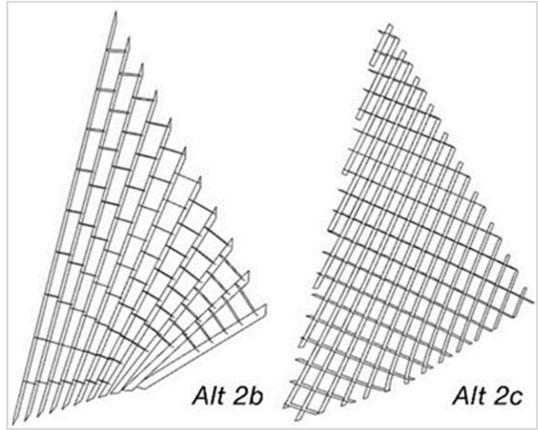


Figure 9. Roof construction alternatives 1 and 2a-c

First alternative

Bamboo was chosen as the material in this alternative (figure 9 top left). The round section of bamboo enables for easy connection. Overlaying bamboo members could be simply connected with bolted connections. Special attention is needed to the angle of the hole, as each member and its parallel member are twisting. Thus, even though the connection is simple, the drilling angle and position of each connection need to be tagged in detail.

Dendrocalamus asper bamboo with diameter 10-14 cm was intended to be used in this alternative. But this material was hard to find the location. Other local bamboo would not have the same strength and durability. Based on the team experience, local bamboo would easily crack due to heat and its thin wall. Thus, if this alternative wants to be used, *Dendrocalamus asper* bamboo needs to be imported from Java, which is not preferable.

Second alternative

Alternative 2 differs from alternative 1 in the material selection, which is timber. With its rectangular and straight section of timber, this alternative would have various construction possibilities to solve the double curvature geometry.

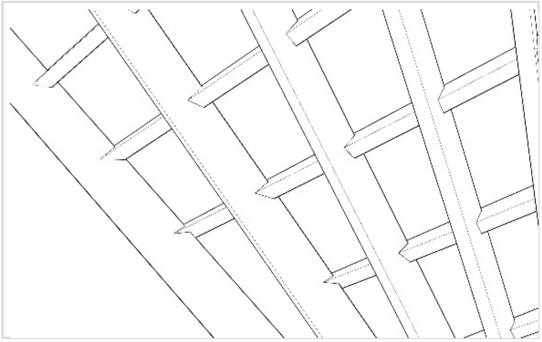


Figure 10. Critical secondary members of Alternative 2a

a) Alternative 2a

In Alternative 2a, the hyperbolic paraboloid surface is solved by using continuous straight planar primary members and pseudo-continuous secondary members (figure 9 top right). The primary members are oriented in a vertical plane for structural purposes. The secondary members, even though arranged co-planarly, are discontinuous in each segment.

While the variation of primary members is not complex, the variation of secondary members is. Each segment of the secondary members is unique. Most geometry of those segments are also critical. Most of the secondary members are not connected with the primary members perpendicularly, and the orientation of the primary member plane does not take the surface normal into consideration. This leads to a critical angle of shape, and non-perpendicular section of most secondary segments (figure 10). Some segments of secondary members also must be omitted because of the extreme shape and position.

b) Alternative 2b

Alternative 2b differs from Alternative 2a in its secondary members. The secondary members of Alternative 2b are connected perpendicularly with one of its connecting primary members (figure 9 bottom left).

c) Alternative 2c

Alternative 2c was inspired by waffle structure. The structure of Alternative 2c consists of a rectangular array of planar timber panels. These timber panels, even though planar, have curved shapes. Similar with the previous alternative 2a, the primary members are continuous, secondary members are quasi-continuous, and connected with wooden shear ties (figure 9 bottom right).

d) Alternative 2d

Alternative 2d is the most explored alternative 2. It uses the similar member arrangement as the Alternative 2a, but instead of intersecting the secondary member to the primary member, the secondary members are overlaid on top of the primary member. This arrangement is used to simplify the fabrication of secondary members and the connections (figure 11).

Figure 11. Roof construction alternatives 2d model

Both primary and secondary members are made of 2 timber joints with shear blocks in between to create a middle gap. Same with the Alternative 2a, the primary members are arranged in vertical planes, while the secondary members are oriented according to the normal vector of the surface at the centre point of each secondary member. This construction would make the fabrication much easier.

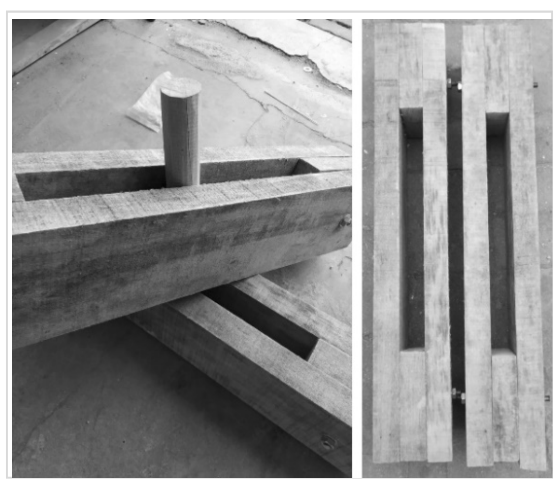


Figure 12. Alternative 2d joints prototype

To connect the primary and secondary members, steel or wooden rods could be inserted in the gap of the members (figure 12). The rods could be then connected to the members by bolts. The rod length should be unique depending on the angle of the connecting members, but the variation could be simplified into several variations. The complexity would be the position of the rods and the bolts relative to the members.

Third alternative

Alternative 3 is the planarized version of the previous alternatives. The hyperbolic paraboloid surfaces were replaced with planar triangle surfaces with the diagonal edge valleys and ridges. The perimeter edges of the roof were still maintained; thus, it still has the same skyline and plan (figure 13).

The structure used in this alternative is a single-layer folded grid structure (Zhou et al. 2012). Each surface consists of straight timbers arranged creating a parallelogram pattern. This arrangement creates grid that, conceptually, act as rigid surfaces. The grid frames are then connected with each other creating a rigid folding structure with stronger rigidity in the folds. To connect each frame, the perimeter members merge into ridge and valley members.

The grid members are laminated wood to create tall sections of the members. Primary (vertical) members are slightly bigger than the secondary (horizontal) members. Same with Alternative 2a, the primary members are continuous, while the secondary members are quasi-continuous. Similar with the Alternative 2s, shear ties are used in this alternative to connect the primary and secondary members. But, since it is planar, there are only 2 types of the shear ties with different parallelogram sections.

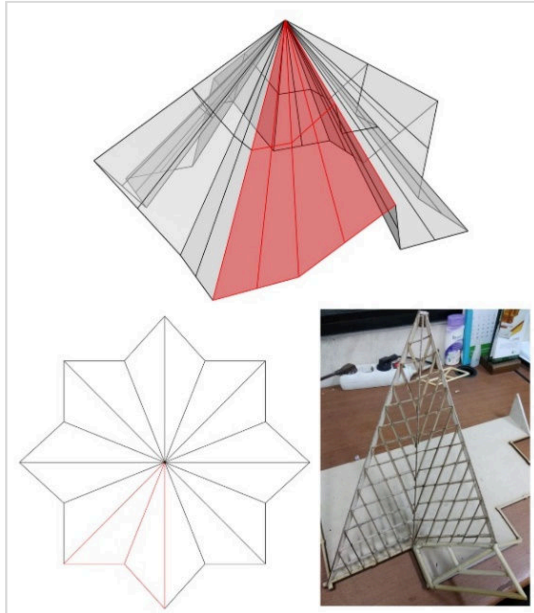


Figure 13. Third alternative: Geometry and scaled model

The alternative 3 was chosen for the development. The curved surfaces were simplified into planar surfaces without losing the monumental effect needed in the interior.

Construction

Roof frame of this mosque requires longest time compared to other parts from procurement until erection process.

To determine which timber species to be used for the roof frame, the architect's team surveyed the wood availability on the site and region. After they found several types of wood, compression test was conducted in Tadulako University laboratory. The strength test showed that the Kumea Batu wood has the highest strength than other woods in the market. Thus, the team chose this timber for frame structure component.

In procurement and fabrication of the material, builders cooperate with one local furniture factory. The procurement was done stage by stage because this project requires so much wood quantity. The available woods were treatment through natural drying process by stacking wood using wooden sticks for almost 4 months. Although most of the existing wood has been in the warehouse for a long time, this process still be done to ensure the wood was well dried and ready for use.

After the drying process, the woods went through smoothing, cutting, and laminating process. There are 4 different timber section used (figure 14). The biggest are the ridge members with dimensions of 9 cm x 60 cm. Slightly shorted were the valley members with 50 cm height. The primary members are 6 cm in thickness and 30 cm in height. All those members were laminated from the secondary members which have dimension of 3 cm x 30 cm. The lamination was done with bolt and glue. Unique compared to other members, the ridge and valley members is strengthened with 3 mm steel strips at the bottom. It is useful both preventing the member from buckling during the assembly and resisting tension stress at the lower part of the members.

The connection consists of steel and wood components (figure 15). The secondary members are connected with primary members using two type of wooden shear block. Meanwhile primary and ridge-valley members are connected with bespoke steel joints. At the lower end of primary members, different bespoke steel joints were used. The primary members end joints would be connected to steel bars planted on concrete ring beam, while the ridge and valley members would be clamped to planted steel plates.

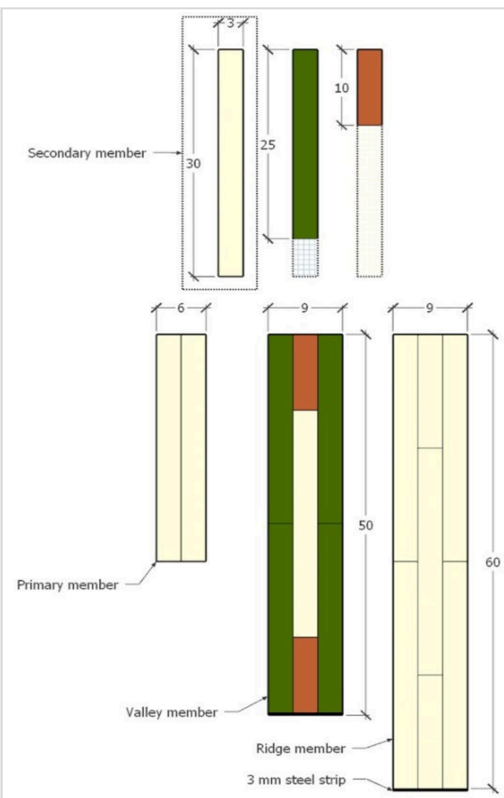


Figure 14. Timber member sections

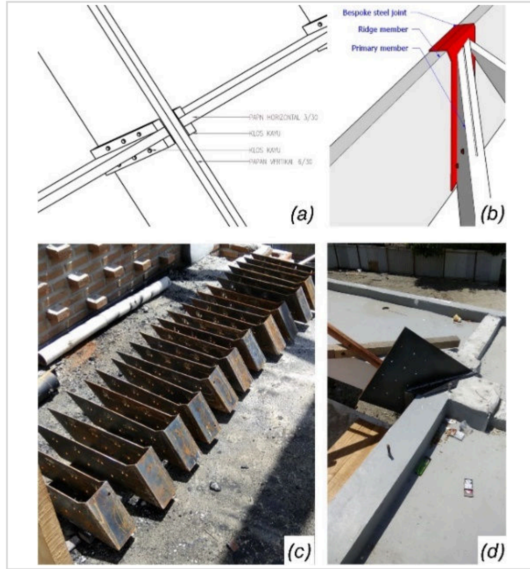


Figure 15. Connection detail: wooden shear block (a), ridge to primary member (b), primary member lower end (c) steel joints, and steel plates and bars on concrete ring beam (d)

Figure 16. Wood sampling to roof structure erection process

Once the timber sections were ready, they were combined to form the structural timber members. To prevent errors, each timber sections were marked. Glue, screws, and bolts were used to attach the timber sections. The glue was epoxy type. This gluing process was done manually by wooden clamp. The screws and bolts were used after the gluing process.

The members were not fully laminated to its full length in the factory. The members were still divided into several sections to ease the mobilization process from the factory to the construction site. After components arrived in the site, lamination continued, and the connections were reinforced with 3 mm iron plate connection on the bottom side (figure 14). Finally, the erection process continued manually with the use of tack pulley. The process is summarised in figure 16.

The roof construction took 11 months, while the whole mosque required 21 months of construction. It has been used as mosque for the community since its opening on 22 November 2020. It is also serves as reminder of the earthquake disaster and solidarity between Palu and Aceh province. The exterior result showed that, with smooth roof tile, the valley line is not too apparent (figure 17).

Figure 17. Exterior of Nurul Hasanah Aceh Mosque in Palu City

Lesson learned from the alternatives

The comparison between the alternatives is summarized in table 2. There are subtle differences between each alternative, but it could be generalized into two aspects: (1) Structural system, (2) Eccentricity and Construction Complexity, and (3) Interior surface texture.

Structural system

There are 3 types of structural system emerged in the options: Folding, Gridshell, and Single-layer grid structure. Folding structure is used in all options in a form of the roof ridges. Folding structure concept uses the depth of the structure to increase the rigidity against out-of-plane loads and decrease the depth of in-plane material needed (D'Acunto 2018). Compared to flat roof which the vertical load is perpendicular to the surface, the folding structure should have thinner surface.

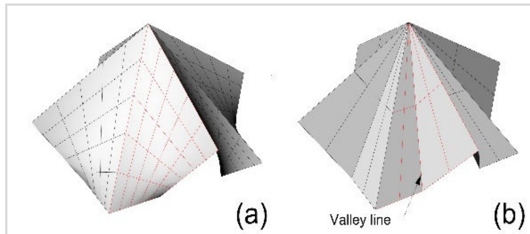


Figure 18. Folding surface with (a) and without (b) combination of hyperbolic paraboloid surfaces

The alternative 1 and 2s structure could be defined as combination of Folding and Gridshell structure. Gridshell could be defined as networks of rods and rigid joints forming spatial curved surface (Chilton and Tang 2016). The double curvature surface gives additional rigidity throughout the surface. Gridshell was used in the alternative 1 and 2s to eliminate the valley fold that usually shown in the Folding structure, such as in the Alternative 3 (figure 18). The Alternative 3 uses only the Folding structure concept. It creates the need of valley members which should not be needed in the Alternative 1 and 2s (figure 14 and figure 18b).

The Gridshell structure, conceptually, is more suitable for distributed load than concentrated load. This is more suitable for a long span roof structure. Meanwhile, folding structure is more suitable to resist linear load along the ridges and valleys. Thus, conceptually, using the Gridshell for roof should be more structurally efficient than folding structure. But, with the relatively short span Gridshell used in the alternatives, the structural efficiency is still questionable compared to the construction efficiency.

Even though the Alternative 3 has Folding structure shape, it consists of straight members. Thus, it could be called single-layer folded grid structure. There are several examples of similar single-layer grid structure despite different term used, such as (1) Shenzhen Universiade Stadium (Zhou et al. 2012), and (2) Hartwald Clinic Pavilion (Šekularac, Jelena Ivanovic-Sekularac, and Jasna Cikic Tovarovic 2012). Different from double-layer folded space grid structure, such as Air Force Academy Chapel in Colorado (Šekularac, Jelena Ivanovic-Sekularac, and Jasna Cikic Tovarovic 2012), the members of the single layer grid structure have to be taller or larger in section (Chilton 2000) (figure 19).

Figure 19. Shenzhen Universiade Stadium (top) and USAFA Cadet Chapel (bottom) (Korab 2023; Zhou et al. 2012)

Table 1. Roof construction alternatives comparison

Variable	1	2a	2b	2c	2d	3
Structural system	Folding structure					
		Hyperbolic paraboloid Gridshell structure				
						Single-layer grid structure
Main material	Bamboo	Timber				
Inter-members connection	Nuts and bolts					
		Wooden shear ties				
					Timber /steel rod	
Construction complexity	Identical nuts and bolts connection, but with unique drilling angles	Unique and some critical shape secondary members		Unique and curved shape members	Identical members	Identical members
		Wooden shear ties with unique sections	Wooden shear ties with half identical and half unique sections	Identical shear ties	Identical connection, but with positions and angles	Identical shear ties
Main advantages	Easier construction due to round section	Easier material to obtain (timber)				
		Conceptually, it is the structurally efficient	Half less complicated connection compared to 2a	Simplest connection among alternative 2s	Continuous and identical member	Simplest construction among all alternatives
Main disadvantages	Lack of appropriate local material	Critical shape of secondary members		Laminated timber that is more difficult to fabricate	The design of the connection still needs to be tested	Flat grid structure which less impressive and less structurally efficient
	Number of unique connections					
			Non-continuous secondary member	Lost the "curved shape" interior surface texture		
	Stronger curved shell structure					

Figure 20. Antwerp Law Courts timber Gridshell (Rogers Stirk Harbour + Partner 2023)

But, in closer inspection, all of examples above consisted of triangle mesh in its plane. It means that the mesh acted as a truss in its in-plane direction. Compared to that, the timber members of Nurul Hasanah Aceh Mosque form rectangular or parallelogram mesh, similar to a timber Gridshell structure of Antwerp Law Courts built in 2005 which is also very similar to the second alternatives. (figure 20) (Rogers Stirk Harbour + Partner 2023).

Eccentricity and construction complexity

A beam or truss members will experience bending moments if there is an eccentricity of connections. The comparison between the the hyperbolic paraboloid-shaped alternatives shows that the eccentricity negatively correlated with construction complexity. This phenomenon also occurs in conventional lattice girders (Saidani 1998).

The first alternative was the easiest to construct due to the round section of bamboo. Though it also means less efficient sections for out-plane load direction, it should be able to be solved by the grid density and number of layers. The connections could use dowels, rope, or both (Widyowijatnoko 2012).

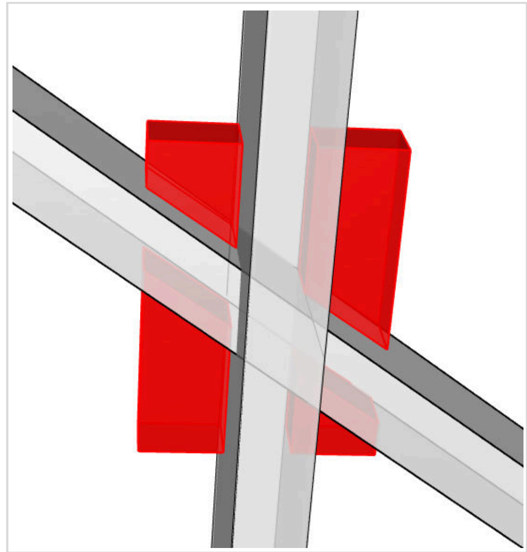


Figure 21. Visualisation of parallelogram wooden block ties

Compared to the bamboo members, the square section of timber would need to be attention towards its connection. Alternative 2a is the most ideal structurally among the alternative 2s, due to the absence of eccentricity. But it has the most complicated connection among all alternatives. To connect the primary and secondary members, 4 wooden blocks could be used as shear ties. With the non-perpendicular and unique connection of primary and secondary members, these wooden blocks would also be unique and have a parallelogram section (figure 21). The arrangement of Alternative 2b makes the secondary members not coplanar, thus creating eccentricity. But, this arrangement makes, at least, half of the wooden shear ties to have a rectangular section.

The waffle structure of the alternative 2c makes all the connections of primary and secondary members to be perpendicular. Thus, it could use all similar square sectioned wooden shear ties. The complexity shifted to the timber panels, as they are unique and curved which require attention on how to fabricate it (figure 22).

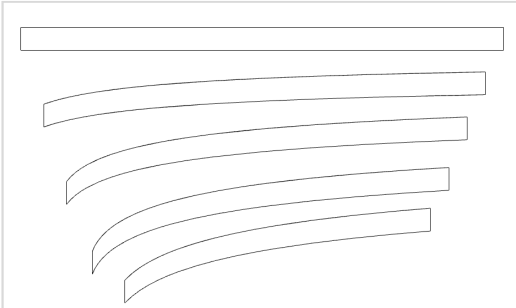


Figure 22. Examples of alternative 2c members

The alternative 2d has much higher eccentricity. It has the advantage of straight and similar members, and a simpler method to connect between primary and secondary members. But this connection is also the disadvantage of this alternative. While it is easier to construct, how it behaves structurally was still in question. It would require additional time and resources just to make sure if this connection is strong enough to resist the eccentricity. Even if the connection was assumed to be rigid, the eccentricity of force would introduce torsion to the members which also would require further analysis.

Interior surface texture

This section discusses about the effect of member orientation and member direction to interior surface texture. As mentioned by Charleson (Charleson 2005), an exposed structure could contribute architecturally by modulating and texturizing a surface.

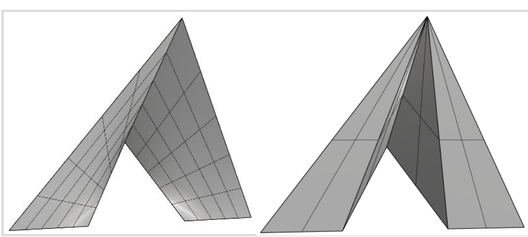


Figure 23. Hyperbolic paraboloid and planar surface viewed from interior

The 3D model, mock-ups, and the built structure of the alternatives suggested that the arrangement and orientation of the members texturize the surface. The alternative 1 (figure 24 top-left) was considered to have the best interior surface texture among the hyperbolic- paraboloid-shaped option. It does not have member orientation and the direction of the members visualizes the isocurves of the hyperbolic paraboloid surface (figure 23 left).

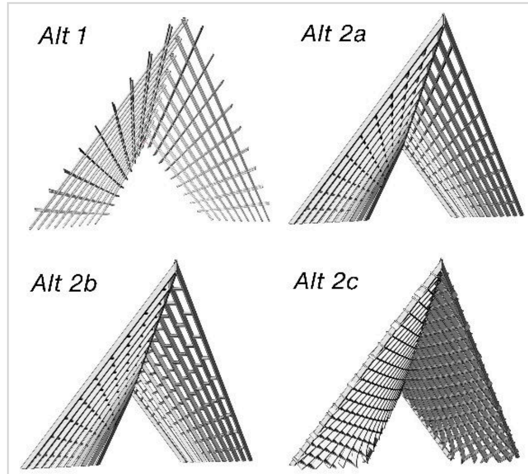


Figure 24. 3D model of the alternative 1, 2a-c, viewed from interior

With the use of rectangular timber section, the rest of alternatives would require attention towards the member orientation. Alternative 3 was the simplest one with its planar surface (figure 23 right).

On the other hand, the hyperbolic paraboloid surface of the Alternative 2s ideally would require twisting member with its Z axis perpendicular with surface normal. But this option was immediately not explored due to the timber hardness. Alternative 2a and 2b have the primary members vertical, which deviate from the surface normal. In certain area, the deviation is significantly apparent. In addition to that, the secondary members of Alternative 2b does not follow the isocurve of the surface (figure 24).

The alternative 2d perhaps have the optimized texture. The member follows the direction of the isocurves. The orientation simply based on the average normal vector along the members. Figure 25 suggests that the orientation deviation is not significantly apparent.

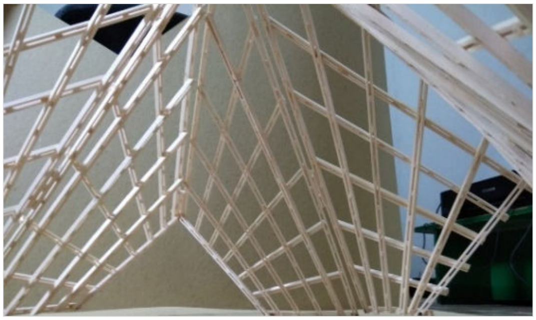


Figure 25. Mock-up of the alternative 2d viewed from interior

Figure 26. Interior of Nurul Hasanah Aceh Mosque in Palu City

The alternative 2c eliminates inconsistency of the member orientation (figure 24 bottom-right). It gives texture of regularity. But its perpendicularly arranged member makes a detached texture from its hyperbolic paraboloid surface. The straight projection of the members gives the impression of trimmed rectangular mesh.

This is similar to build alternative (alternative 3). Its parallelogram arrangement did not follow the isocurve of the planar surface. But this arrangement is structurally more efficient and buildable than isocurve arrangement which will converge the main member to the top of the roof. Furthermore, since the surface itself is planar, the parallelogram texture still echoes the roof surface (figure 26).

Future improvements

The design development of Nurul Hasanah Aceh Mosque in Palu has shown that there is technical improvement that could be done to further enrich Indonesia long-span bamboo and timber structure.

The alternative 1 shows the important of availability of bamboo for realizing long-span bamboo structure. While bamboo existed almost in every major island in Indonesia, the uncertainty is still a problem. As an organic material with significant number of varieties, a big data about bamboo logistic and its properties would be important.

The construction of the timber roof of Nurul Hasanah Aceh Mosque in Palu could suggest several inputs for long span timber construction in Indonesia. The use of steel plate connections could be easier to be fabricated than mortise-tenon connections which require highly skilled wood craftsman. The steel plate connection could also simplify the erection due to its modularity. The long duration from sampling and procuring the timber, despite of the timber potential in Sulawesi, also suggests that a good documentation and supply chain would be crucial for the implementation of timber construction in Indonesia.

The alternative 2s struggles with irregularity in the timber members and connection. The concept of digital fabrication could be applied in these cases. The use of CNC router and milling could be used to create unique connections and timber members (Dunn 2012). In combination with that, the use of multi-objective tools could optimize the structural integrity, form, and construction complexity of the structure.

Other technological solutions that could be used to implement the hyperbolic paraboloid shape with smoother texture of the interior would be using twisting members. The algorithm to generate the member geometry would not be difficult. But creating twisting laminated timber members, such as in Antwerp Law Court timber Gridshell (figure 20), would require fabrication improvements.

Conclusions

Nurul Hasanah Aceh Mosque in Palu pioneers the long span single-layer folded grid timber roof structure in Indonesia. The use of single-layer folded grid structure enables the creation of wide and monumental space which are important for a mosque. The construction of Nurul Hasanah Aceh Mosque also marks important milestone in long span roof construction which dominated by steel and concrete.

The design exploration of Nurul Hasanah Aceh Mosque in Palu showed complexity of design to construction process. Being flexible with the implementation of structural system gives more variation to structural design. Constant iteration between the architect team and builders enables the realisation of innovative construction.

This article has shown the inseparable structure, construction, and architecture aspect of a complex architecture project. The type of structural system and its eccentricity correlates closely with the complexity of the fabrication and construction. Other than that, the structure arrangement also should consider the effect to its interior, as it corresponds to the texture and modulation of interior surfaces.

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Andry Widyowijatnoko contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Agus Dwi Hariyanto contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

Imam Prasetyo contribute to methodology, supervision, and validation.

Rakhmat Fitranto Aditra contribute to methodology, supervision, and validation.

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