Nature Integrated Architectural Design: Construction of a Habitable Tree House in Khon Kaen

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Received: 20 Apr 2021; Revised from: 1 June 2021; Accepted: 7 June 2021
Print-ISSN: 2228-9135, Electronic-ISSN: 2258-9194 doi: 10.14456/built.2021.......

Abstract

Worldwide biodiversity is in severe and accelerating decline, often due to land use changes, resulting in a loss of ecosystem services. Northeast Thailand, including Khon Kaen, has seen a reduction in forest cover from 90% to 14% in the last century. New types of sustainable, nature integrated architecture is needed in remaining patches of forest; this will simultaneously preserve biodiversity, sustain ecosystem services, create economic value, and enable nature-based lifestyles and experiences for humans. This paper describes the construction process of a habitable, nature integrated tree house on a 0.5 hectare plot of native forest, in Khon Kaen, Thailand, using locally available materials. The tree house, with ~62 m2 of living space is supported exclusively by mature native trees, using locally manufactured tree house attachment bolts (TABs). Functions of the resulting space include sleeping, working, bathing, cooking, eating, and guest visits. The results of the construction are proof that habitable, tree supported dwellings are feasible in Khon Kaen, Thailand.

Keywords: Nature Integrated Architecture, Biodiversity, Tree House, Sustainable Architecture

1. Introduction

Worldwide biodiversity loss is severe and accelerating, resulting in a loss of ecosystem services that benefit humanity (Bongaarts, 2019). Northeast Thailand has seen dramatic land use changes in the last century, resulting in its biodiverse forest cover plummeting from 90% in the 1930s to just 14% in the mid-2000s (Vityakon et al., 2004). The current remaining forest cover is often degraded forest or monoculture, such as eucalyptus or rubber tree plantations, making even small plots of native forests vital to the survival to many species and discovery of their benefits. Additionally, forests intercept rain, sound, wind, dust, light pollution and CO_2, produce oxygen, and reduce urban heat island effects.

Standard construction in the Khon Kaen area is slab over ground with large scale soil disruption and concrete use resulting in a high environmental cost. Forest and environmental restoration will require construction that integrates with nature and is designed for mutual benefit. Tree house design considerations vary considerably because of climate and ecological variations. The local climate of Khon Kaen is hot and humid so mixed mode ventilation is desired, as well as materials with high insulating and low heat retention properties. Torrential downpours are common in the wet season, affecting design of the roof and fenestration. Tree characteristics including growth rates, movement, wound response, stability, canopy structure, health, life expectancy, as well as root and soil conditions are all considered. The design of the Khon Kaen tree house (KKTH) includes attachment to trees, weight, wind loading, safety, views, accessibility, function and flow of space, plumbing, lighting, appliances, and usage, reflecting overlapping human and environmental needs.

The result of construction is proof that a habitable, tree-supported, nature integrated tree house blending western design and local materials is possible. All of this is achieved while existing biota are minimally displaced and able to thrive surrounding the building envelope.

2. Tree houses in context of nature integrated architectural design

2.1 Tree house history

The Merriam-Webster dictionary defines a tree house as simply "a structure built among the branches of a tree". This broad definition includes many kinds of micro architecture, and stilt houses, simply built among trees. A narrower definition of tree supported structures still varies far and wide across the earth and dates back centuries. The oldest such structure still standing is the Pitchford Hall tree house which is over 300 years old (Nelson, 1994). The tree supported the house until 1977 when posts were added to the house and the tree, as the tree started cracking and rotting due to its age and own weight. Asia has many old historical references to tribes living in tree houses. The Korowai tribe of Irian Jaya (Indonesia) still live in tree houses typically from 2 m to 40 m off the ground (Figure 1). It is thought that they escape pests and rival tribes with their designs (Jodidio, 2017).

In the late 1990's tree houses entered the modern era. Julia "Butterfly" Hill lived on two small platforms 60 m above ground from 1997 to 1999 to protect a 1500 year old Redwood tree named "Luna" from logging (Jodidio, 2017). This gained media attention and raised awareness of living with trees. Also in 1999, the Garnier Limb® was developed by Michael Garnier through years of collaboration by many specialists at the World Treehouse Conference. It is considered the original tree house attachment bolt (TAB). The TABs and combination of customizable brackets allowed tolerances for tree girth growth and movement (Nelson, 2014). This advancement in tree house hardware enabled much heavier loads to be attached directly to living trees for longer timespans with less injury to them.

Permitting and engineering of treehouses can be a difficult, complex and costly matter. Michael Garnier spent more than 12 years to receive permits for his first commercial treehouses of Peter Nelson, Michael Garnier, Jake Jacob and Scott Baker (Jacob, 2019). This required extensive engineering reviews, including Finite Element Analysis of both trees and structures by Charles S. Greenwood, P.E. Special variances are usually required to satisfy building codes. Such variances are used to satisfy section R 402.1 in the IRC building code, treating trees as "rot resistant foundations" (Greenwood, 2013).
The famous builder Pete Nelson now exclusively builds permitted treehouses under the company name Nelson Treehouse and Supply Co. The company has built over 300 treehouses. Builds include studios, residences, bed & breakfasts, spas, resorts, and even a brewery (https://nelsontreehouse.com/).

2.2 Tree house as nature integrated design

Andy Wasowski conceptualized "nature's envelope" to be native habitat left as undisturbed as possible surrounding the footprint of a dwelling (Wasowski & Wasowski, 2000). As native habitat, with its stability, scenic beauty, and biodiversity keeps disappearing, that

Figure 1. Korowai tribe's Tree House. (Source : http://what-dhell.blogspot.com/2014/10/the-tree-houses-of-korowai-tribe-of-new.html)

which remains becomes more important to protect. Simultaneously, many humans are attracted to nature and wish to interact with it. Tree houses have a unique niche in the sense that they can achieve integration with nature, even within their footprint.

Nature Integrated Architectural Design encompasses a set of three principles. The first is to build habitable structures within nature's existing envelope with minimal disruption. The second is the physical connection of the structure to a living ecological system. The third principle is that the usage and life cycle of the structure should be sustainable in the long term for both humanity and the ecological system.

As tree houses require living trees in their design, their integration to nature is not only automatic, but must accommodate trees and their associated soil and organisms to be successful in the long term. Trees do not live on their own, but rather live together with a system of symbiotic organisms. Tree supported tree houses are therefore a further symbiosis between humans and their surrounding ecology. Such a symbiosis requires research, planning and observation, raising ecosystem awareness of all involved. Tree houses built with the principles of Nature Integrated architecture could serve as a catalyst for forest conservation and restoration. Pete Nelson describes tree houses as "the ultimate return to nature". Forest ecosystems are considered the most complex and diverse land types of all. Life in a forest habitat is particularly high in two zones; the upper zone of the canopy strata, and the interface between forest litter and topsoil. Tree houses typically occupy the space between the two, and can be designed to keep both soil and canopy ecosystems intact.

2.3 Future for Thailand

Famous treehouse builders Pete Nelson and Michael Garnier have introduced the world to "Treesorts", or resorts with treehouses designed for overnight stay (Peter Nelson, Michael Garnier, Jake Jacob and Scott Baker, 2019). This concept can be brought to Thailand's resort industry. Trees such as "Yang Na" (Dipterocarpus alatus) could host adventure style recreation as zipline platforms or treehouses with great heights and views.

Treehouses can be built in the most environmentally sensitive areas with little impact. For example, a possibility of building a firefly viewing treehouse at Lumpoo Bangkasob on Bang-krachaow Island (district Phra Pradaeng, province Samut Prakarn) was explored with entomologist Dr. Anchana Thancharoen (Kasetsart University). This protected mangrove forest is particularly sensitive to any soil disruption which treehouse construction could avoid. An elevated tree supported structure may have slower degrade in the mangrove environment where daily tides and saltwater rapidly degrade ground based structures. In addition, a site visit at Lumpoo Bangkasob presented the existence of mature Firefly Mangrove Trees (Lythraceae sonneratia), with large, dense, and buoyant root mats known as pneumatophores. Attaching to such trees could provide for a highly sink-resistant structural foundation despite muddy, silty soil.

Thailand's rubber plantations with grid-like spacing amongst the trees could serve to build economical and practical treehouses. The preset spacing would allow for prefab modular design. The flexible softwood characteristics of Rubber trees (Hevea brasiliensis) would constrain height and loads, but reduce metal fatigue allowing for economical attachment possibilities.

3. Construction of Tree House in Khon Kaen

3.1 Site Evaluation

An approximately 0.5 hectare area of native forest in suburban Khon Kaen was selected as a site for building a habitable tree house (Figure 2). Most trees on the site were harvested by hand approximately 40 years ago for lumber and charcoal production. Regrowth featured primarily bamboo and mixed hardwoods. As the canopy recovered, the bamboos have been replaced by mixed hardwoods. Hence the area is classified as secondary regrowth of lowland tropical deciduous bamboo forest. The area never had any known major soil changes, or stumps removed. The canopy was generally about 20 meters in height, fairly uniform, with the tallest measured tree at 24 m. The understory was considered mature and fire resistant as there were no grasses or bamboos present. The most dominant upper canopy species were identified as Pradu Tree (Pterocarpus indicus) and Mai Daeng Tree (Xylia xylocarpa). The most dominant mid story tree was identified as Ga-jien tree (Polyalthia cerasoides). All three of these species were considered native hardwoods, with high termite resistance. Mai Daeng and Pradu were considered as apex species for the forest type. There were over 10 above ground termite mounds >50 cm tall on site. This indicated fertile, uncompact soil. The land had a gentle, fairly uniform west facing slope, < %5 grade. On the uphill side of the slope there was a 6 m wide road that had ~8 m tall overhead wires with an overhead grounding wire. This was considered to reduce the likelihood of a lightning strike affecting the trees on site.

3.2 Tree Selection

Mai Daeng, Pradu and Ga-jien were all considered as native and most desirable for the site. Mai Daeng was considered ideal for a habitable house because of its slow growth, strength and high density (Specific gravity 1.2). There were two Mai Daeng trees on site that had died years before and were still standing without showing signs of rot or termite attack. This provided evidence of strength, rot and termite resistance of this species. There were only three Mai Daeng trees on site that had diameter at breast height (DBH) >30 cm. One was not considered because of a lack of suitable trees nearby. The second had

Figure 2. Tree House Location.

an uneven crown and some older wounds from pruned branches extending into its trunk. The third was considered as ideal, having a healthy, uniform crown, nearly vertical trunk, and many suitable trees to build in nearby. Of these nearby trees, a group of three Pradu trees, all with DBH >30 cm were selected as candidates for a foundation. No Go-jien trees in the area had a DBH>30 cm, but a Ga-jien on site with a DBH of 18 cm between the group of Pradu trees and an existing pathway was chosen as having potential for a small structure.

3.3 Functions

The KKTH consists of three connected, yet independent structures with a total living space of ~62 m2. The first is a master bedroom/bathroom supported by a single tree, Mai Daeng. The second structure contains a guest bed and bathroom, kitchen, mixed use space, and laundry area supported by a group of Pradu trees. The third structure is a foyer and staircase supported by a single tree, Ga-jien tree, and a single concrete curbstone. The KKTH has modern amenities and appliances serving the functions of sleeping, working, cooking, eating, entertaining, guest stay, views, privacy and bathrooms (Figure 3).

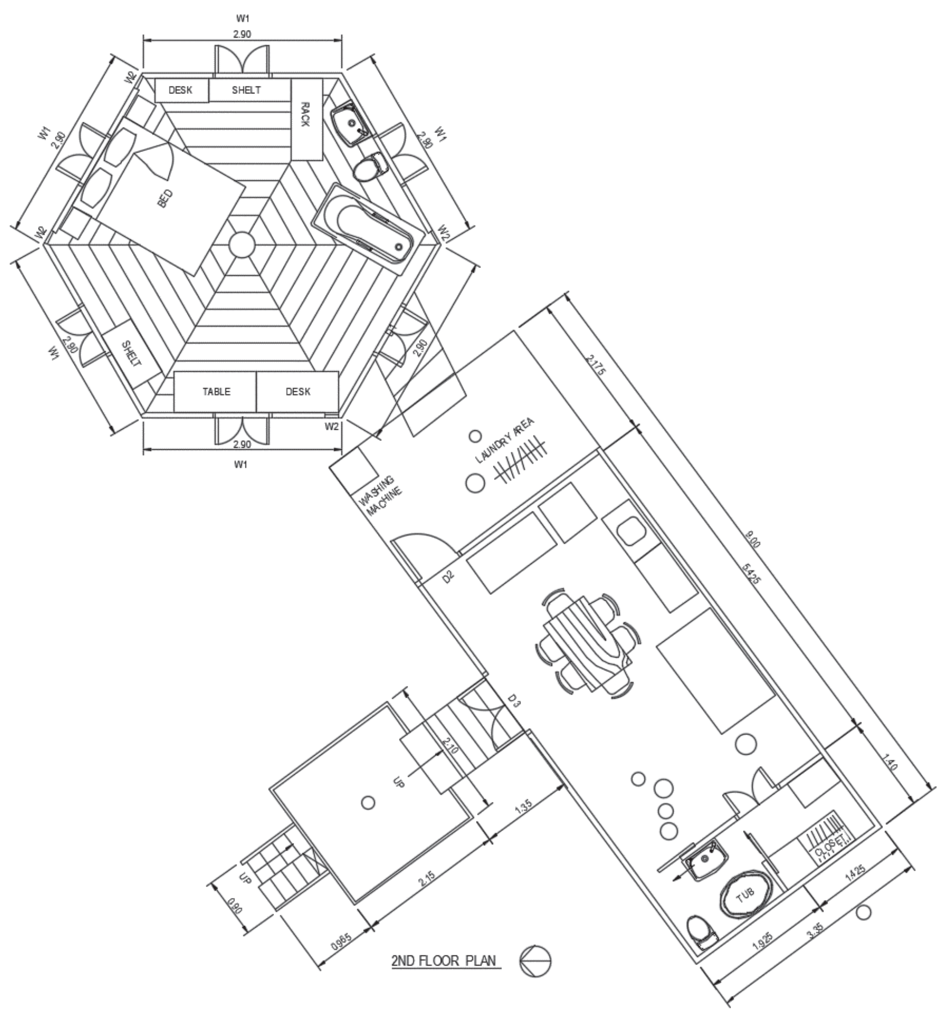

Figure 3. Tree House Plan.

3.4 Trees as foundations

The spacing and observed characteristics of the selected trees on site provided a natural blueprint for the house foundation. The Mai Daeng tree (Xylia xylocarpa) with a DBH of 42.3 cm was the strongest tree with the least sway. This coupled with its uniform crown and straight trunk made it a good candidate for a single tree structure. To keep this balance, the structure was also designed to be symmetrical. This required the tree to be in the center of the house. Having a tree in the living space creates the challenges of weatherproofing and bark shedding. Trees continually shed segments of bark upon wood expanding. However, as Mai Daeng grows slowly, its rate of bark shedding is also slow. Since both the growth rate and movement is low for a Mai Daeng it makes weatherproofing more feasible. The low sway rate and assumed stability allowed for a single tree treehouse with the floor approximately 4 m above grade. The diameter constrained the number of TABs able to be installed at one horizontal plane to 3 m, giving rise to a hexagonal design. A final consideration was leaf cover. The Mai Daeng on site only lost part, but not all leaves during the dry season. This indicates roots are either deep enough to reach groundwater and/or fungal and termite relationships are assisting the tree during the dry season to provide the tree some water. This allows for a more transparent roof as solar gain is tempered most if not all of the year.

The group of three Pradu trees were spaced to allow for arguably the most common type of tree house foundation, a set of two main beams. On the south end, the two main trees were spaced apart as to enable each to support a main beam running by. The north end had only one Pradu tree. This called for it to receive a tri-beam (yoke), to support the two main beams out from the tree center. Although the main beams were not parallel, the floor joists could be cantilevered as desired above to make the main floor frame a rectangle. As the Pradu trees were witnessed swaying considerably more than the Mai Daeng in the wind, this structure was placed lower (approximately 3 meters above grade) than the Mai Daeng structure. At this height a landing was required to make a safe staircase. As the Ga-jien tree was roughly in the center between the existing path and the planned structure it was considered as a support for a landing/ foyer area. With a DBH of only 18 cm, the design called for attachment points at only 80 cm and 150 cm above grade for stability.

3.5 Construction of Mai Daeng structure

3.5.1 Main support

A portable metal scaffold was setup to help install upper TABs and the main beams at approximately 4 m above grade. Using a template for positioning, and a three stage hole bit for boring, three 46 cm long TABs were turned into the tree to a depth of 19 cm and at 120° to each other (Figure 4). The main beams were then screwed together with two 4 cm x 20 cm x 240 cm Kempas (Koompassia malaccensis) wood planks with 1cm spacers in between to provide an airgap. A radial spine was bolted into the end with three ½"x 4½" bolts. The radial splines were slid over the TABs and secured with a nut. A light wooden template replica of a knee brace complete with bracket was made. It was then strapped into place one beam at a time for drilling a 1 inch guide bore. The 10 cm x 15 cm x 300 cm resin wood (Dipterocarpus alatus) knee brace and 45° knee brace bracket assemblies were then slid onto the TABs and swung up into place one at a time and secured to a notch in the main beams with two 5/8" x 6" lag bolts.

Scaffolding made from site sourced Eucalyptus wood was then setup over the whole Mai Dang tree structure footprint for safe and efficient work, and to minimize construction activities causing soil compaction and/or root damage under the tree (Figure 5). Three double plank Kempas wood beams were screwed together with spacers in the same fashion as the main beams with a minimum length of 115 cm and 60° angles cut on the ends. All three main beams were connected together with these crossbeams by turning through two ½" threaded rods on both ends, and securing with nuts and washers. The three main struts were then connected together by 10 cm x 15 cm x 180 cm crossbeams with one 1" threaded rod turned through on each end with and secured with nuts and washers. Off these supplemental cross beams, three supplemental main beams were fashioned matching the original main beams to make a hexagonally spaced main beam frame. The supplemental beams were secured with bolting plates and ½" bolts on the top and bottom. The cross beams on the bottom were then backed up by supplemental struts back to the original struts, putting more load into compression.

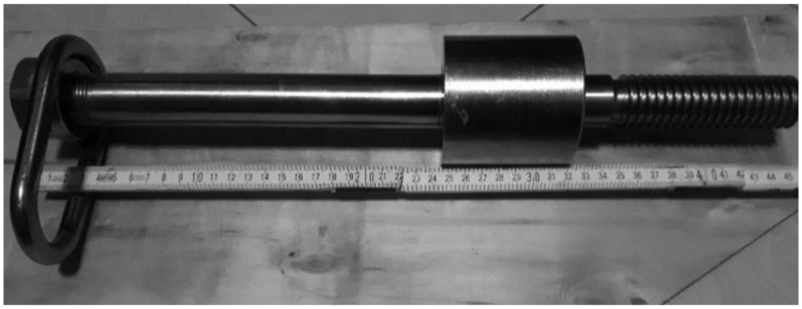

Figure 4. TAB.

Figure 5. Scaffolding.

Figure 6. Floor framing.

3.5.2 Floor frame

Six double plank wood beams at 300 cm length were made in similar fashion to the main beams. They were bolted with bolting plates onto the six main beams. 4 cm square wood was then screwed to the bottom of each beam to support the floor joists. The floor joists were 4 cm x15 cm Resin wood at lengths of 75 cm, 150 cm and 200 cm. They were spaced at 50 cm on center and were fastened at each end with screws. All framing then had 4 cm square Resin wood rails added and leveled on the top of the sides of each floor joist to create a wider and level frame for floorboards to be later fastened with hidden screws (Figure 6).

3.5.3 Walls

Six wall sections of 230 cm x 300 cm were individually framed from 3 cm x 6 cm Resin wood studs spaced 40 cm on center. They were clad with 18 mm thick finger jointed rubber wood panels measuring 122 cm x 244 cm. The panels were fastened whole and the shutters and doors were cut out after. The cutouts were reused and finished into shutters and doors. The panels ran past the wall studs by 14 cm to shed rain water past the floor. The walls were raised one at a time, and the floor plate screwed to the outer floor frame and the corners screwed together (Figure 7).

3.5.4 Storage loft

Two 4 cm x 20 cm x 520 cm parallel reclaimed hardwood beams were installed flush with the top of the wall 152 cm apart and centered in the house. The beams were supported on each end by a tripled wall stud and by round, site sourced 8 cm diameter Mai Daeng posts in the center. 4 cm x 7 cm reclaimed hardwood was used for the floor joists in between, spaced 30cm on center. The loft was completed screwing down the same rubber wood panels used for the walls as flooring.

3.5.5 Roof frame and roofing

Two TABs were installed at approximately 8 meters above grade to support a hexagonal ring beam. The ring beam was made of six 4 cm x 20 cm x 100 cm reclaimed hardwood planks bolted together with bolting plates. Twelve roof rafters were then screwed to the ring beam and to the tops of the existing wall frames. Reinforcing blocking was added as needed for strength. Purlins using reclaimed hardwood measuring 4 cm x 7 cm were then screwed to the rafters at an average of 50 cm on center. Clear 2 mm mini-wave polycarbonate sheets were installed on the east and west facing roofs. Green 2 mm mini-wave polycarbonate sheets were installed above all the other sections. Branch penetrations were sealed with a combination of spent inner tubes and canvas. The canvas was secured to aluminum channel with hook and loop fastener. The aluminum channel was secured to the roof with rivets and silicone adhesive. Above the ring beam a turret was framed to house 6 awning windows roughly 80 cm x 90 cm, made from clear 3 mm polycarbonate sheeting. This supported the turret roof which was shaped around the tree as needed. The turret roof was covered with 3mm flat clear polycarbonate sheeting. The trunk was sealed in the same fashion as a branch penetration (Figure 8).

3.5.6 Flooring

The flooring was installed after the roof to avoid damage from rain. It was made of 1″ x 6″ planks of reclaimed Gung (Dipterocarpus tuberculatus) wood, previously lacquered on one side. The flooring was secured by screwing up through the flooring rails from underneath. The lacquered side was installed facing outside, except for in the bathroom area. The floor center around the tree was made from finger jointed rubber wood panel. It was made in two half hexagonal parts with a cutout matching the tree plus a 2 cm air gap. It was screwed from the top to enable easy removal for future trimming as needed for tree growth. The gap was filled with aluminum screening rolled and wedged in (Figure 9).

Figure 7. Installation of walls.

Figure 8. Roof details.

Figure 9. Flooring.

3.6 Construction of Pradu structure

3.6.1 Tri beam installation

A TAB was installed in the north Pradu tree approximately 3 meters above grade. A tri-beam was assembled as shown in fig? It was attached to the top TAB and leveled. A 1″ guide hole was then drilled through the strut brackets. The tri-beam was then removed to install the bottom TAB. The tri-beam was hoisted in place and secured on the TABs with thread locker and nuts (Figure 10).

Figure 10. TAB and Tri-beam installation.

Figure 11. Floor frame and flooring installation.

3.6.2 Main beam installation

Lines were strung from the tri-beam ends past the two individual Pradu trunks to represent the main beams and locate optimal positions for installing TABs. TABs with dynamic triangles were installed on two south facing Pradu trunks. Reclaimed dense hardwood beams measuring 5 x 25 cm x 10 m were hoisted into place. The center of the span was reinforced and became a doubled beam, bolted with a series of ½″ x 5″ bolts. 4 cm square blocking was used to provide an airspace in the doubled beam sections. The main beams were held in place on the yoke ends by two tunnels fashioned from blocks attached to the yoke.

3.6.3 Floor frame and flooring

The floor frame was made from mixed reclaimed hardwood milled to 11.5 cm x 3 cm to 4 cm. Joists were spaced near 50 cm on center as trees allowed (Figure 11). As joist hangers are not available in Thailand, blocking was fastened to the joist ends and the rim joists with screws. Framing was spaced away from trunks at a minimum of 10 cm. Single headers were bolted to joists with blocking as needed to frame around tree trunks. All joists were fastened to main beams with 4 cm square x 30 cm Resinwood. Reclaimed Resinwood heartwood decking measuring 1″ x 6″ were screwed down to the framing. Half of the decking measured 7 m long which improved stability. Three areas were reinforced due undesirable amounts of vertical sway in the floor. A knee brace was added from the north corner with a 10 cm square strut at 45° angle, using a TAB and knee brace bracket to attach back to the Pradu trunk. Across from this brace there were four trunks <10 cm in diameter which penetrated the floor and were attached to the floor framing using 5/8″ threaded rod. On the south end, a single beam was added past the floor under the main beam tails to help support the cantilever. This beam was supported by another Pradu trunk and fixed to it with a TAB and dynamic triangle and a strut bolted to the end of the beam fixed back to the same trunk with 1¼″ threaded rod.

3.6.4 Walls

The exterior walls were stick framed in sections with mixed reclaimed hardwoods. All wall studs (4 cm x 6.2 cm x 2 m) were milled to 62 mm wide to ensure uniform wall thickness and straighten the reclaimed lumber. Blocking was fastened for every 50 cm of wall height that was to receive solid siding. Resinwood (average 12 mm thick and 15 cm wide) board and batten siding was screwed to most frame sections before wall raising, with an overlap of 7 cm past the bottom plate. The sections were made in a length so as to support a-frame roof trusses, and the last stud ran by the top plate to provide attachment points for the tie beams and rafters of the roof trusses. Interior cross walls and the loft wall were framed with two story studs, serving as walls with integrated roof a-frames. Studs were either notched around the bottom plate (standing on end) or rotated 90 degrees to accommodate wall purlins. These were then bolted together with thread locked carriage bolts, and on top to the principle rafters. Screws were also driven through the floor from underneath through each floorboard to fasten the walls. In the bathroom, kitchen and mixed use space area, where the upper half of the exterior walls were open framing, aluminum screening was stapled on, or 3 mm flat polycarbonate panel windows installed.

3.6.5 Roof framing and roofing

The loft end wall and the two cross walls each had a center post (4 cm x 11 cm) with a u-shaped notch to receive a 10 m long ridge beam. The ridge beam was hoisted into place and bolted to the center posts with 10 mm carriage bolts. Four tie beams (4 cm x 11cm) were then bolted to the walls. The remaining 8 principle rafters were then installed by bolting to the end studs of the wall sections, and toe-screwing to the end of the tie beam, and screwing to the ridge beam. Four king posts were bolted to the center of the tie beams, ridge beam and principle rafters with 10 mm carriage bolts. Three climbing lines were set up with anchor points roughly 15 meters above grade to enable safe roof work from harnesses. Resinwood purlins (4 cm x7 cm) were then screwed to the rafters. Purlins were kept a minimum of 15 cm from main trunk with diameters >25 cm and 25 cm from trunks in between 10 and 25 cm. In the guest bedroom and mixed use space area purlins were spaced 50 cm on center to accommodate green mini-wave polycarbonate roofing. The roofing panels were then screwed on and trunk penetrations sealed in the same fashion as in the Mai Daeng structure. In the Nipa palm (Nypa fruticans) leaf thatch roof area, purlins were spaced 90 cm on center. Blocking was added to the rafters to match purlins. Eight sets of common rafters consisting of ~7 cm diameter debarked round eucalyptus trunks were notched and fit flush with the installed purlins to accept Nipa palm thatch panels. After fitting they were bolted together with carriage bolts. Trunks penetrating the roof < 10 cm diameter were immobilized with blocking and ½" threaded rod. The Nipa palm thatch panels (120 cm x ~50 cm) were nailed on with 1½" umbrella head roofing nails in rows spaced 7 cm apart, with a 15 cm overlap on each end. Roofing was finished with a roof cap consisting of 40 cm wide mini-wave polycarbonate sheet strips screwed down.

3.6.6 Construction of stairs and foyer

Reclaimed mixed hardwood joists and beams were milled to 3 cm x 11 cm for the structure. A 30 mm hole in line with the Pradu structure was drilled through the Ga-jien tree at roughly 80cm above grade. A 1 m long, 1¼" threaded rod was turned, centered and leveled through the hole. Two 30 mm holes were centered on two 1m beams and they were fixed to the threaded rod with nuts and washers on both sides. The process was repeated with another perpendicular set of matching beams on top. A third rod and twin beam set was installed at roughly 1.6 m above grade perpendicular to the Pradu structure, but with a 2 m beam. This was connected to the lowest set of beams with 4 knee braces. Joists were spaced on top of these beams at 42.5 cm on center creating a 2.1 m square platform. Four additional knee braces were screwed to the floor frame and back to the second beam set.

An alternating staircase was built to connect the foyer to an existing pathway. The reclaimed Mai Daeng treads were fastened to a set of three stringers with dado joints and 4 cm square, bi-directionally bolted blocking. A reclaimed concrete curbstone was leveled on the ground without digging and used to support the stringers. Reinforcing bracing connected the stairs back to the lower set of beams on the Ga-jien tree. A Mai Daeng wood staircase reclaimed from an old house was used in one piece to connect the foyer to the Pradu structure. It was attached to the Pradu structure with three 12 cm x 28 cm heavy duty strap hinges and twenty-one 10 mm bolts. The bottom of the staircase simply rests on the foyer platform where it is free to slide during windy conditions. A four stair staircase was built and attached in the same manner to the Mai Daeng structure.

Twelve ~7 cm diameter debarked eucalyptus posts were notched and bolted to the foyer frame to hold the roof frame. The roof frame was made with 7 cm diameter cross beams, ridge beam, and bracing to hold the rafters.

The rafters were 5 cm diameter round eucalyptus spaced at 40 cm on center. An angle grinder was fitted with a flap sanding disk to make rounded notches for joinery. After fitting, all joints were bolted with 10 mm carriage bolts. Roofing was finished with Nipa palm roof panels in the same fashion as the Pradu structure.

Figure 12. Bathroom and Sanitation system.

3.6.7 Plumbing for Daeng House

A toilet was installed with a rubber flange to ensure that the wooden floor would stay dry. A clawfoot bathtub/shower combination was installed. An outlet with a small mechanical fan was installed to provide airflow to maintain a dry floor during or after usage. The waste pipe of the toilet was plumbed to a septic tank. The greywater outlets from the septic tank and sinks were plumbed to a dry well. Both the dry well and septic tank were hand dug more than five meters from the tree trunk to avoid disrupting major anchoring roots. A vent pipe for the septic system was installed on a nearby tree to a height of 14 m with ½" threaded rods and pipe hangers. Pipes were fixed near the floor of the house to avoid strains on fixtures during movements. Fixed connection points on all pipes were near the centers, to allow elbows to flex freely during wind events (Figure 12).

4.1 Conclusion

The KKTH is physical verification that a habitable structure with modern amenities supported exclusively by trees is feasible in Khon Kaen, Thailand (Figure 13). TABs were locally milled with SCM440 steel sourced in Thailand. All major components including the brackets, bolts, threaded rods, roof, wall, floor, and structural beams were all locally sourced, made in Thailand, and are readily available. The total cost of the materials used in the KKTH was approximately 600,000 THB. Total labor time involved in accruing materials and performing construction was approximately 1,500 hrs.

Standard construction supports the needs of sleeping, eating, working, entertaining, guest visits and bathing. The KKTH provides these functions, but additionally provides a direct connection to a living ecological system. The bathroom and kitchen recycle water and nutrients back into the KKTH structure via the host tree's roots. This creates a circular flow between the forest and occupants of the KKTH.

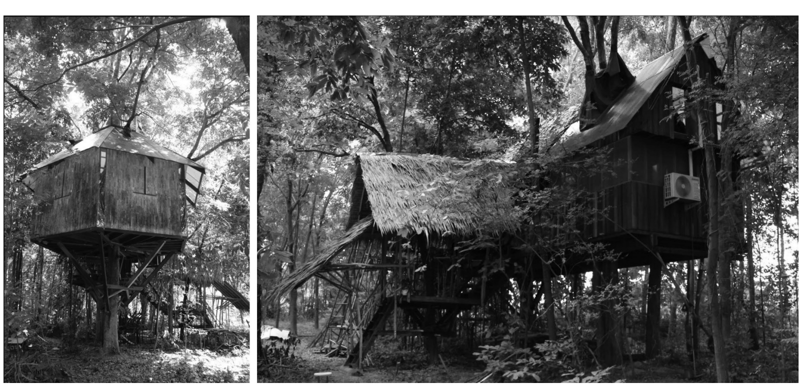

Figure 13. The complete KKTH.

The KKTH provides a living ecological shading envelope encompassing a type of permanent "forest bathing". This setting provides refuge from the typical stress of urbanization

4.2 Suggestions

Treehouses in Thailand have a high potential. The abundant tree species provide many choices. The warm climate makes construction simpler and year round use practical. Applications could range from gazebo type structures, to coffee shops, dwellings and classrooms.

The limitations of treehouses in Thailand are that little to no research or data exists on attaching structures to living trees. For tree houses in Thailand to become more common, accepted, and standardized, requires advancements in arboriculture and design. Arborists with advanced tools such as sound tomography, load cells, inclinometers and elastometers can gather a variety of data of the characteristics and strength of living trees. Engineers could gather data of the strength of attachments, such as TABs to these living trees. The combined data could be used to reduce uncertainties and create Thai building code standards for tree supported structures. Wind modeling and 3-D point cloud software can computerize architectural designs unique to individual trees and their landscapes.

Perhaps future housing developments in Thailand could start in an existing urban forest, and expand in lockstep with urban greening as new trees grow large enough to support more structures.

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