FINAL REPORT

Consultancy to improve the environmental and economic impact of buildings promoted by the **Malagasy Red Cross Society** and the **AICRL** (Aide Internationale de la Croix-Rouge Luxembourgeoise)

Maroansetra, 04-05/2025

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2025

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1. INTRODUCTION

1. (a) Background and previous collaborations

In January 2024, Ms Isabel de la Vega, from the AICRL - Shelter Research Unit (AICRL-SRU), contacted Jaime while she was on a mission in Madagascar to request support in the improvement of the design of a house using bamboo as structual material (two model bamboo houses had been built by the Red Cross (RC) in the North East of Madagascar – this model is referred to as bamboo house version below). There was room for improvement and the RC was looking for some upgrading of those first experiences, mainly regarding costs and building details. Therefore, Jaime provided a set of plans describing an improved bamboo house model as his first collaboration with the Luxembourg Red Cross.

In June 2024, Jaime Espinosa was contracted by the AICRL-SRU as external consultand to design and implement a training workshop to take place in a rural area near Antalaha town, in the North-East of Madagascar based on the improved bamboo house design (this model is referred to as bamboo house version 2).

The participants of the workshop shall be local professional carpenters as well as technicians and volunteers of the Red Cross of Madagascar, and the whole training program shall be delivered within 10 working days, based on the time taken to build the previous bamboo houses (bamboo house version 1).

n comparison to version 1, the proposed upgraded model focused on extending the expected life of the building, reducing its cost and improving its environmental impact. The training workshop took place in Valambanina, Antalaha district, from 28 August to 8 September and 10 local carpenters, as well as 9 RC members (volunteers and staff) were trained. It led to the construction of the first version 2 model bamboo house.

The main improvements from version 1 to version 2 are the following:

<u>Extend expected life of the building</u>: Avoiding direct sunlight and water (direct rain, rain splash and soil moisture) on structural bamboo elements, their life expectancy shall be at least doubled. Therefore, bamboo columns and shear studs are anchored to the foundation, but not inserted in it, and the non-structural walling system is placed in the outer face of the structural elements. This way, the only bamboo exposed to direct sunlight and water (either direct rain, splashing or ground water) is non-structural bamboo, that eventually could be replaced without compromising the structural core of the building.

<u>Reduce building cost</u>: Removing threaded bars, washers and nuts, substituting them with bamboo pegs extracted from the walls of bamboo culms, together with the use of manual tools (instead of electrical tools), shall reduce estimated building cost of the bamboo model house.

<u>Improve environmental impact</u>: Besides substituting threaded bars, washers and nuts with bamboo pegs as well as using manual tools instead on electric ones, both changes meaning a substantial improvement in the environmental impact of the house, the formwork used to pour the concrete for the foundation ring beam shall be made out of bamboo, avoiding the use of timber, beyond the frames and shutters of the window and the door.

In January 2025, the AICRL conducted a review and evaluation of the two model bamboo houses built, version 1 and version 2, identifying their advantages and disadvantages of each model. Based on these findings, the AICRL team decided to launch the development of a third version of the bamboo house and decided to contract Jaime Espinosa, again as external consultant, to design the improved 'Bamboo house – Model A' (version 3) and to provide a training workshop for its construction in Antalaha.

In addition to that, it was decided to request the development of the 'Bamboo house – Model B', adapted to flood prone areas (as bamboo cannot be planted into the ground to make stilts, a specific model had to be developed for flood prone areas), and the provision of a training workshop for its construction in Maroantsetra.

The present report is only related to the 'Bamboo House - Model B' design and corresponding building during a training workshop. A separate report has been drafted for the 'Bamboo house - Model A' (version 3) design and corresponding building during a training workshop.

1. (b) <u>Goals and approaches</u>

The Terms of Reference for the mission object of the present document started to be discussed in January 2025 between the author, Mr Igor Sujar and Mr Sylvain Martin. The contract was signed on February 17th. The mission started on March 26th departing from Madrid and arriving in Antananarivo on March 27th. The departure from Antananarivo was on May 8th, arriving in Madrid on May 9th.

On March 30th the consultant departed from Antananarive to Antalaha, and returned to Antananarive on April 11th.

The training workshop started in Valambanina on March 31st and finished with the diplomas hand over to participants on April 10th.

On April 14th the consultant departed from Antananarive to Maroansetra, and returned to Antananarive on May 5th. On April 15th a participatory design workshop for the validation of the model house to be built during the workshop took place in the office of Red Cross in Maroansetra.

The training workshop started in Marogisa on April 18th and finished with the diplomas handover to participants on May 3rd.

The deliverables of this second part of the mission in Antalaha are the following:

'Bamboo house - Model B' project. Architectural project of improved prototype considering positive aspects of previously built model houses and adapting it to flood-prone areas. This technical project was validated by the target communities during a participative validation workshop and used during the training workshop in Maroansetra. Includes: Plans, bill of quantities (BoQ) and specifications.

Training workshop in Maroansetra. 13-day practical training workshop in Maroansetra addressed to beneficiaries of the project, carpenters and Red Cross' staff in Madagascar with the goal of building a 'Bamboo House - Model B'.

2. RESULTS

2. (a) <u>Bamboo house - Model 'B'</u>

Bamboo house - Model 'B' is an adaptation of Bamboo house - Model 'A' (version 3). The main specificity of Bamboo house - Model 'B' is that it is adapted to flood-prone areas: It has been designed taking into consideration the lessons learnt in the training workshop related to Bamboo house - Model 'A' (version 3) during the first mission of the current consultancy in Antalaha between the 30th of March and the 10th of April 2025 as well as the feedbacks received fron the target communities during the participative validation workshop on April 15th in Maroantsetra.

The first prototype of the Bamboo house - Model 'B' was built during a training workshop taking place in the village called Marogisa, in the Commune of Maroantsetra from the 18th of April until the 3rd of May 2025.

The main difference between Bamboo house - Model 'A' (version 3) and Bamboo house - Model 'B' lies in the foundations. Model 'A' (version 3) has concrete foundations and a cement floor whereas Model 'B' is built on wooden stilts and has a flatten-bamboo floor. The upper structures of the two versions are nearly identical.

The adaptation to flood-prone areas is based on local building techniques together with field tests carried out by the International Federation of the Red Cross (IFRC) and the Malagasy Red Cross in collaboration with British universities. One of the key conclusions of those tests is that foundations consisting of timber posts should be buried around 100 cm to be resistant enough in case of cyclones.

All the building elements in contact with the ground (foundation posts and stairs) are made of local hardwoods (named locally *'hintsina'* and *'nanto'*) because of the limitations of bamboo in contexts of humidity shifting conditions, i.e. buried, partially or totally.

A connection between timber posts and the bamboo structure was designed accordingly to ensure the structural continuity.

The improved, adapted to flood-prone areas, version of the model house, named 'Bamboo house - Model 'B', includes the following advantages:

- Optimized foundation, using hardwood posts only in the perimeter of the house releasing uninterrupted room for storage under the house, without compromising safety, and implementing and innovative connection between timber and bamboo.

- Extended roof eaves in all the four sides of the house, particularly in the front side, creating a roofed veranda that the previous model was lacking.

- Gables are finished with the same material as the roof, 'kasaka' (leaves from ravenala), to prevent leaks even when heavy rain falls with strong winds.

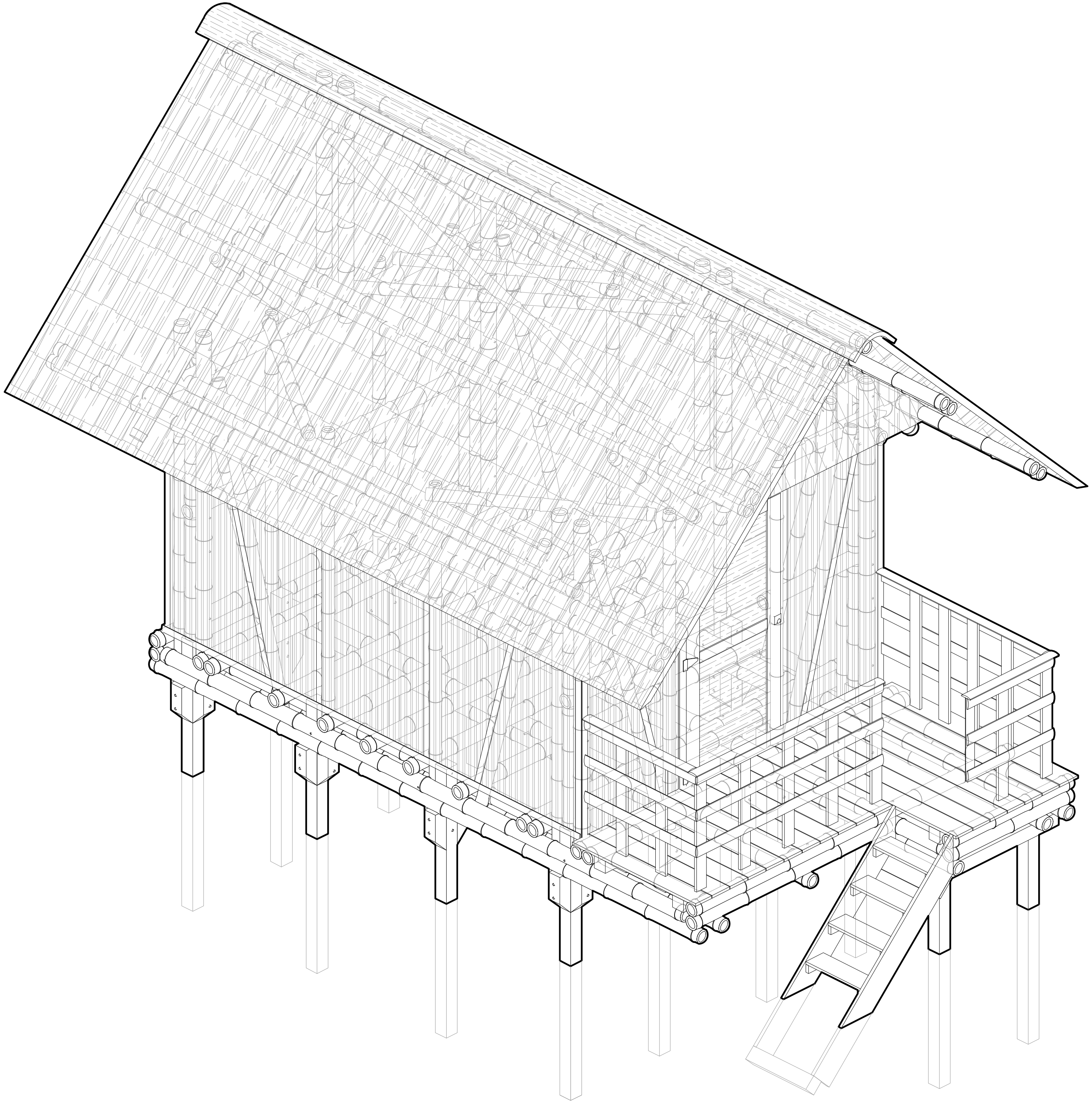
- Proper construction detailing and implementation of the connections between the walls and the openings, and between the walls and the foundation.

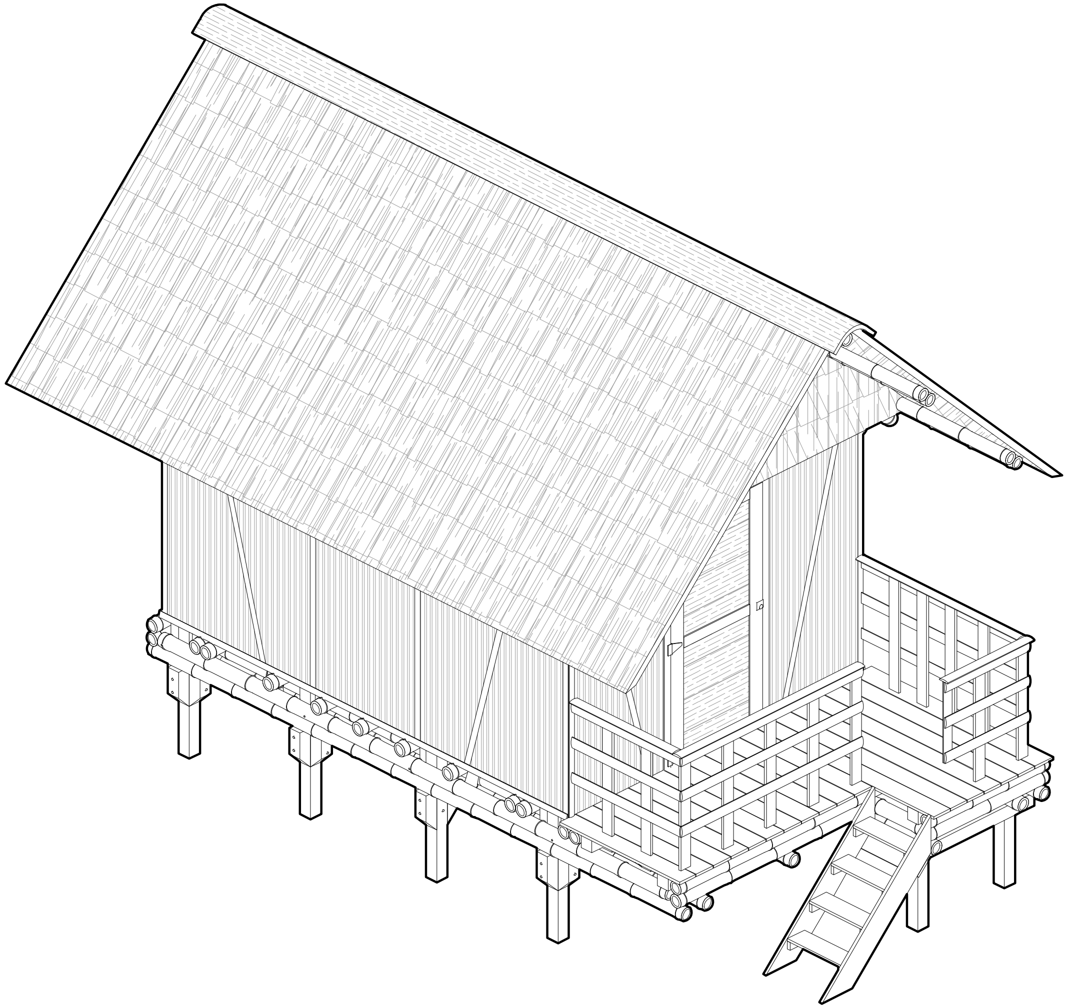
- Use of natural rope, 'tady zavy' (inner face of a local tree's bark) for attaching the walling system to the main structure.

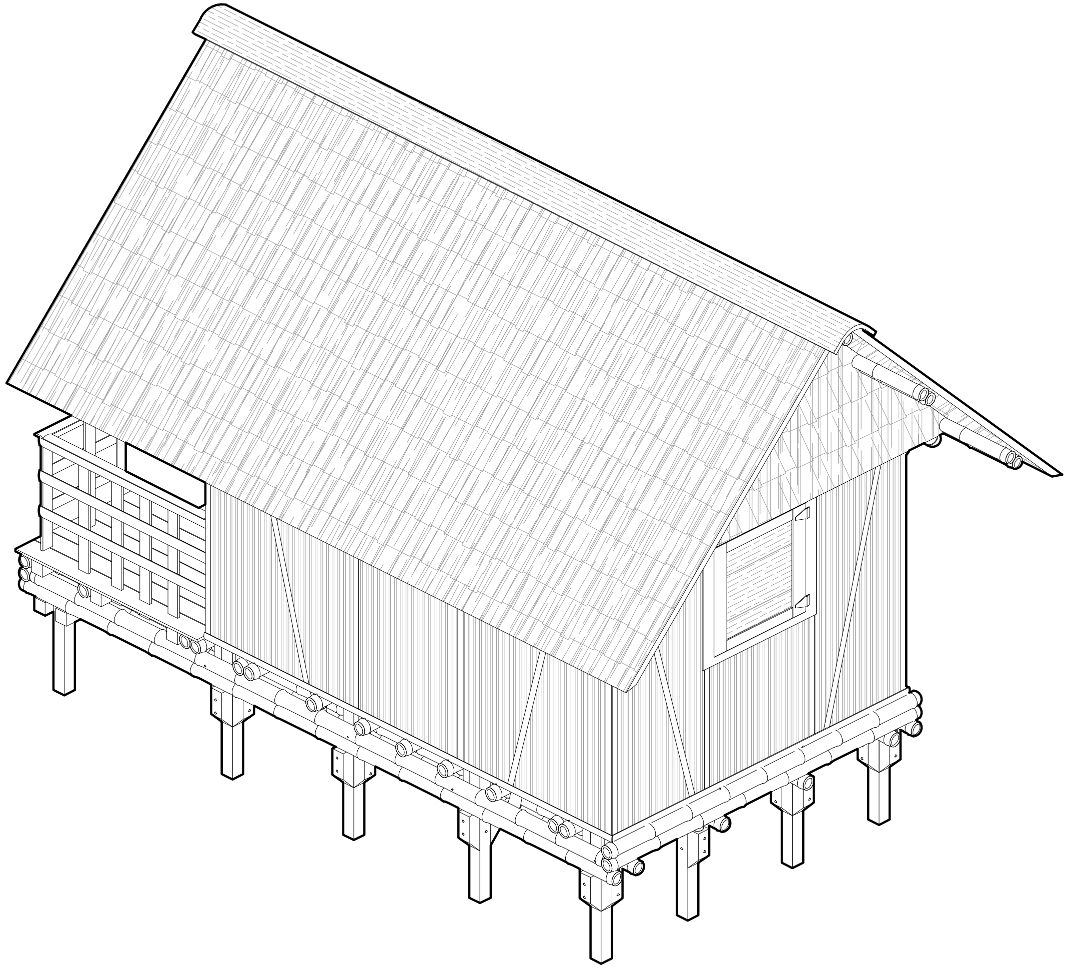
- Innovative roof ridge consisting of a prefabricated sandwich panel using flatten bamboo at the bottom and on top, and several layers of 'kasaka' in between.

As described in the following technical drawings, the 'Bamboo house - Model 'B' has a rectangular floor plan of approximately 3 by 4 meters. Its entrance door is centered in one of its short sides and opposite to the window opening. There is a veranda and the landing of the access stairs in the front side of the building.

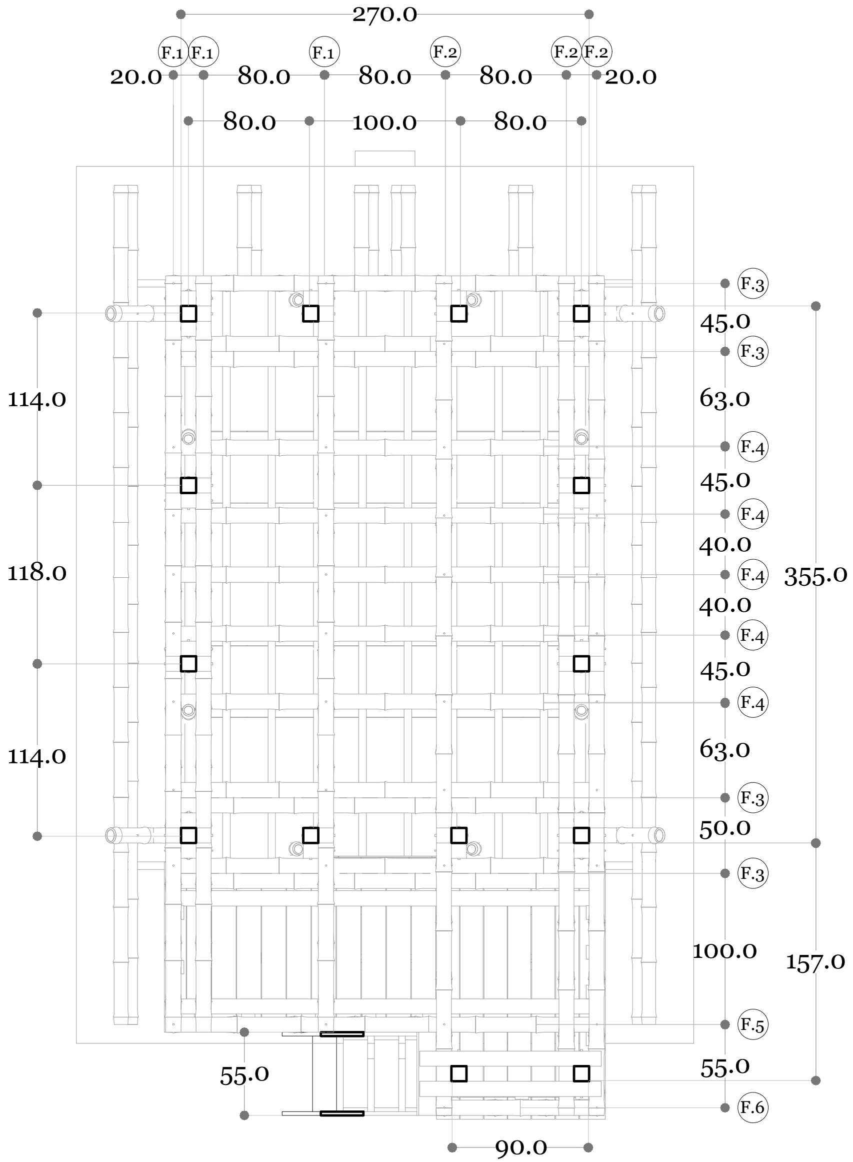
Following, an excerpt of technical drawings used as the basis for the training workshop (the whole set of plans and technical drawings is attached to the this report as annex) and its corresponding bill of quantities.



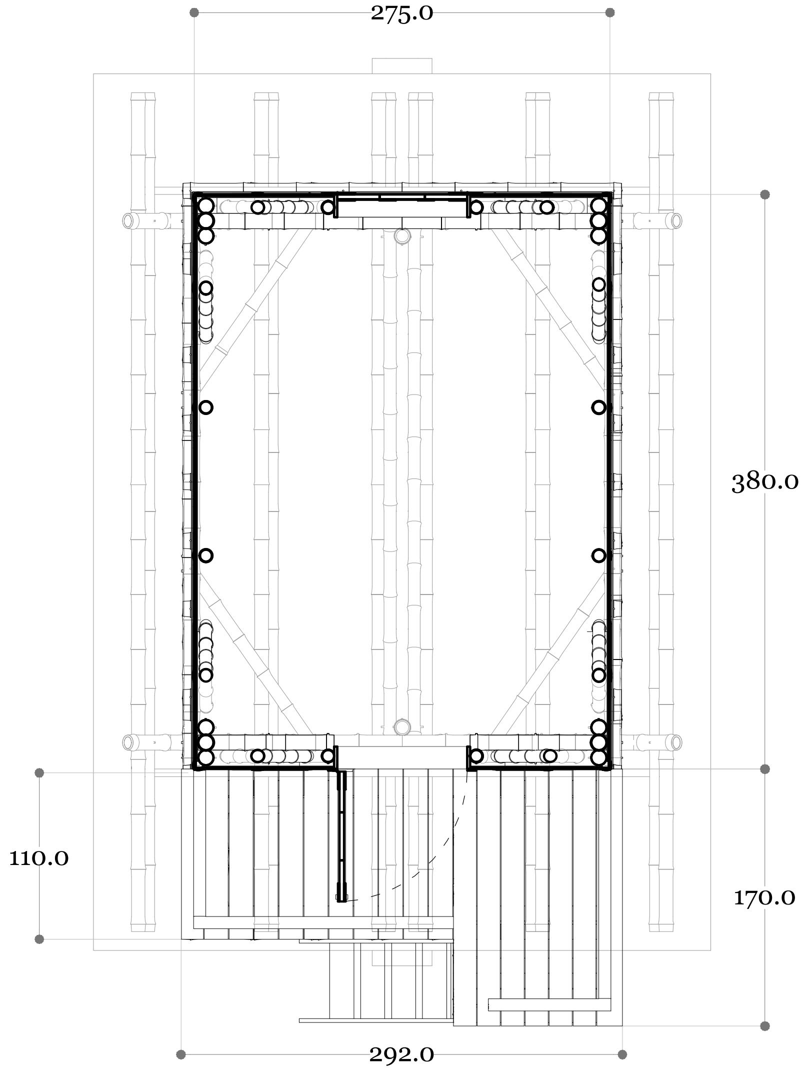




PERSPECTIVES **_I-B.01_**

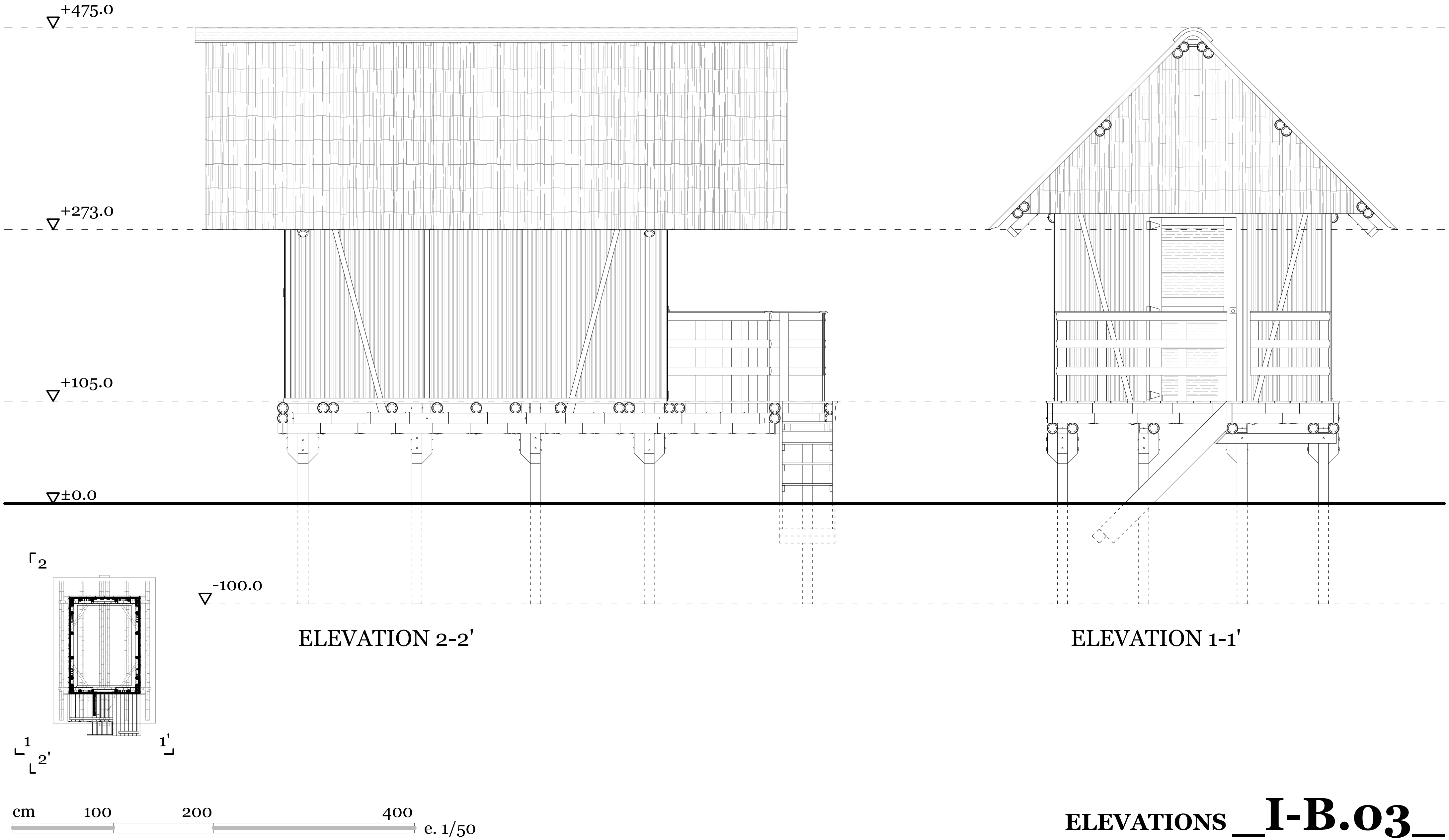


FOUNDATION + FLOOR SLAB
[I-B.11] / [I-B.12]

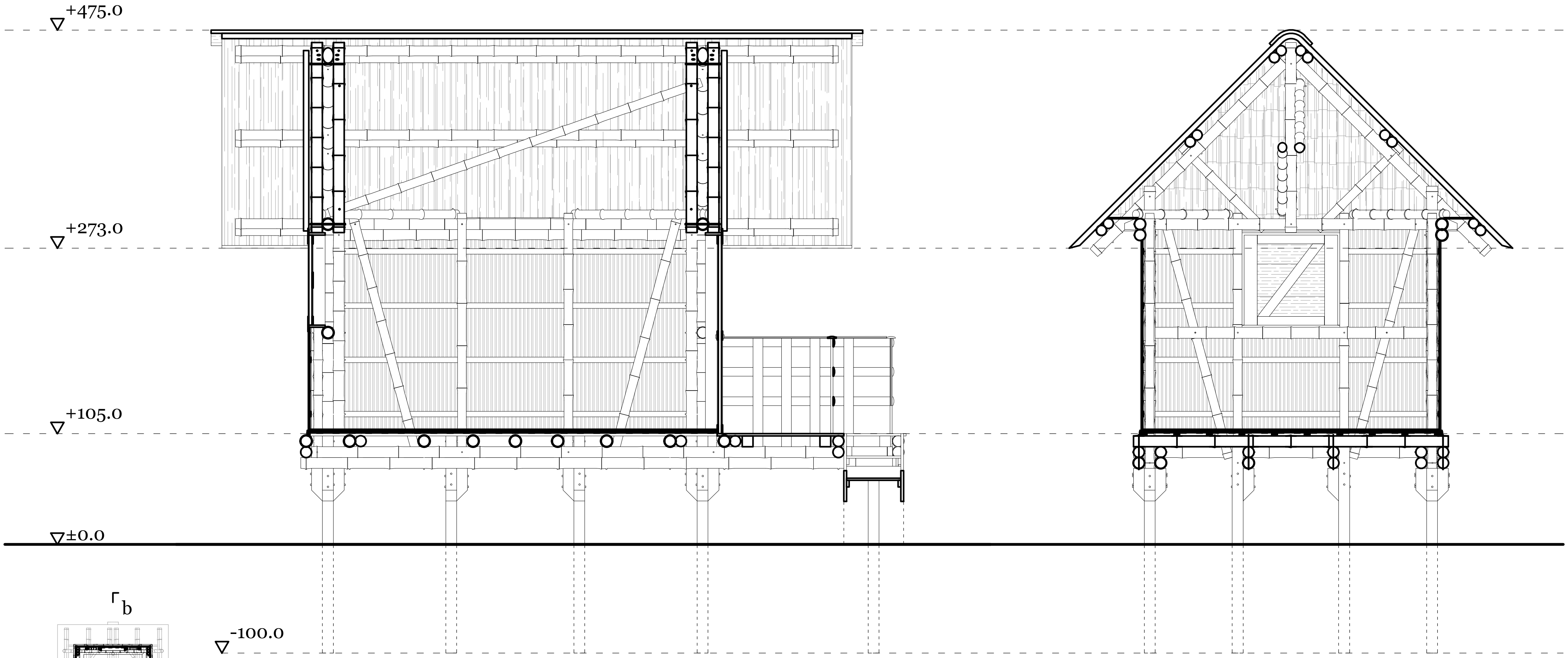


FLOOR PLAN

cm 100 200 400 e. 1/50

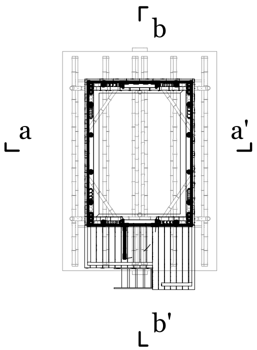


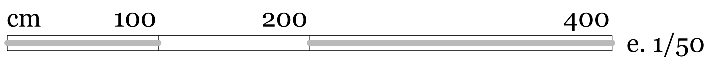
ELEVATIONS _I-B.03_

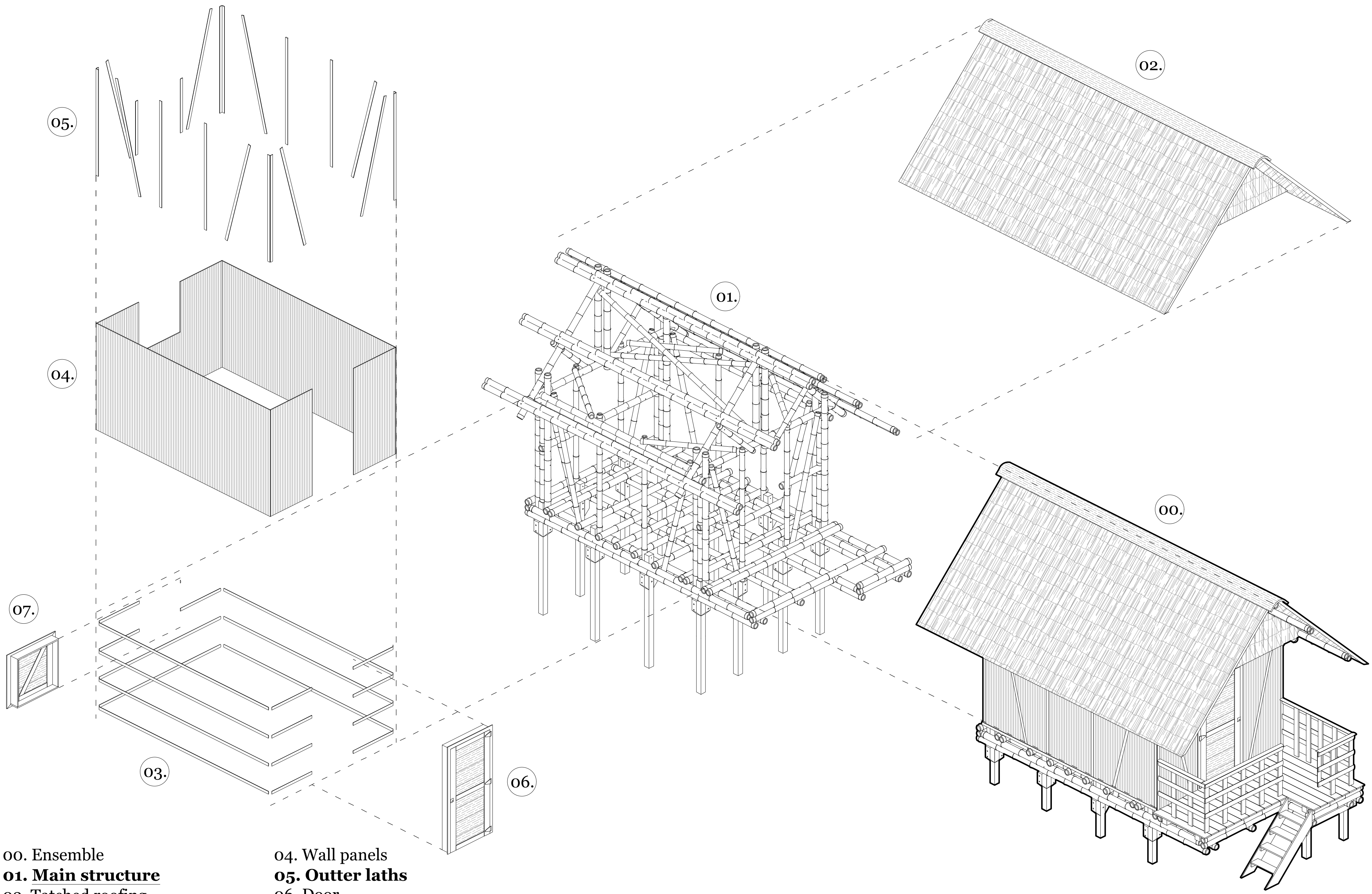


SECTION b-b'

SECTION a-a'







00. Ensemble
01. Main structure
02. Tatched roofing
03. Laths substructure
04. Wall panels
05. Outter laths
06. Door
07. Window

CONSTRUCTIVE ELEMENTS _I-B.05_

Bill of quantities for 'Bamboo house - Model B'

Item, units	Quantity	Unit. price (Ar)	Total (Ar)
Bamboo culms, 8m	60	23.000	1.380.000
Timber 10x10cm, 4m	16	20.000	320.000
Timber 16x4cm, 4m	4	20.000	80.000
Planks planed 4 faces, 4m	5	20.000	100.000
Planks planed 4 faces (rod of 8 and 6), 4m	7	7.000	49.000
Flatten bamboo, m2 (triple layer floor, window and door)	45	5.000	225.000
Falafa, pack (ravinala branches, pack of 100)	5	14.000	70.000
Tsiriky 4m, unit (ribs of falafa panels)	8	1.000	8.000
Tsiriky 3m, unit (ribs of falafa panels)	8	1.000	8.000
Tady zavy, packs of 3	85	200	190.000
Fitoroka, unit (rafters to attach kasaka)	32	1.000	32.000
Kasaka, pack (ravinala leaves, pack of 100)	9	14.000	126.000
Bamboo roof ridge	1	7.000	7.000
Nails, kg	5	8.000	40.000
Door lock, unit	1	13.000	13.000
Hinge, unit	6	1.500	9.000
Bolt	3	2.500	7.500
		Total:	**2.664.500 Ar**

2. (b) Structural analysis

The design concept behind the 'Bamboo house - Model B' is to achieve a spatial structure through triangulation of all the structural elements by hinges or articulations. This way, no bending moment happens in the joints of the structure and no stiffness needs to be beard by them. It is the tridimensional structure as a whole what provides the required stability.

Despite not having structural calculations for this particular case because of lacking mechanical values of the hardwoods used for the foundation, the calculations performed for the 'Bamboo house – Model A' (which foundation stands on the ground, instead having a foundation based on posts) are the same from the bottom of the structural supports up. To rely on the performance of the buried posts, all the recommendations from the previously mentioned field tests are followed.

A structural analysis was done, just as in any building project, to justify the structural performance of the housing project considering the allowable stresses of every and each structural elements, as well as the maximum displacement of the structure as a whole. For this analysis, in order to apply the finite elements method, the software SAP2000 v22.1.0 was used.

The building codes and standards considered for the analysis are the following:

Colombian national building code, Peruvian national building code, and the structural bamboo ISO standards, titled ISO 19624:2018 Bamboo structures — Grading of bamboo culms — Basic principles and procedures, ISO 22156:2021 Bamboo structures — Bamboo culms — Structural design, and ISO 22157:2019 Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods.

The bamboo material properties considered are those recorded in the national building code of Colombia (NSR-10, Capítulo G.12 – Estructuras de Guadua) and Peru (Reglamento Nacional de Edificaciones – Normas E.100):

Bending, allowable stress (f_m)	150 kgf/cm^2	14.71 MPa
Tension, allowable stress (f_t)	180 kgf/cm^2	17.65 MPa
Compression parallel, allowable stress (f_c)	140 kgf/cm^2	13.72 MPa
Compression perpendicular, allowable stress (f_{cp})	14 kgf/cm^2	1.37 MPa
Shear, allowable stress (f_v)	12 kgf/cm^2	1.17 MPa
Modulus of Elasticity, mean 0.5 ($E_{0.5}$)	95000 kgf/cm^2	9316.32 MPa
Modulus of Elasticity, mean 0.05 ($E_{0.05}$)	75000 kgf/cm^2	7354.99 MPa
Modulus of Elasticity, minimum (E_{min})	73000 kgf/cm^2	7158.86 MPa
Specific weight (γ_c)	900 kgf/m^3	8825.98 N/m^3

The most critical load taken into account to run the analysis was the wind load of the strongest cyclone registered in the area in recent years, i.e. 250 km/h winds peed.

In 2022 the category 4-equivalent tropical cyclone named 'Batsirai' highest winds were 230 km/h.

Displacements by wind load (W)

Maximum displacements by wind load (W) are shown in the following table and figure:

Joint	X (m)	Y (m)	Z (m)	H (m)	Desp. X (m)	Desp. Y (m)	Desp. Z (m)	Δ/H	Estado (<0.010)
90	4.20	3.15	1.63	1.63	0.000000	0.001849	0.001091	0.001131	OK
91	-0.40	3.15	1.63	1.63	0.000000	0.001849	0.001091	0.001131	OK

Table 1: Displacements caused by wind load (W)

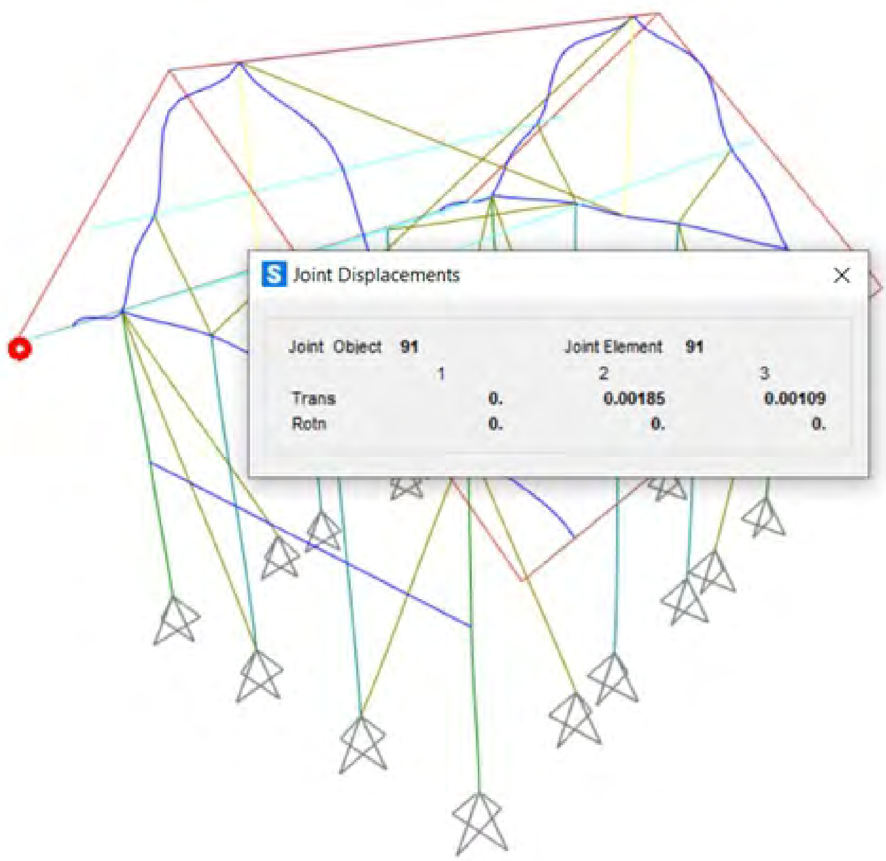


Figure 1: Maximum displacement caused by wind load (W)

It is observed the sum of reactions to wind load is 0 kg in axis X, 3562.90 kg in axis Y and -3061.88 kg in axis Z. There is no bending moment in any support.

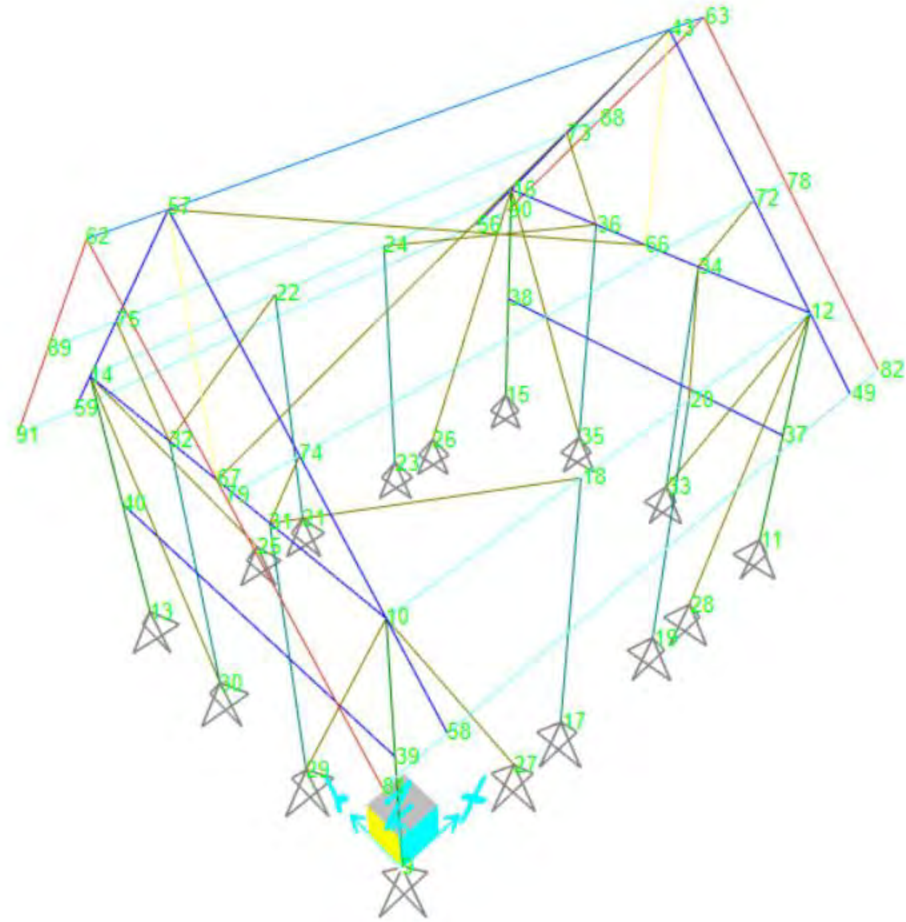


Figure 2: Reactions caused by wind load (W)

TABLE: Joint Reactions					
Joint	OutputCase	CaseType	F1	F2	F3
Text	Text	Text	Kgf	Kgf	Kgf
9	W	LinStatic	4.43	130.9	1044.95
11	W	LinStatic	-4.43	130.9	1044.95
13	W	LinStatic	-5.91	130.49	-1388.09
15	W	LinStatic	5.91	130.49	-1388.09
17	W	LinStatic	0.04301	16.7	27.41
19	W	LinStatic	-0.04301	16.7	27.41
21	W	LinStatic	-0.05782	16.11	-40.83
23	W	LinStatic	0.05782	16.11	-40.83
25	W	LinStatic	222.87	12.34	-494.45
26	W	LinStatic	-222.87	12.34	-494.45
27	W	LinStatic	-167.8	13.11	372.28
28	W	LinStatic	167.8	13.11	372.28
29	W	LinStatic	0.35	787.59	-2082.27
30	W	LinStatic	-0.42	674.21	1030.06
33	W	LinStatic	-0.35	787.59	-2082.27
35	W	LinStatic	0.42	674.21	1030.06
Total			**0**	**3562.90**	**-3061.88**

Table 2: Reactions caused by wind load (W)

Allowable stress design

The demand / capacity ratio does not go beyond 0.359 in columns and 0.513 in beams, both below the value 1 which would posse a risk for the structure.

Columns: Compression design

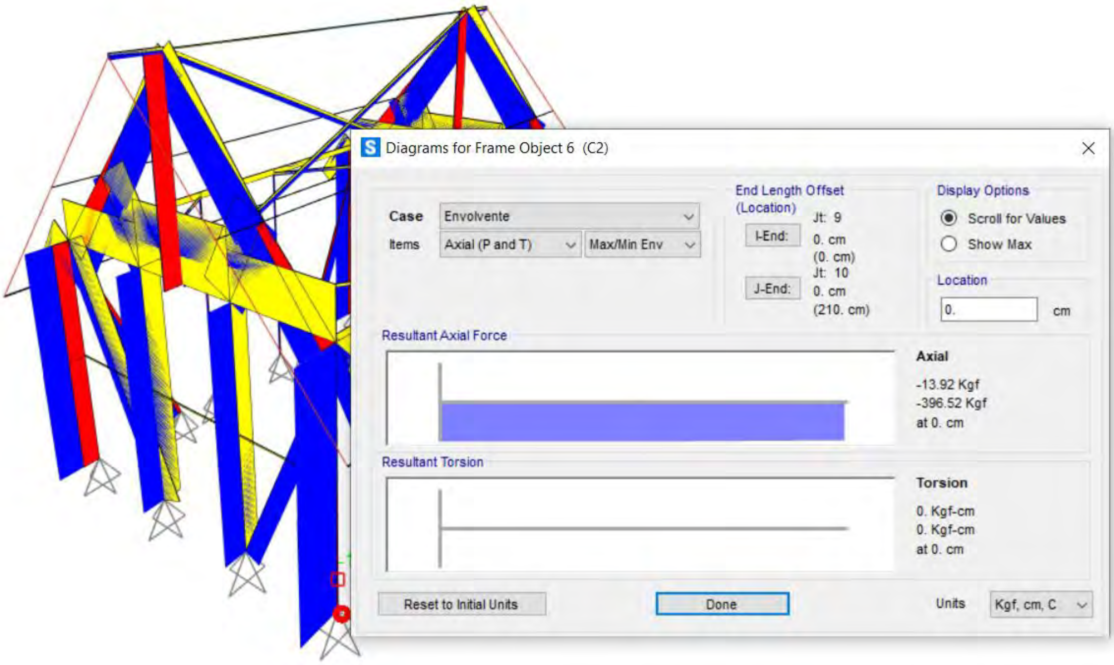


Figure 3: Columns with higher demand/capacity ratio

Beams: Flexural design

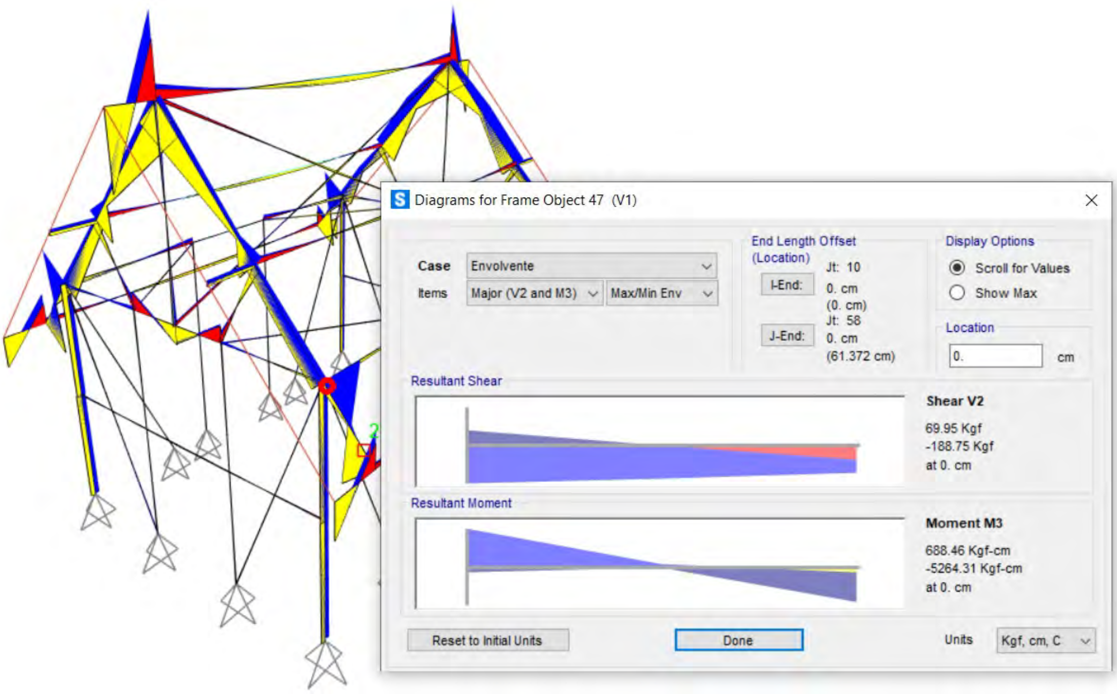


Figure 4: Beams with higher demand/capacity ratio

2. (c) Training workshop

On April 14th the consultant departed from Antananarive to Maroansetra, and returned to Antananarive on May 5th. On April 15th a participatory design workshop, led by Mr Igor Sujar, for the validation of the model house to be built during the workshop took place in the office of Red Cross in Maroansetra. The training workshop started in Marogisa on April 18th and finished with the diplomas handover to participants on May 3rd.

Planning

On April 16th, a site visit to the selected plot of land where the training workshop was going to take place was requested by the consultant. The plot was in a village called Ambodivoanio.

The consultant found out that the selected site was over an hour away from Maroansetra downtown, involving a half an hour motorbike ride, then crossing a river on a canoe (loading the motorbikes on the canoe to embark, and unloading them on the other riverbank to disembark) and finally another half an hour motorbike ride on the other side of the river, of course on mud roads almost totally covered by water because of the heavy rains, apparently out of season, but still happening on daily basis.

Very concern about his personal safety because of the commuting explained above and since no building material had been delivered yet, the consultant suggested that the training should be conducted in another location.

After a round of concertation with the local team and the management team in Antananarivo, it was decided to move the training to the village of Marogisa.

Logistics

No materials had been purchased before the start of the training workshop. Maybe some of them had been ordered but not delivered and there were periods of pause due to lack of available material on site.

The most remarkable issue regarding the weak logistics of the activity was the fact that all the timber that arrived at the site was not dry. Even softwoods are very hard to work with when their humidity content is high. Here there were extremely hardwoods with a high humidity content, making them outstandingly heavy and even more difficult to drill.

Finalizing the workshop positively was possibly because in the end the carpenters brought some of their own tools and the consultant brought from the beginning some with him as well (over those included in the list of tools and equipment required, handed over before the start of the mission).

Technicians

Unfortunately, there was a lack of interest from some of the CRM technicians who attended the workshop while others seemed more interested.

Attendees

There were, as attendees, 26 carpenters (highly committed and motivated from the very beginning until the end of the workshop), 1 bamboo grower and 3 representatives from the company providing the bamboo used during the workshop. Other attendees were the translator/interpreter (Britto) and local Red Cross staff and volunteers. Between 30 and 40 participants, depending on the moment.

It is remarkable how interested all the carpenters were, not only following the explanations but also making highly relevant questions and very appropriate comments. Also drawing by themselves the graphics and plans represented in the flipboard to facilitate the communication between the consultant and the participants, despite the language barrier. The commitment of Britto (the translator/interpreter) together with the availability of a flip board on site made a real difference with previous workshops in pedagogic terms.

Besides the Head of project, there were two other women attending the workshop. This is the first time, in the consultant's experience collaborating with the Malagasy Red Cross, to have female carpenters as trainees. It is very important to promote gender equality and women empowerment in this kind of capacity building activities.

Day-to-day workshop schedule

Day 1 – 18/04/2025
(opening ceremony)

- Introductory theory lesson
- Reception of bamboo culms from supplier
- Grading of selected culms
- Pegs making

Day 2 – 19/04/2025

- Prefabrication of columns

Day 3 – 22/04/2025

- Prefabrication of lateral beams
- Prefabrication of floor beams

Day 4 – 23/04/2025

- Prefabrication of trusses

Day 5 – 24/04/2025

- Assembly of frames

Day 6 – 25/04/2025

- Prefabrication of stilts (1)

Day 7 – 26/04/2025

- Prefabrication of stilts (2)
- Layout of foundation

Day 8 – 28/04/2025

- Foundation trenches dig
- Frames lift-up
- Lateral frames tied in place
- Floor beams pegging
- Lateral frames pegging
- Horizontal bracing

Day 9 – 29/04/2025

- Vertical bracing
- Roof beams pegging
- Floor rafters pegging
- Roofing starts

Day 10 – 30/04/2025

- Roofing finishes
- Floor double-laths
- Wall substructure
- Flatten bamboo
- Stairs

Day 11 – 01/05/2025

- Flooring
- Wall panels installation
- Veranda (1)

Day 12 – 02/05/2025

- Veranda (2)
- Improved roof ridge
- Window and door

Day 13 – 03/05/2025

(closing ceremony)

Drawings made during the first theory lesson

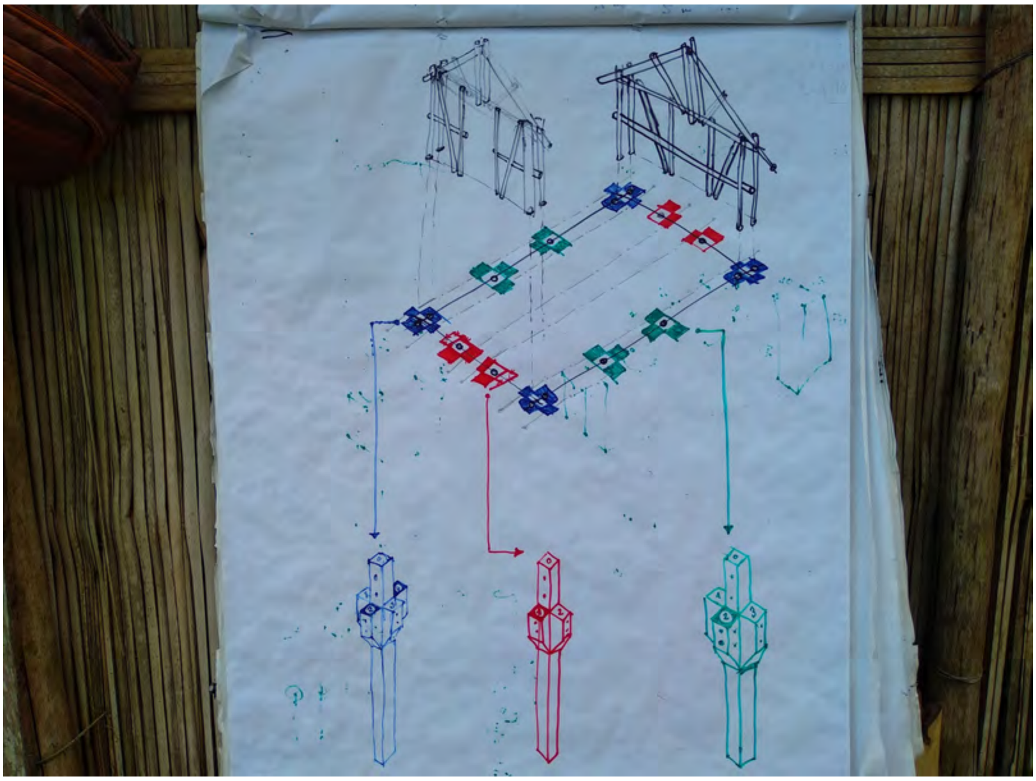
Pegs making by female carpenters

Assembly of one of the main frames

Working on the connection between columns and foundation posts

Prefabricated frame connected to foundation posts

One of the theory lessons along the training workshop



Drawings made to support one of the theory lessons

Attendees taking notes after a theory lesson

A foundation post

Back frame lift up

Level check when both main frames are lifted up

Floor beams and roof beams installation

Bamboo strcuture completed

Walls substructure

Roofing and stairs completed

Flooring (flatten bamboo, double layer) installation

Close up of the bamboo floor slab

Walls, flooring and veranda in progress

Close up of the window frame

Window making in progress

Door making in progress

Bamboo house - Model 'B', interior view

Bamboo house - Model 'B', interior view

Bamboo house - Model 'B', exterior view

Bamboo house - Model 'B', completed, within its context

3. SUGGESTIONS FOR NEXT STEPS

Management of bamboo as a valuable resource

The one used for the structure of the house, *Gigantochloa pseudoarundinacea*, is present in the area, in limited quantities but more numerous than in Antalaha region. Therefore, it is hard to ensure regular availability of raw material (bamboo culms already cured and/or treated, and dry) based on the resources available. Some efforts have been made to propagate different bamboo species, including *Dendrocalamus giganteus*, particularly in the bamboo nurseries promoted by the Red Cross. However, considering the time taken for bamboo to establish a rhizomatic system required to sprout bamboo culms, and the time these culms need to become mature enough to be considered a reliable structural material, the source of raw material promoted today shall be productive in the next 4 to 5 years.

On the other hand, large quantities of *Bambusa vulgaris* (the species used during the workshop to make flatten bamboo to manufacture formworks for the foundation) are widely available in the North-East coast of Madagascar. This pantropical bamboo species, and in particular its green variety, is reported to be food for the critically endangered *Prolemur simus*.

A clump of Bambusa vulgaris *and a close-up showing traces of* Prolemur simus

The author's suggestion is to focus on using the species already available, firstly *Gigantochloa pseudoarundinacea* and in second place *Bambusa vulgaris*. The latter is usually not recommended for construction, arguing that it is supposedly too soft or it has too much sugar content, but there is not scientific proof against the fact that with a proper management (selection, harvest, curing and/or treatment) it is as reliable and long lasting as any other big bamboo.

In order to make bamboo a popular material among local communities, a certain value chain related to the material should be implemented. Selection, harvest, treatment, grading and storage are the key points in processing the raw material from the clumps to the building sites.

Besides using structural bamboo culms, there are a few by products that may benefit the communities. Some of these by-products are useful for building, such as flatten bamboo (to make woven bamboo panels and forms) or bamboo laths, and others are alternatives for increasingly scarce resources, such as fuel: bamboo charcoal may be produced using left-overs of bamboo culms and smaller pieces may be burnt right away.

A summary of a potential value chain for bamboo as building material is the following:

- Selection of the specimens that are already mature enough but yet not too old to be used structurally in construction
- Cut them properly in order to have a clump with culms of increasing quality
- Provide the selected bamboo culms a 'curing' period on their own clump
- Treat them with borax and boric acid (products that may be reused in agriculture)
- Dry them before being stored properly, to ensure the material is well preserved
- Grading of culms, to ease their use in the building site.

Comprehensive habitat approach

After having tested the building systems and applied techniques as suitable in the given socioeconomic context, the built environment should include other services besides shelter. Taking into account that in the traditional and current lifestyle happening in the targeted areas kitchen and bathroom services are always out of the shelter, these additional buildings may be object of prototyping with the same building system:

- Latrines
- Kitchens

This is particularly relevant considering the impact that properly design service buildings or rooms, such as latrines and kitchens, have in extending dwellers' life expectancy.

4. CONCLUSIONS

Traditional Malagasy housing using bamboo instead of timber is a feasible and sustainable alternative in social, economic and environmental terms. Socially, because it is a housing typology which already belongs to the local culture, respecting dimensions and proportions of domestic buildings and only substituting the timber made elements by bamboo made ones; timber elements may be the structure and the openings only, and the walls and flooring as well. From the economic perspective, the financial cost of the alternative bamboo-based building system is within the range of the traditional timber-based system, therefore it poses a competitive or even more economic housing solution. Regarding environmental terms, the vast majority of the materials used for the construction are local, highly renewable resources, and the building system is cyclone proof according to the structural design and the calculations performed.

The **materials and tools** required make it possible to replicate the whole building system even in remote rural areas. Only human power tools are used, like machetes and knives, handsaws, ratcheting brace hand drills, hammers and locking pliers, thus there is no need of an electrical grid or other means of power supply, i.e. diesel generators. The tools are either available on the local market or easy to be done by any welder/metal worker willing to follow the technical specifications.

The **building techniques applied** in the model houses along the training workshops enhance the use of bamboo as building material, addressing well spread misleading statements related to these plants when it turns into a building material, such as its durability, the impossibility of building with curved or short culms, and the limitations of structural connections using bamboo pegs.

A series of **innovative building products** take part in the alternative bamboo-based model house. These innovations use bamboo as building material in different shapes and manners. These innovations may be applied together as in the model houses built along the training workshops or independently. Hence they are considered products for the local building industry. The innovative products are the structure as a whole and the structural elements separately (columns, trusses, beams, rafters), doors and windows, forms (to pour concrete), improved roof ridge, and floor slabs.

Considering **potential future scenarios**, it is worth noticing that the application of the implemented techniques and the innovative building products developed is not limited to this particular building typology of domestic architecture but could be applied to large-span structures and even multistorey buildings, posing a real feasible alternative for whole Malagasy society, starting from the lowest-income population. Proper management of current bamboo resources, despite posing challenges, opens up the possibility for the mainstream implementation of a building material which is widely available, highly renewable and processed in environmentally friendly ways.

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere gratitude to the Luxembourg Red Cross - AICRL (Aide Internationale de la Croix-Rouge Luxembourgeoise), the SRU (Shelter Research Unit) and to the Malagasy Red Cross for for their trust and support, with special mention to Igor Sujar.

Further I would like to thank the Ministry of Foreign Affairs of Luxembourg for financing the whole project.

To conclude, I cannot forget to thank my family and friends, the carpenters participating in the workshop, as well as employees and volunteers of the Malagasy Red Cross involved in this project, specially William 'Dada Will' and Britto.

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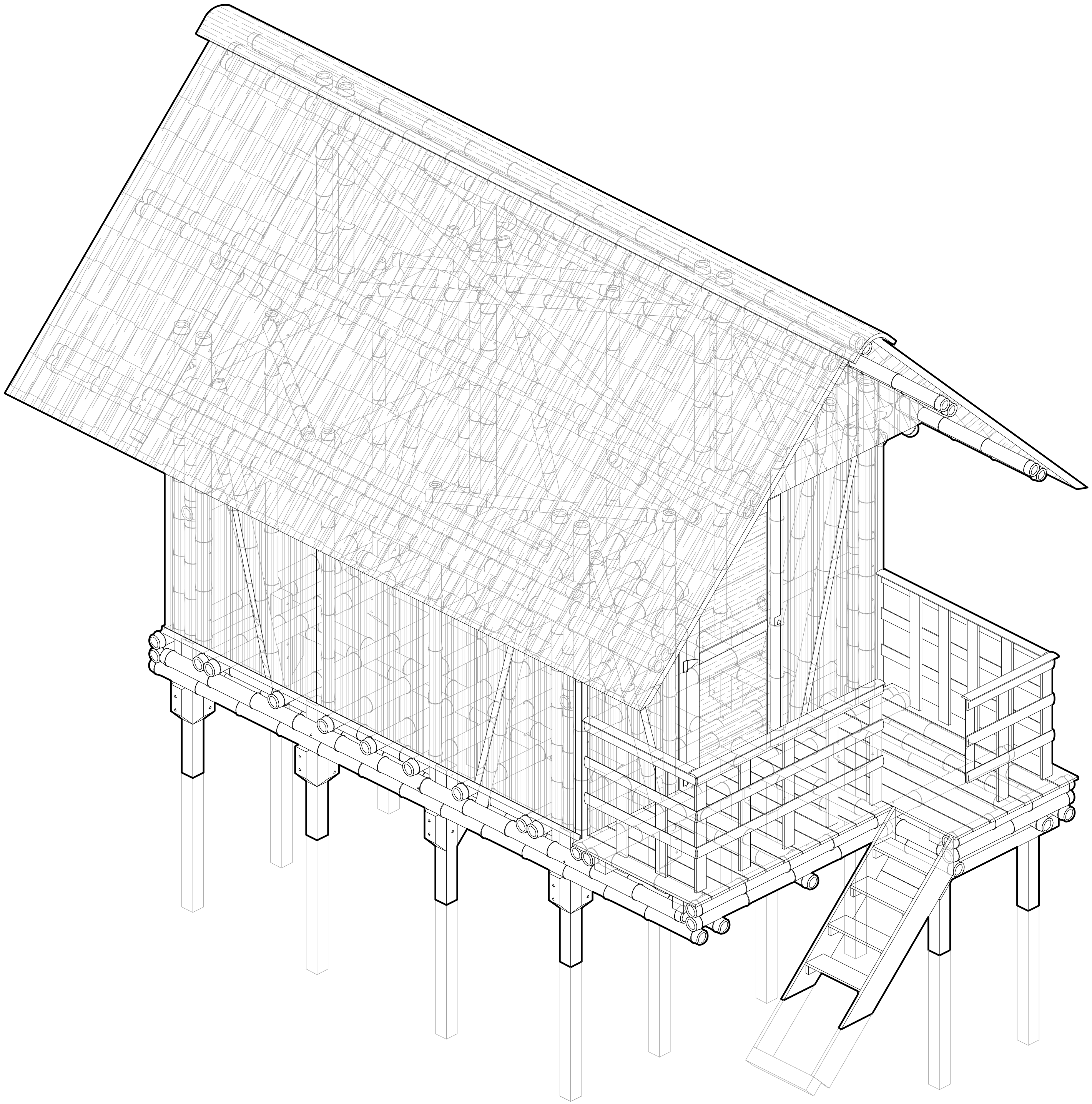
ANNEXES

Technical drawings and plans of Bamboo house - Model 'B'

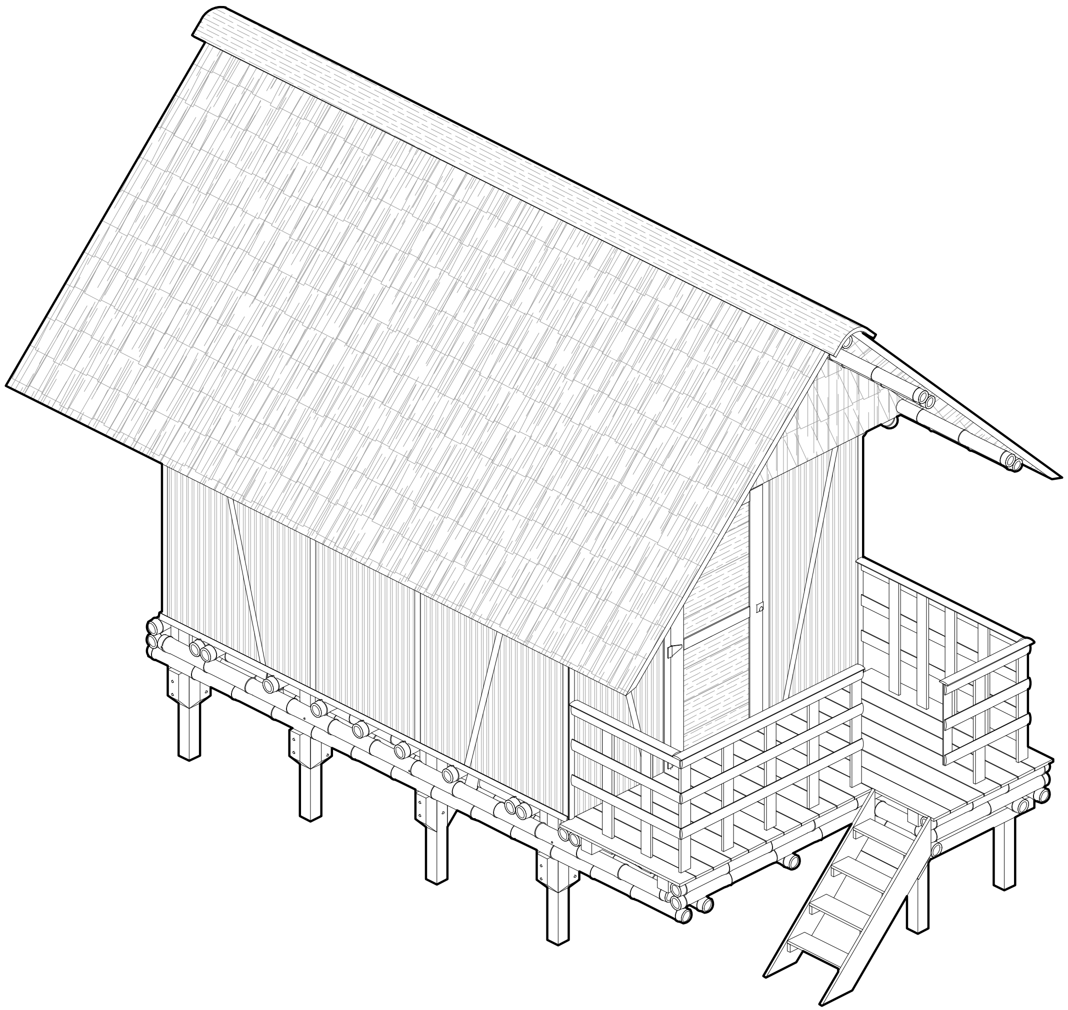
Tools and equipment

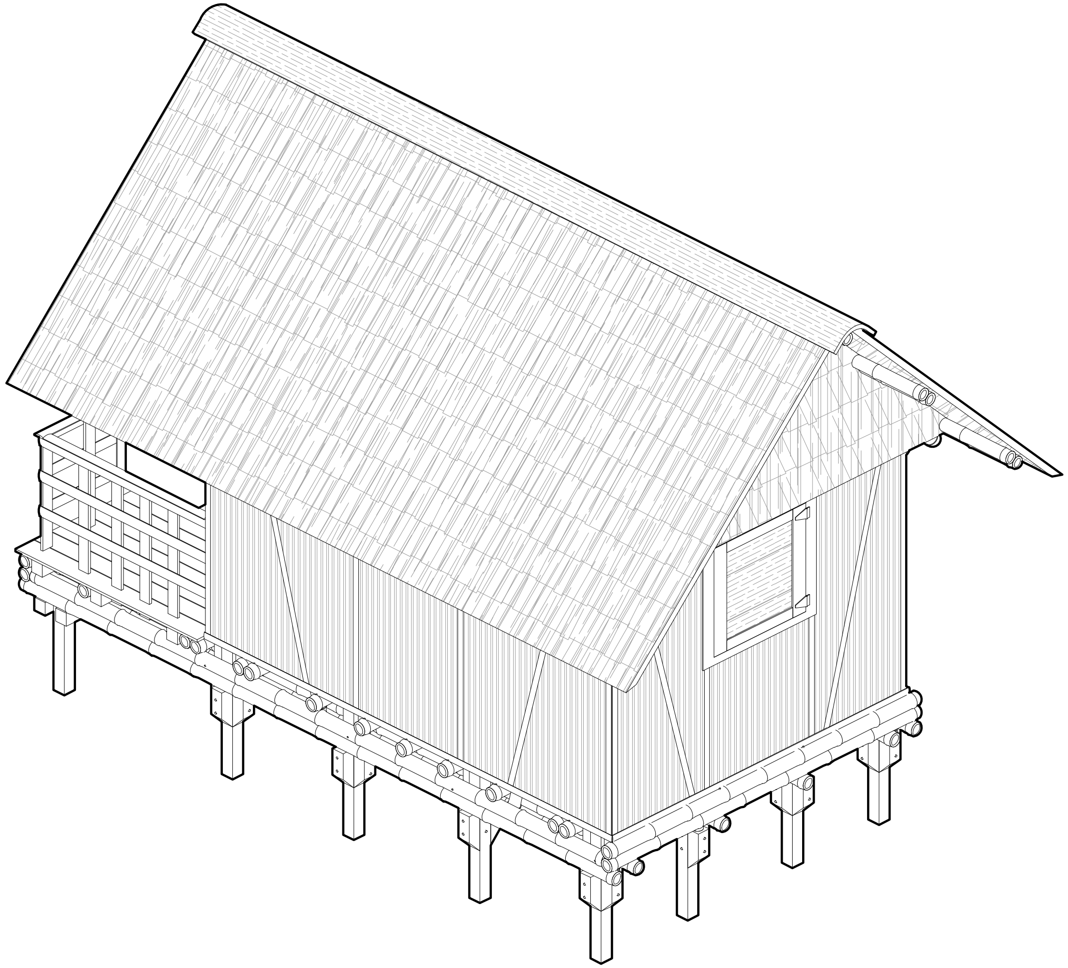
Satellite images of the area

Structural design report (in Spanish)

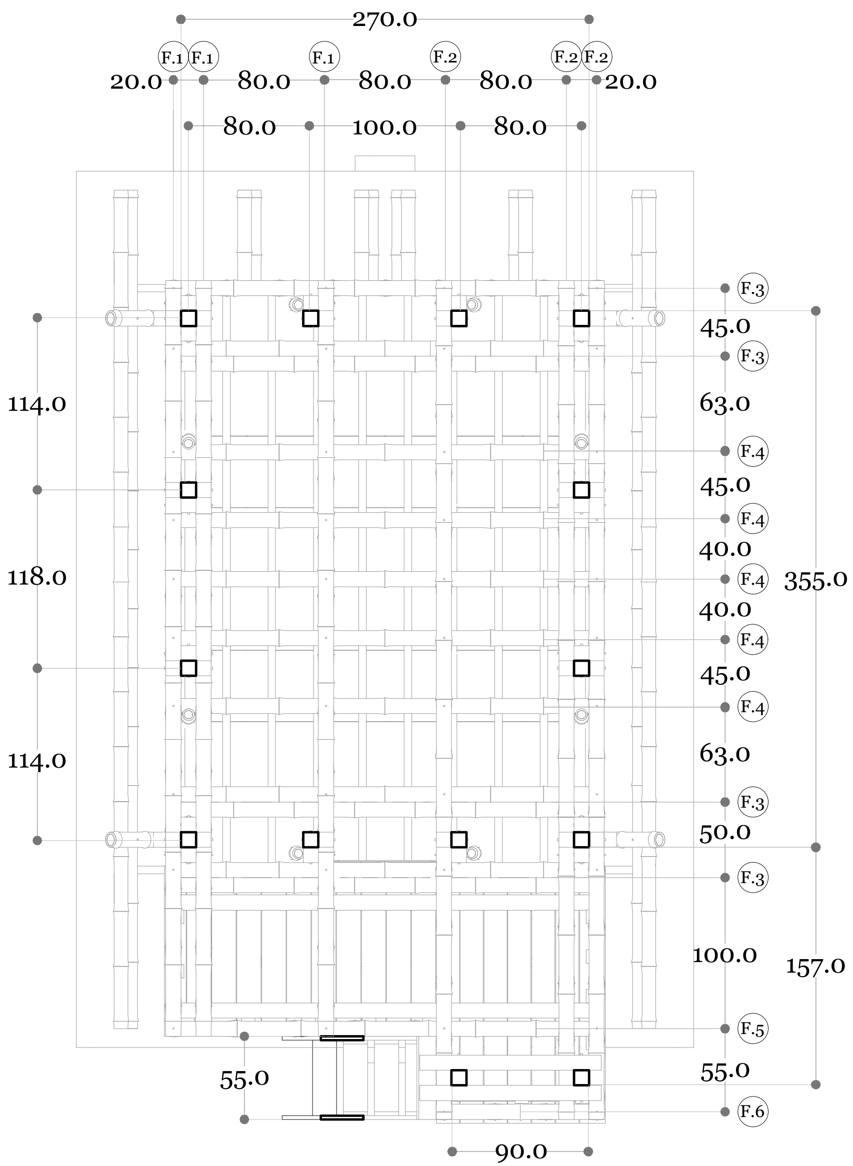


_I-B.00_

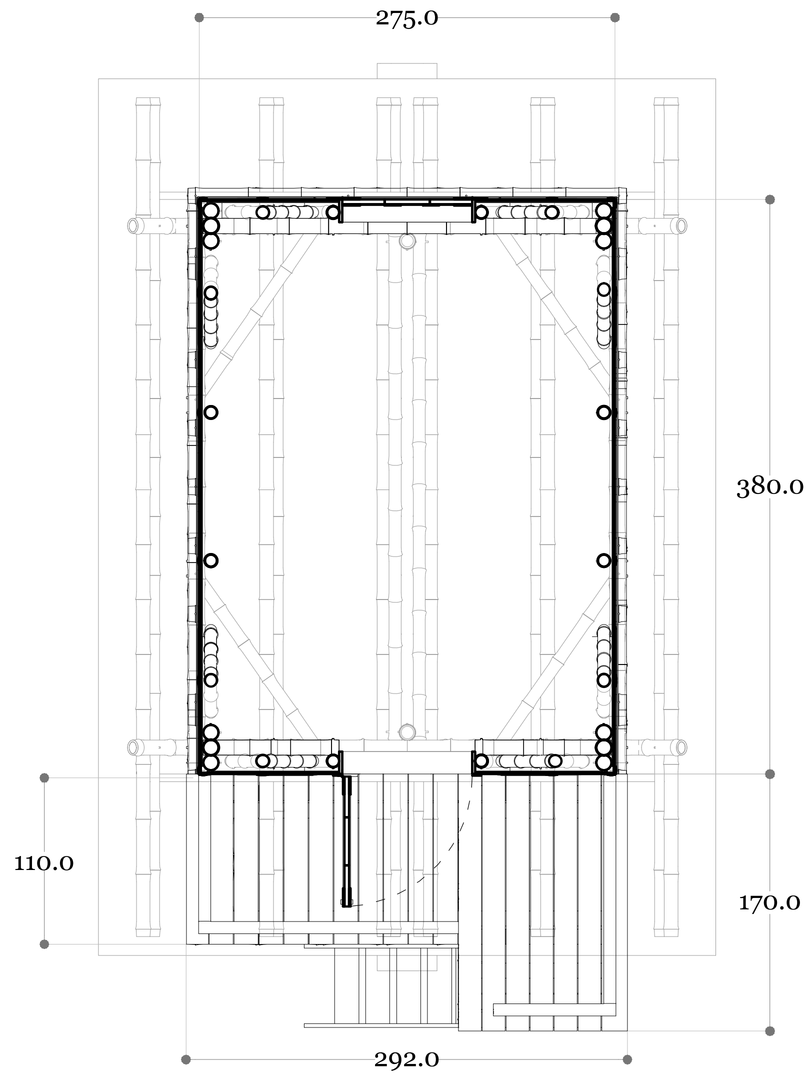




PERSPECTIVES **_I-B.01_**

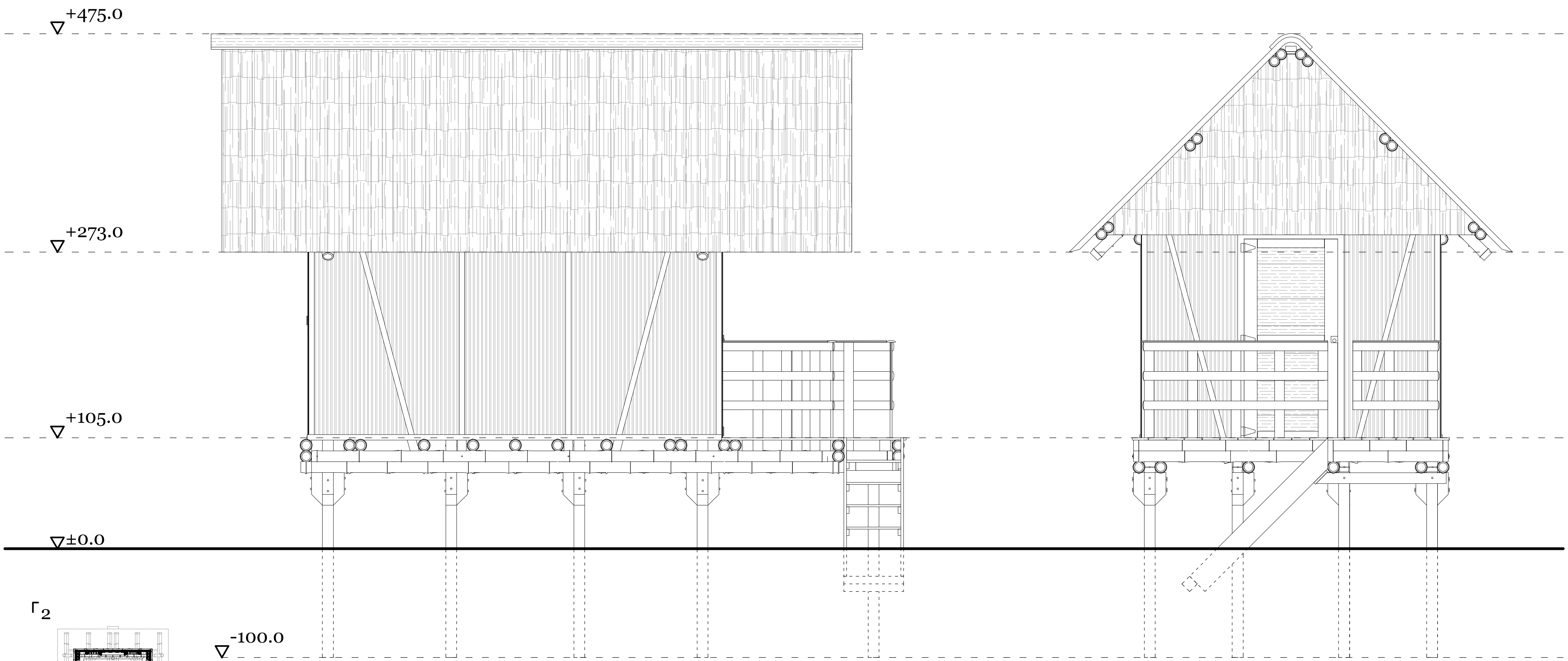


FOUNDATION + FLOOR SLAB
[I-B.11] / [I-B.12]



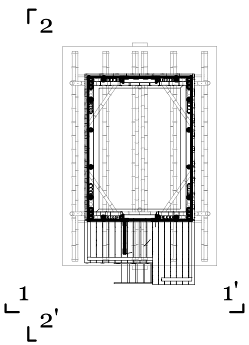
FLOOR PLAN

cm 100 200 400 e. 1/50



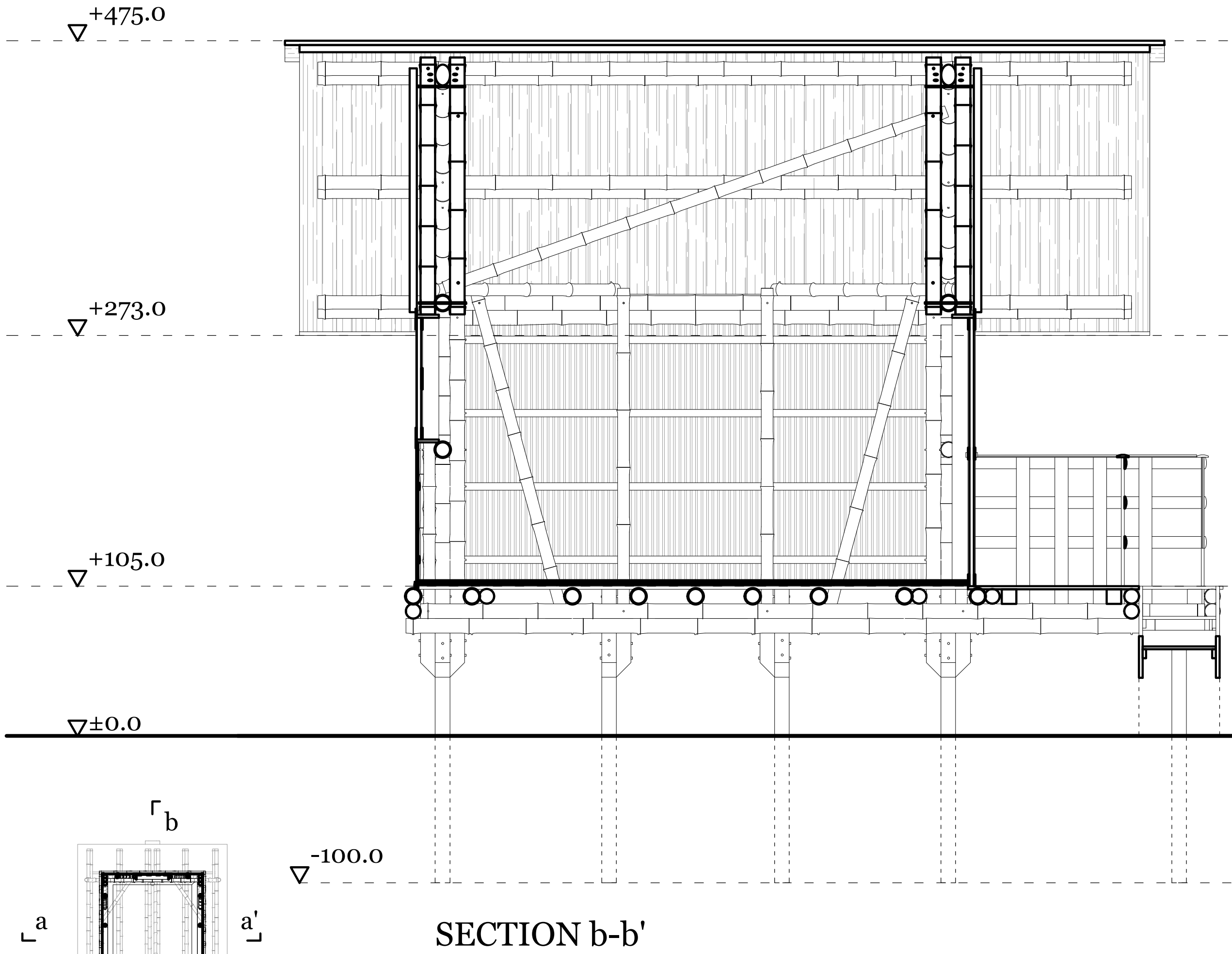
ELEVATION 2-2'

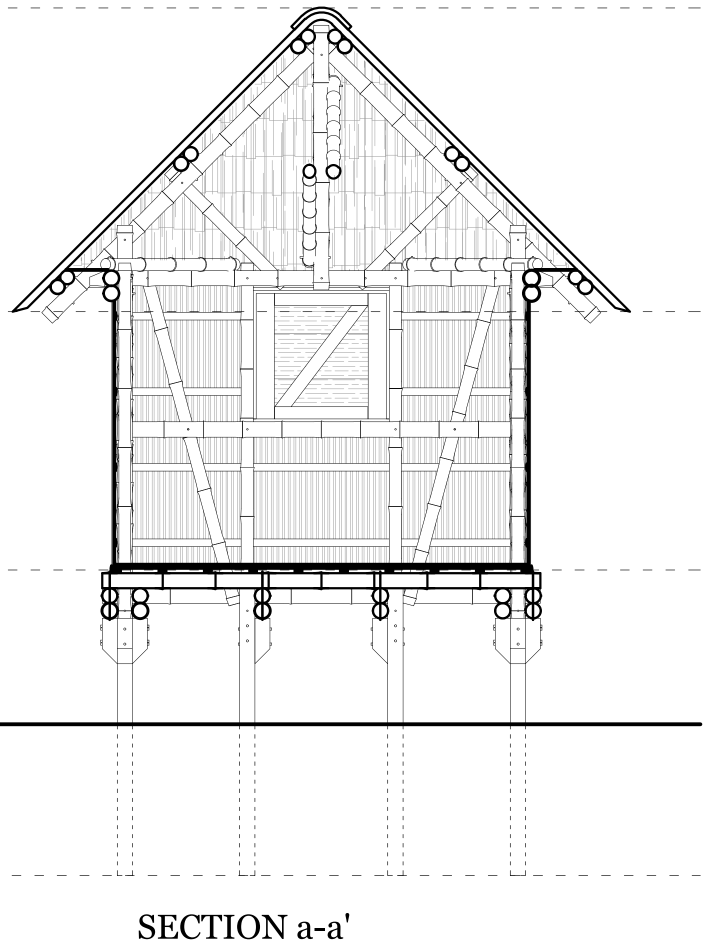
ELEVATION 1-1'

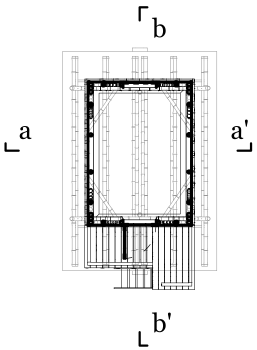


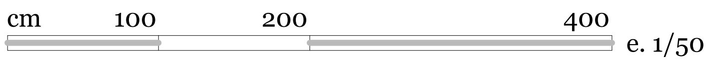
cm 100 200 400

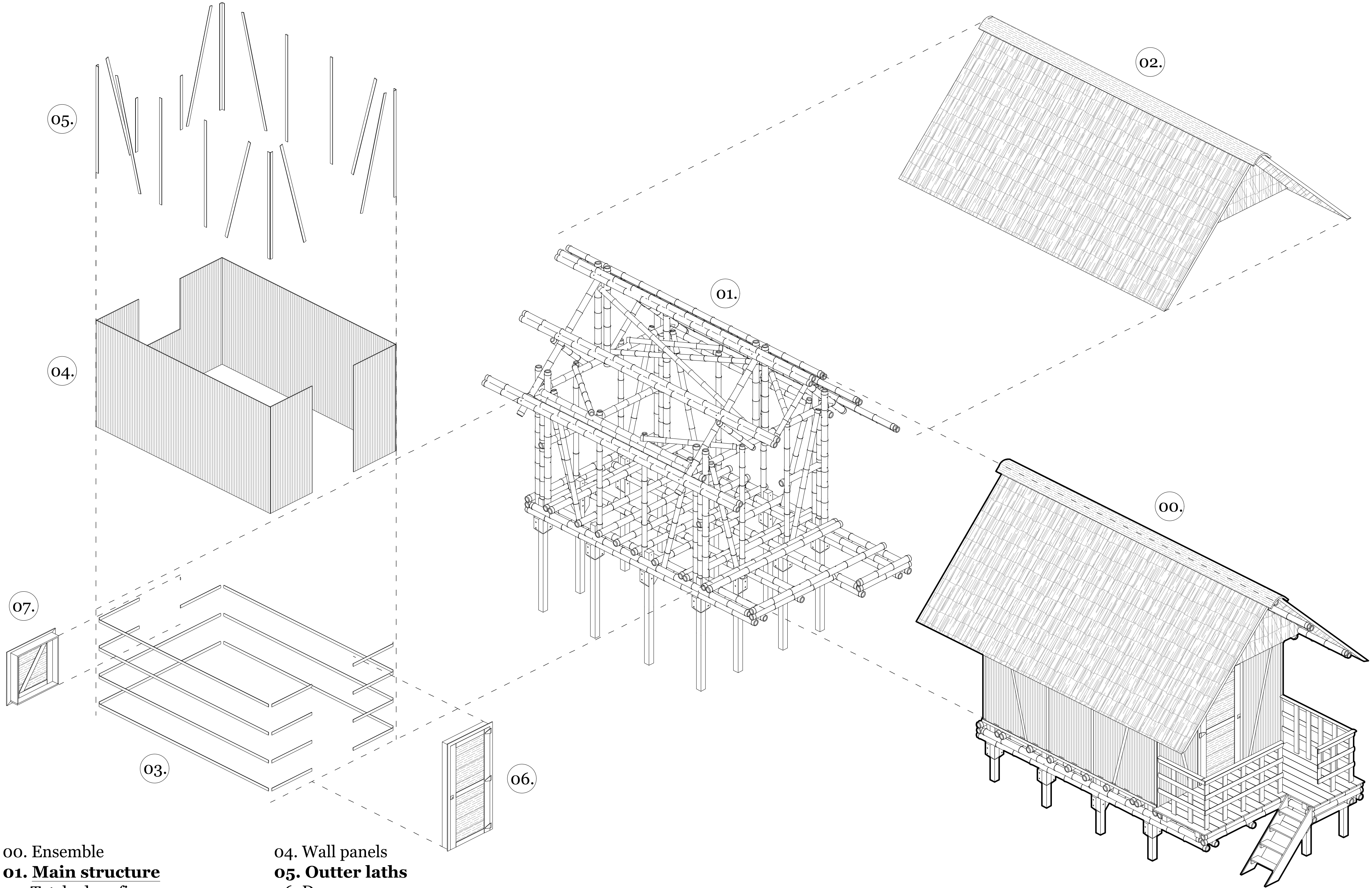
e. 1/50


+475.0
+273.0
+105.0
±0.0
-100.0
SECTION b-b'


SECTION a-a'


b
a
a'
b'


cm
100
200
400
e. 1/50

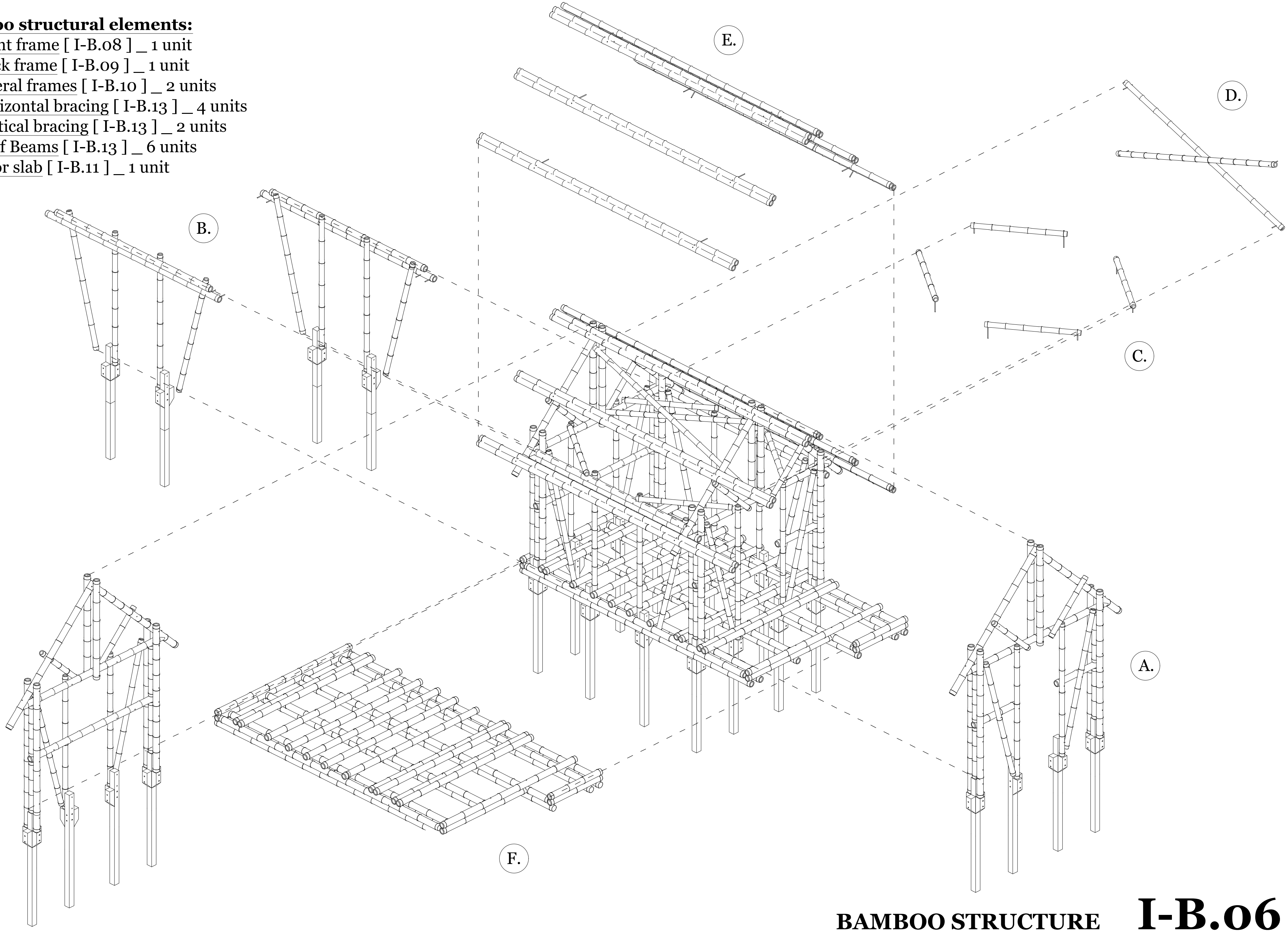


00. Ensemble
01. Main structure
02. Tatched roofing
03. Laths substructure
04. Wall panels
05. Outter laths
06. Door
07. Window

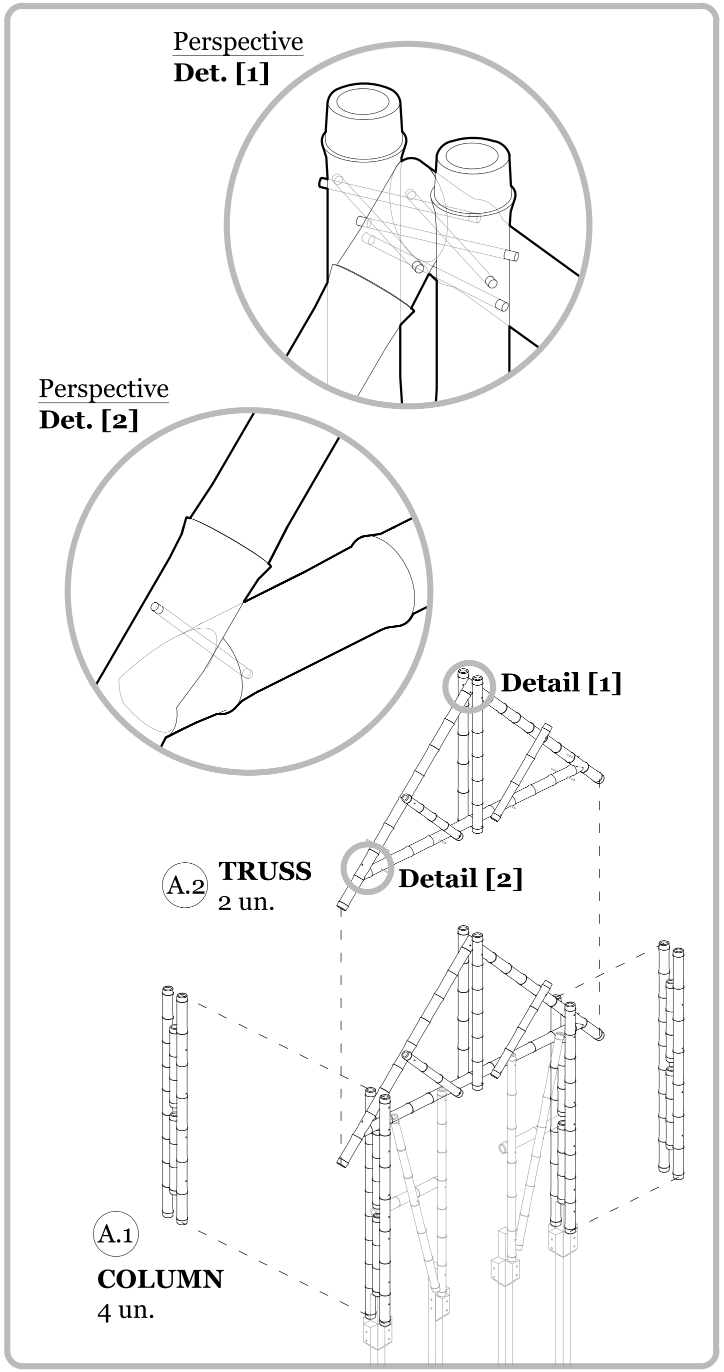
CONSTRUCTIVE ELEMENTS _I-B.05_

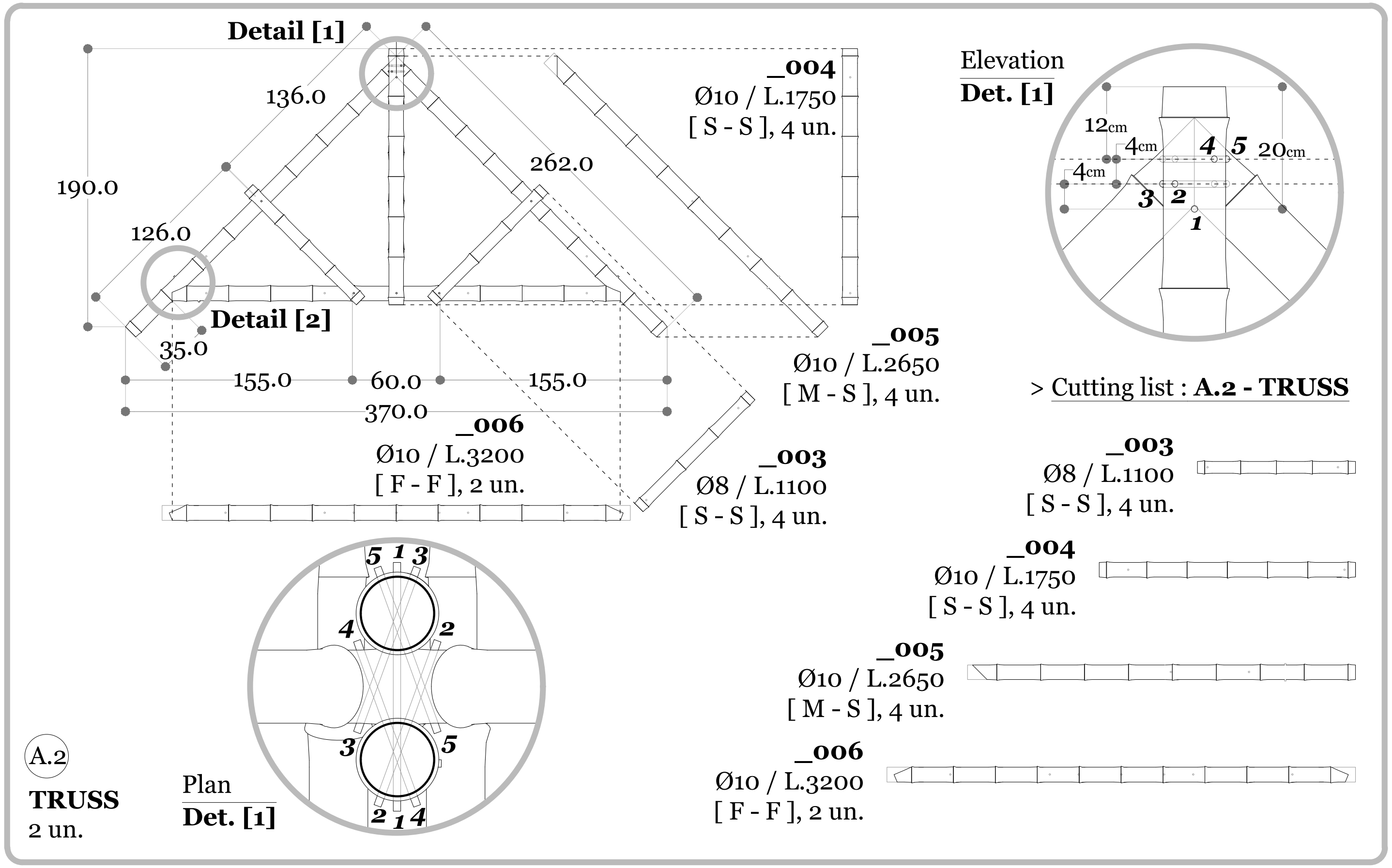
> **Bamboo structural elements:**

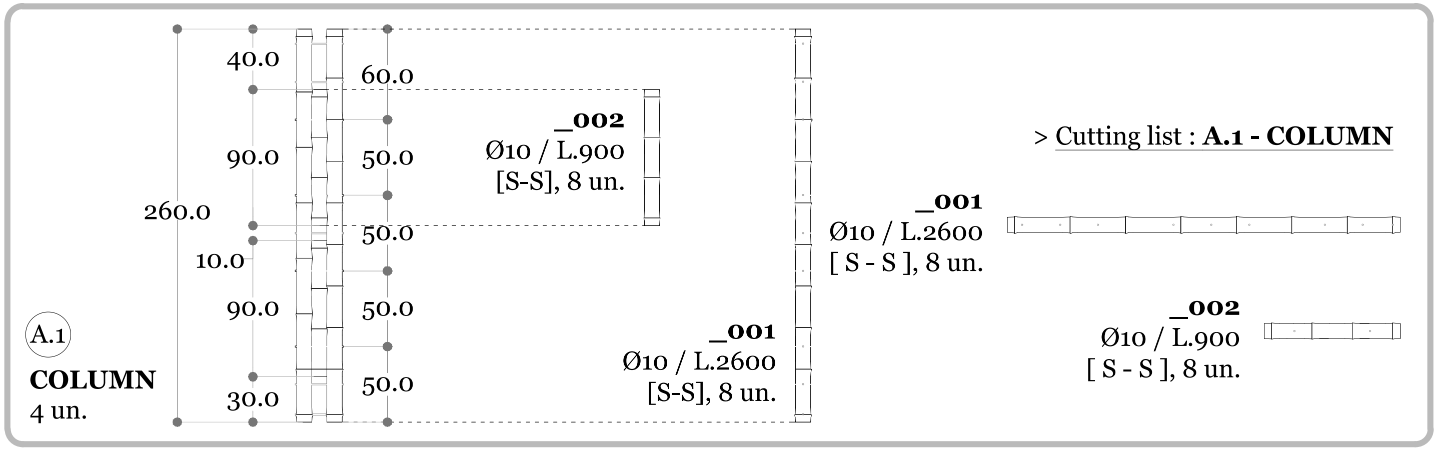
- (A.) Front frame [I-B.08] _ 1 unit
- (A'.) Back frame [I-B.09] _ 1 unit
- (B.) Lateral frames [I-B.10] _ 2 units
- (C.) Horizontal bracing [I-B.13] _ 4 units
- (D.) Vertical bracing [I-B.13] _ 2 units
- (E.) Roof Beams [I-B.13] _ 6 units
- (F.) Floor slab [I-B.11] _ 1 unit

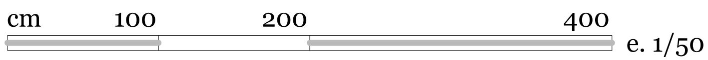


BAMBOO STRUCTURE _I-B.06_

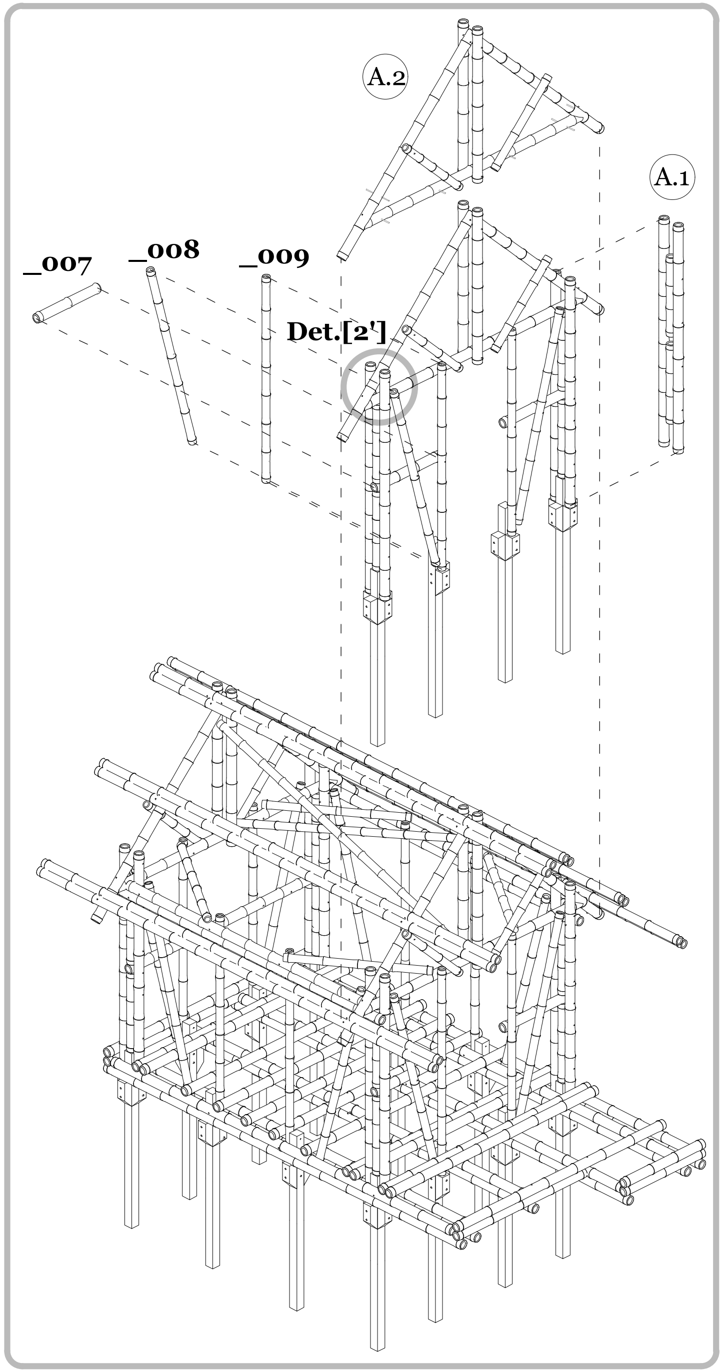


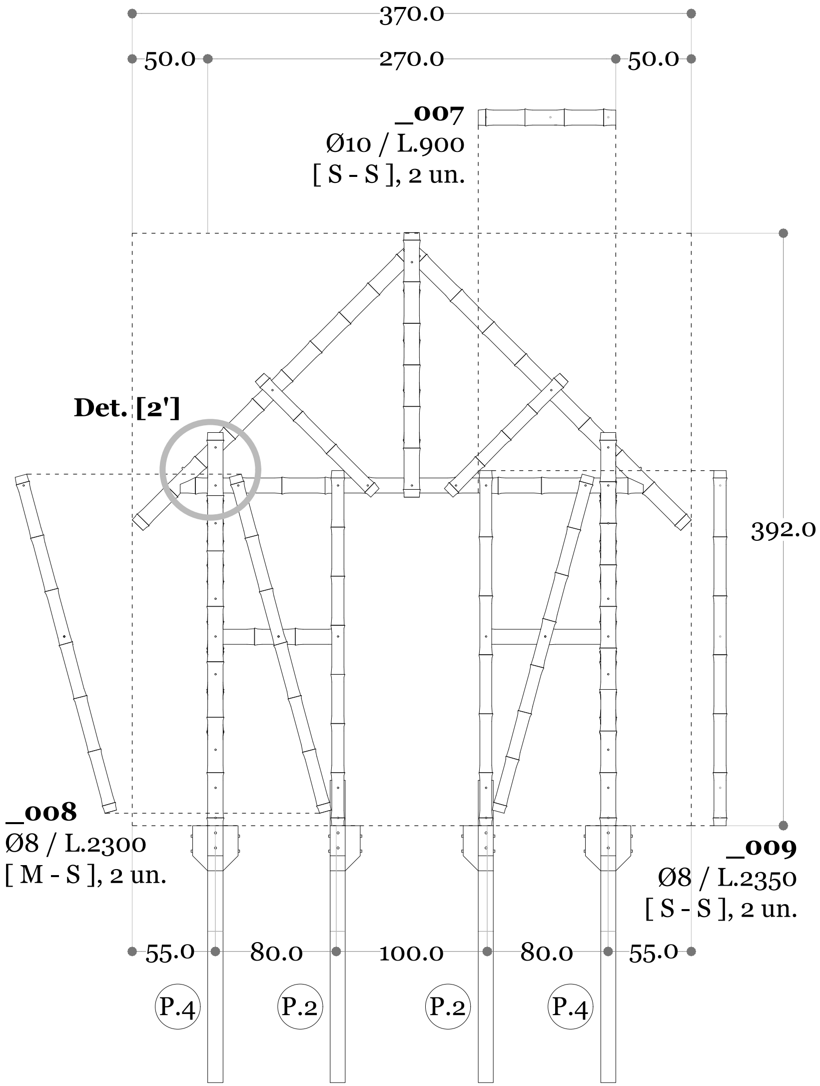






(A.1) COLUMNS, 4 un. / (A.2) TRUSSES, 2 un. **__I-B.07__**

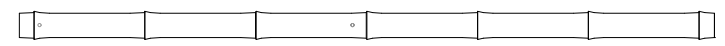




> Cutting list : **(A) FRONT FRAME**

_007
Ø10 / L.900
[S - S], 2 un.

_008
Ø8 / L.2300
[M - S], 2 un.



_009
Ø8 / L.2350
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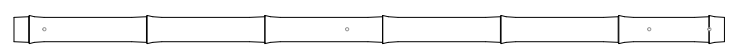
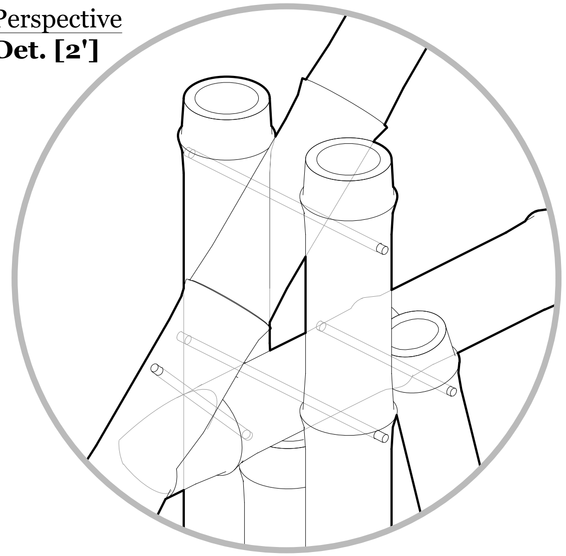
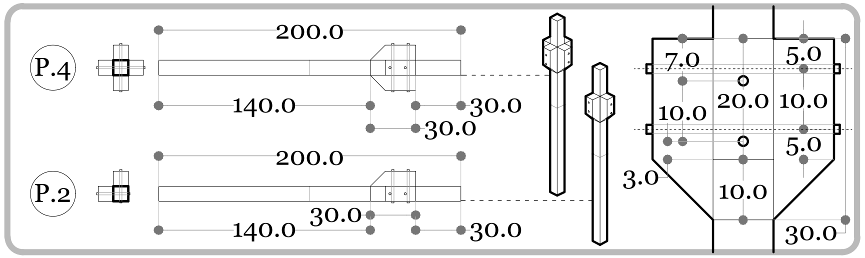


A.1	A.2
COLUMN	**TRUSS**
2 un.	1 un.
[I-B.06]	[I-B.06]

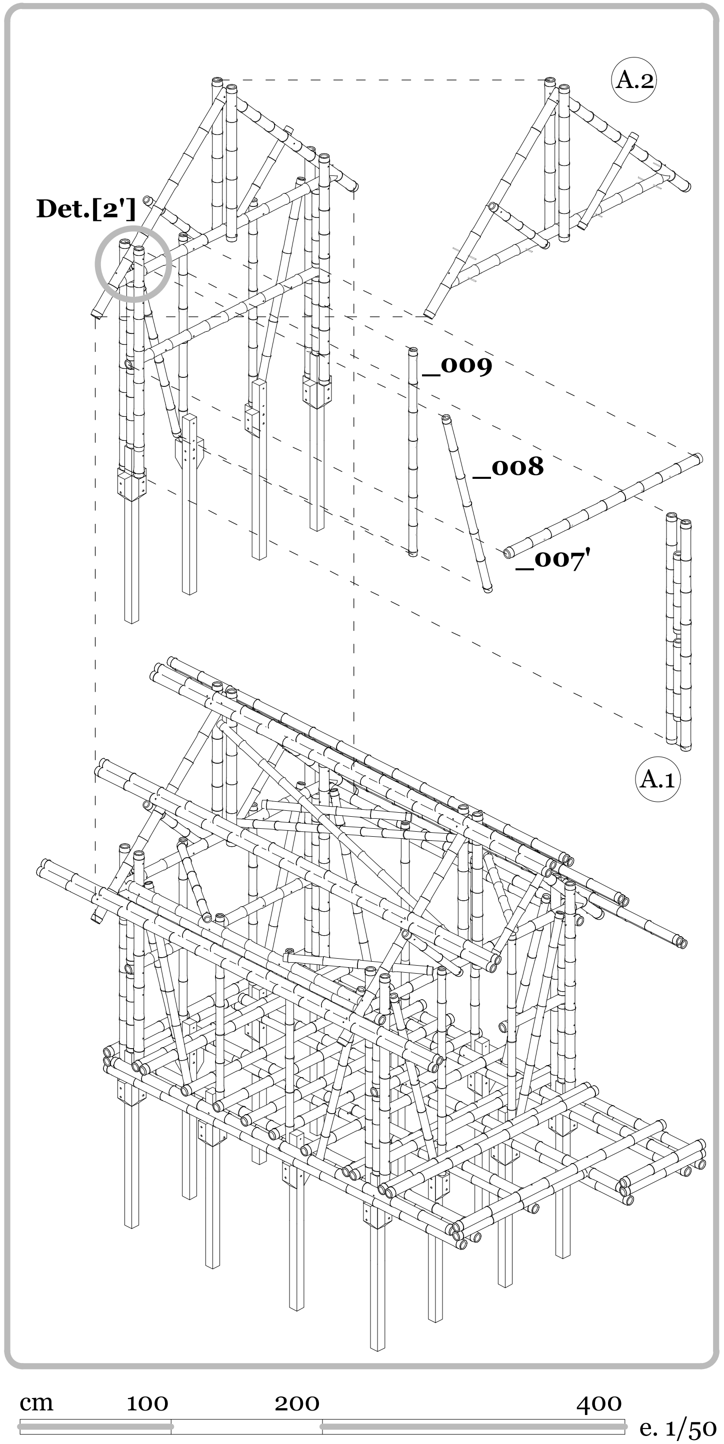
Perspective
Det. [2']

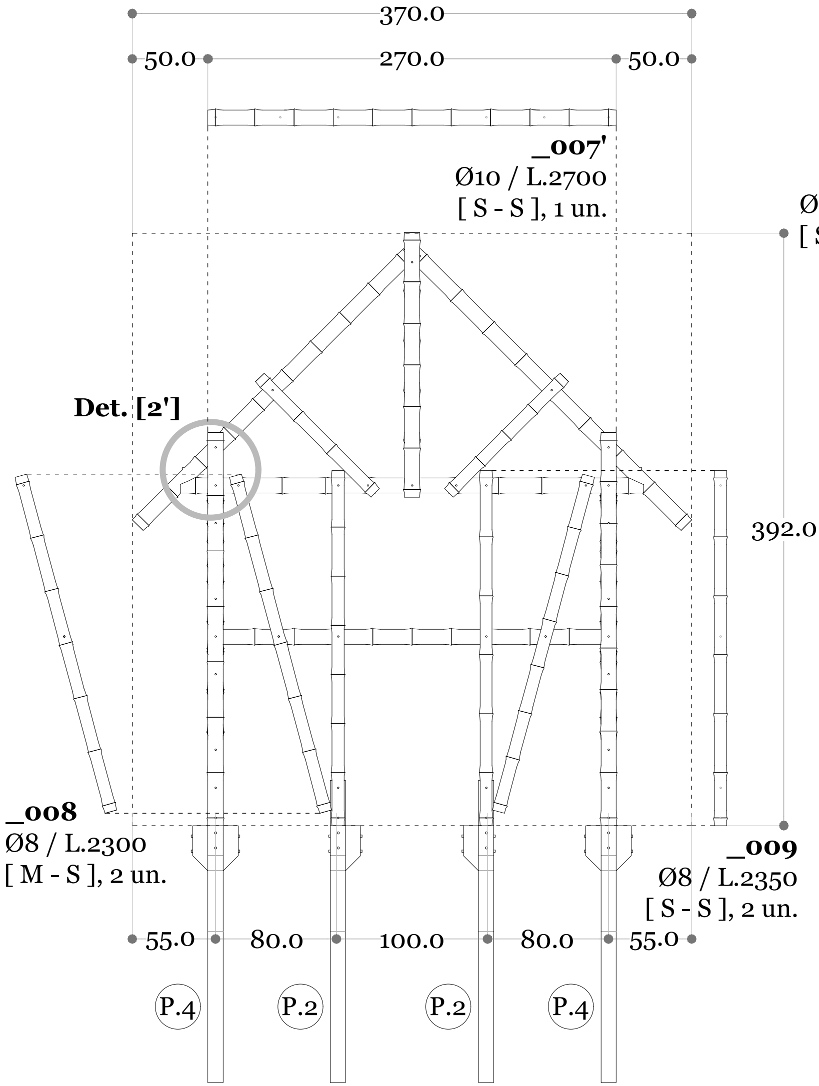




cm 100 200 400
e. 1/50

(A) FRONT FRAME, 1 un. **_I-B.08_**





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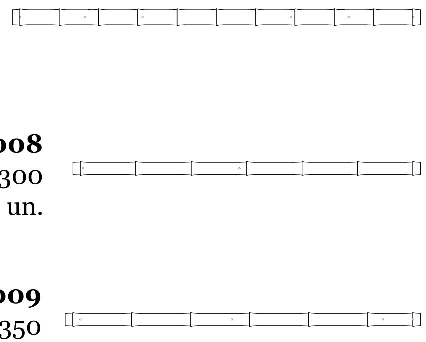
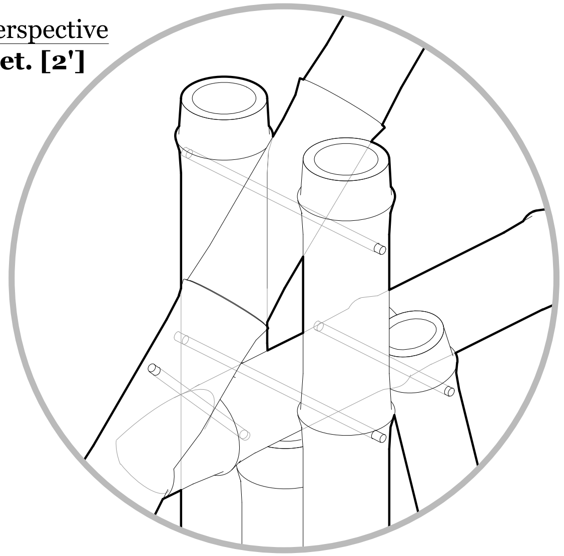
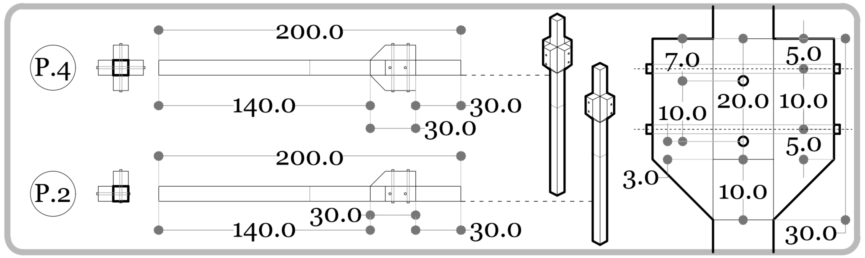


A.1 **COLUMN** 2 un. [I-B.06]

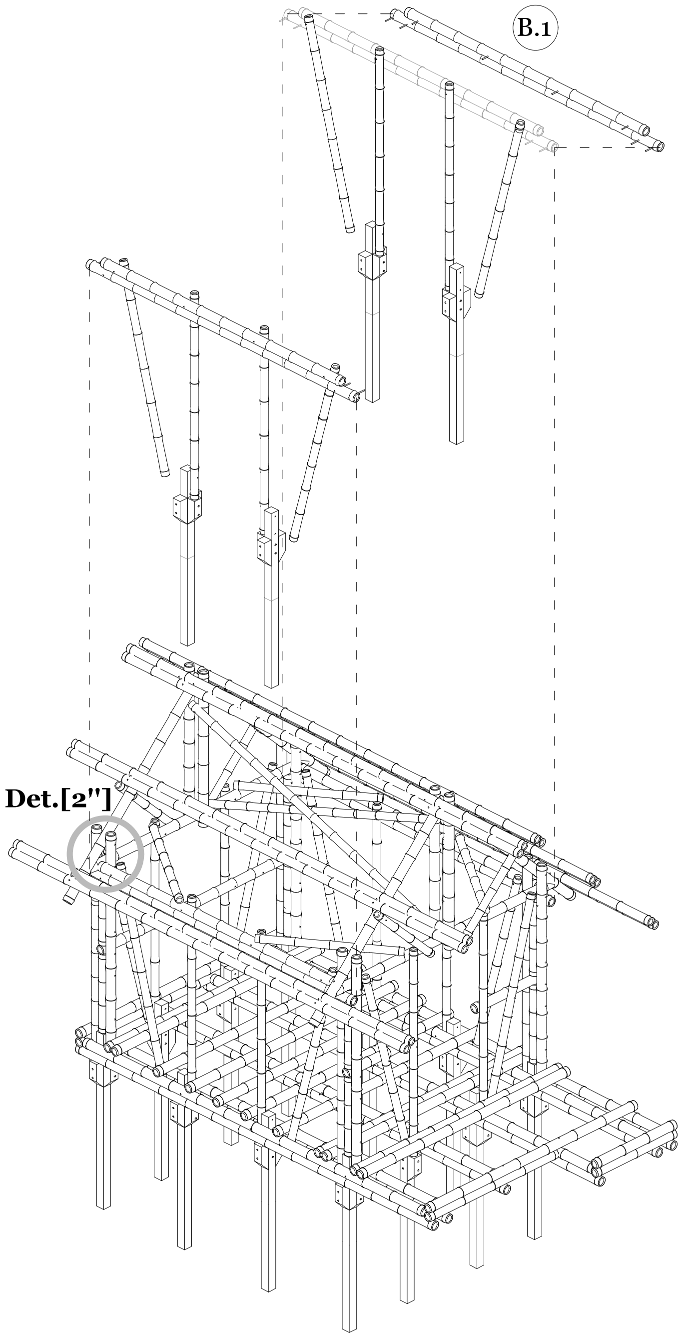
A.2 **TRUSS** 1 un. [I-B.06]

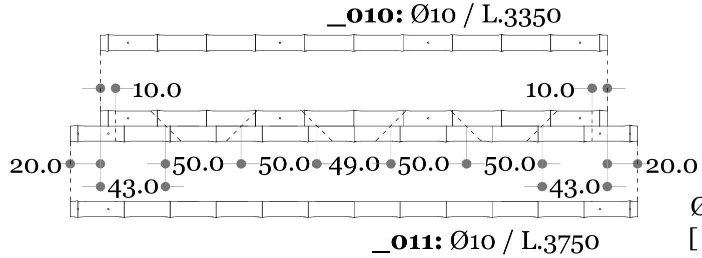
Perspective **Det. [2']**





(A') BACK FRAME, 1 un.



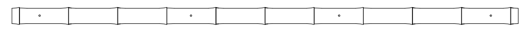


B.1

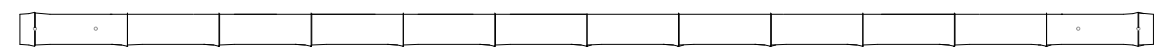
LATERAL BEAM
2 un.

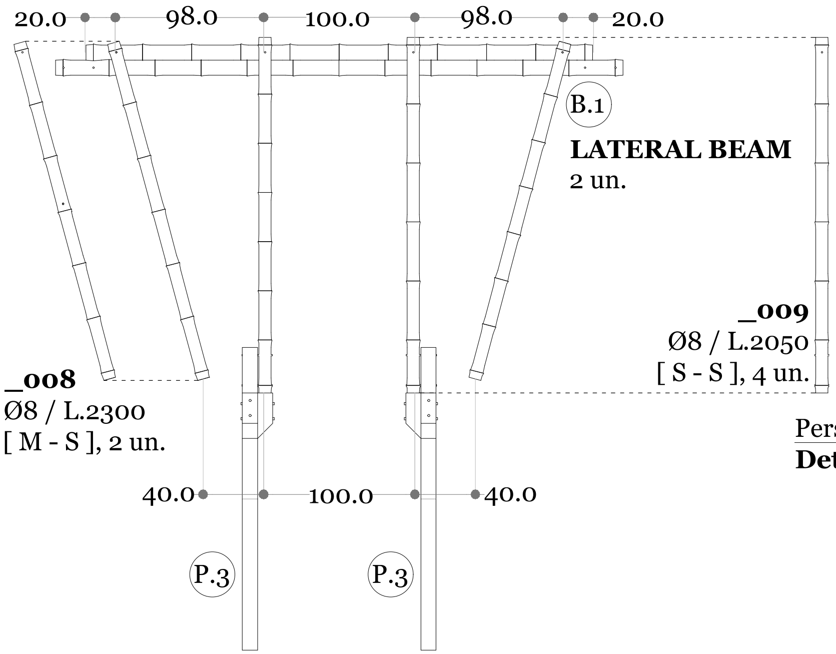
> Cutting list : **B.1 - LATERAL BEAM**

_010
Ø10 / L.3350
[S - S], 2 un.



_011
Ø10 / L.3750
[S - S], 2 un.





LATERAL BEAM
2 un.

_008
Ø8 / L.2300
[M - S], 2 un.

_009
Ø8 / L.2050
[S - S], 4 un.

> Cutting list : **(B) LATERAL BEAM**

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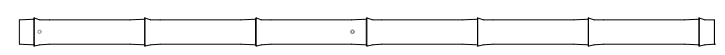
Ø8 / L.2300
[M - S], 4 un.



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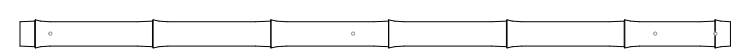
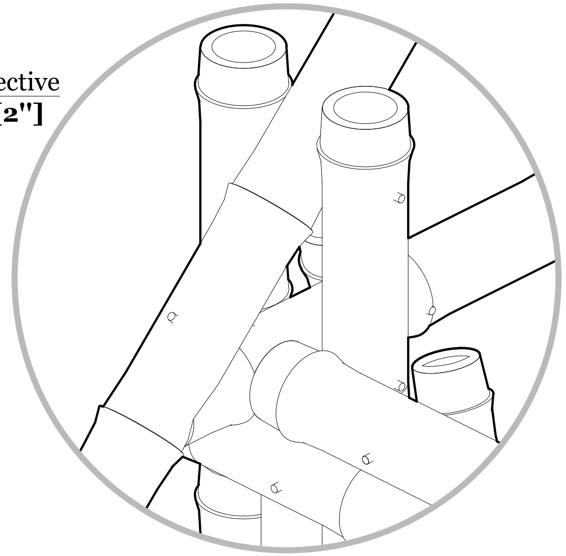
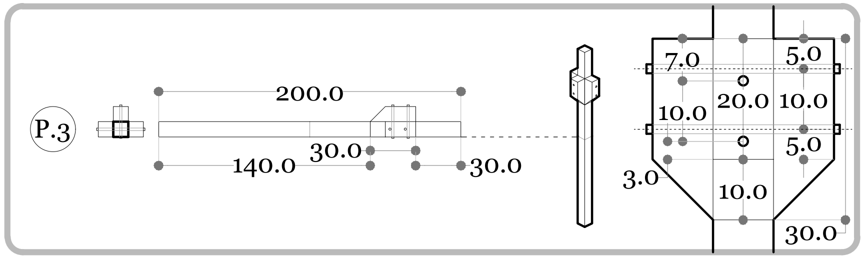
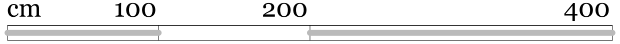


Perspective
Det. [2"]



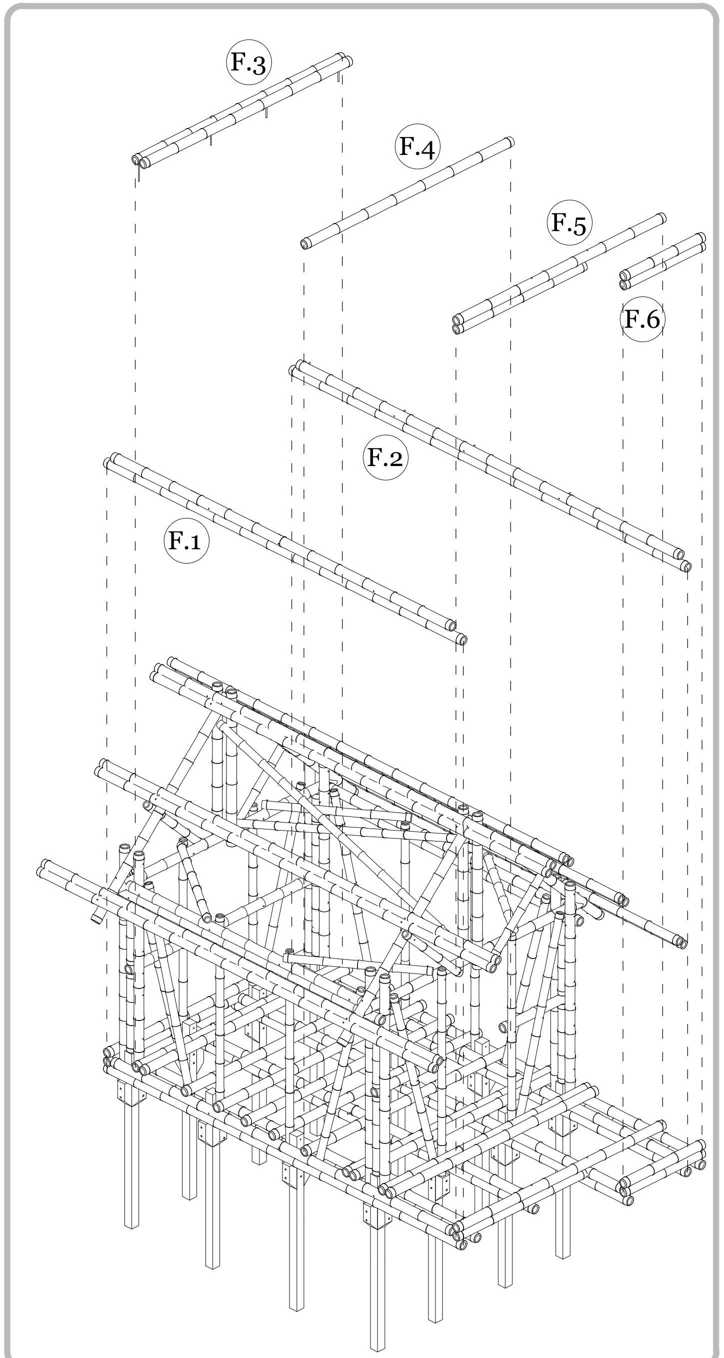


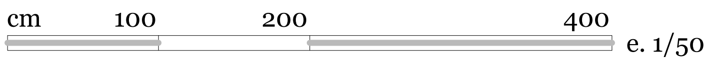


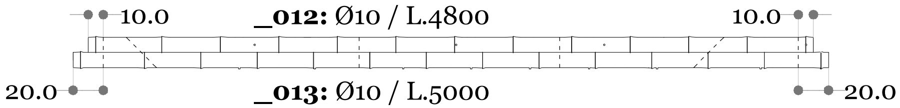
e. 1/50

(B) LATERAL FRAMES, 2 un. **_I-B.10_**

ARCHITECT: **JAIME E. ESPINOSA**







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[VERANDA]

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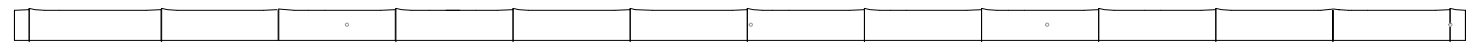
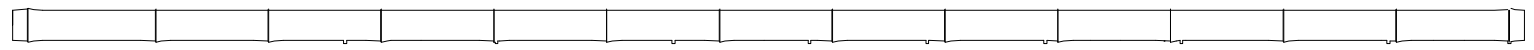
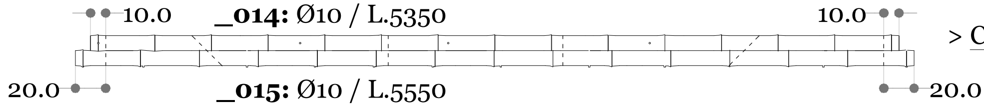


F.1

FLOOR BEAM / VERANDA
3 un.

_013
Ø10 / L.5000
[S - S], 3 un.





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[LANDING]

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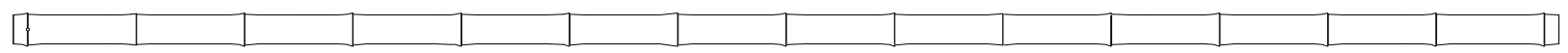
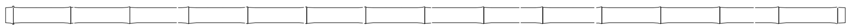
[S - S], 3 un.



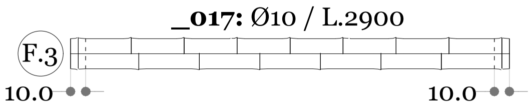
F.2

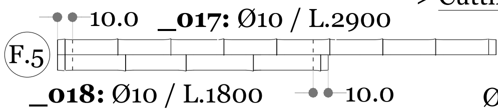
FLOOR BEAM / LANDING
3 un.

_015
Ø10 / L.5550
[S - S], 3 un.



> Cutting list : **FLOOR RAFTERS**
F.3 / F.4 / F.5 / F.6





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Ø10 / L.1100
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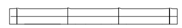
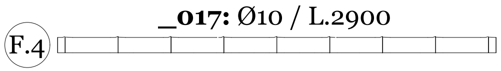
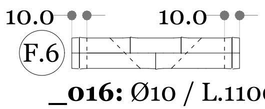




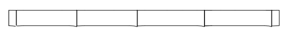
_017
Ø10 / L.2900
[S - S], 14 un.

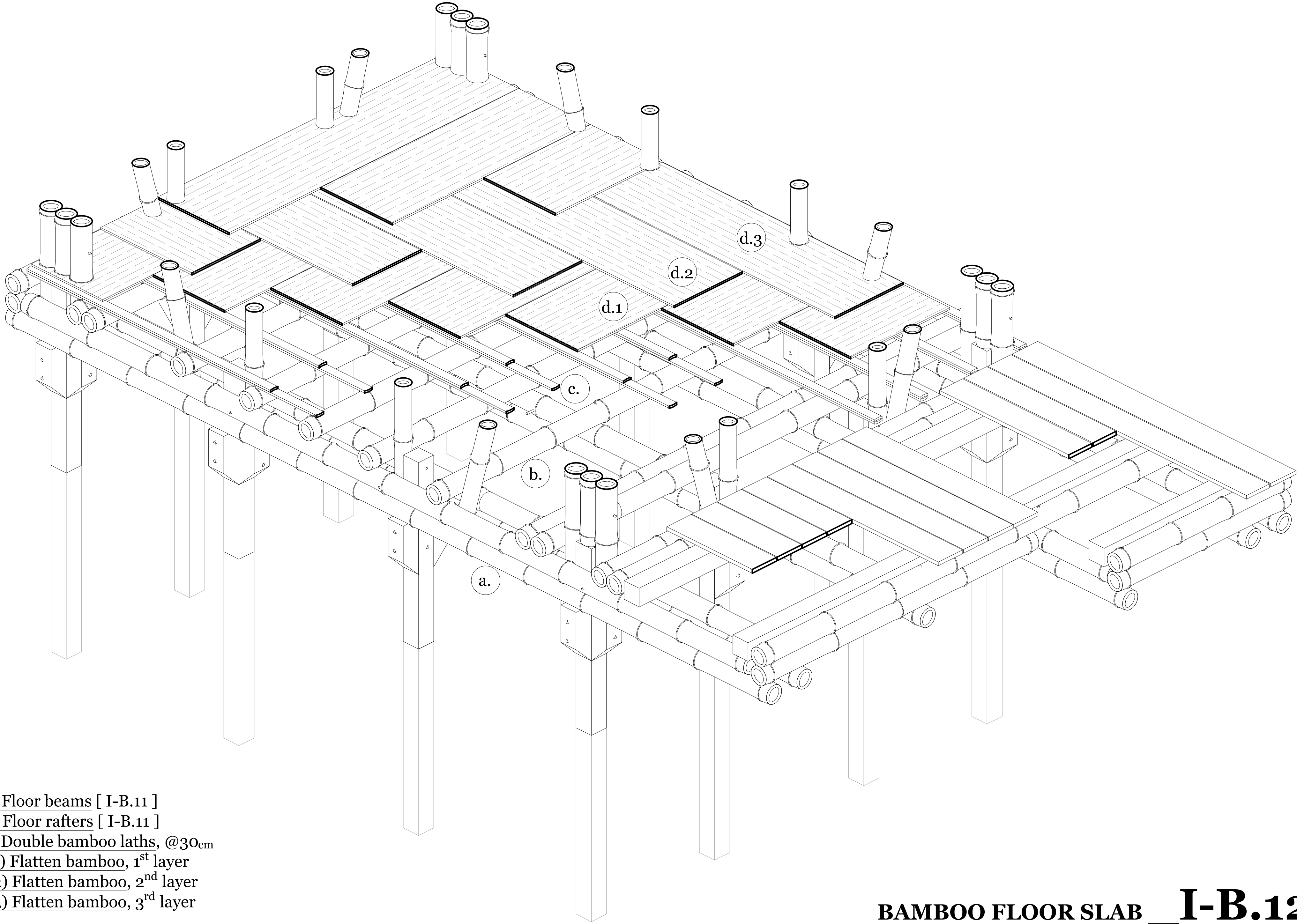
F.3 F.4 F.5 F.6

FLOOR RAFTERS
4 un. / 5 un. / 1 un. / 1 un.



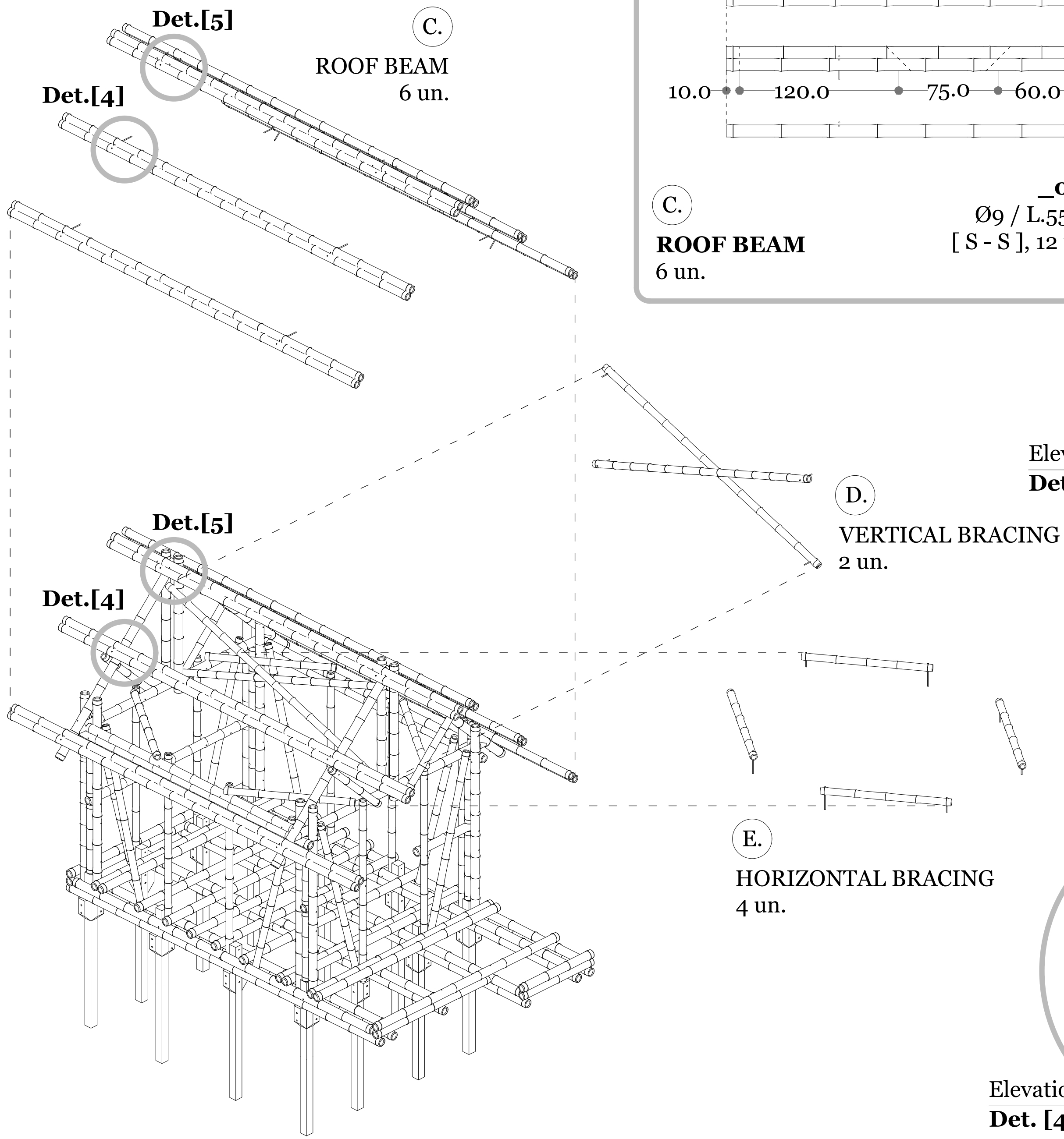
_018
Ø10 / L.1800
[S - S], 1 un.



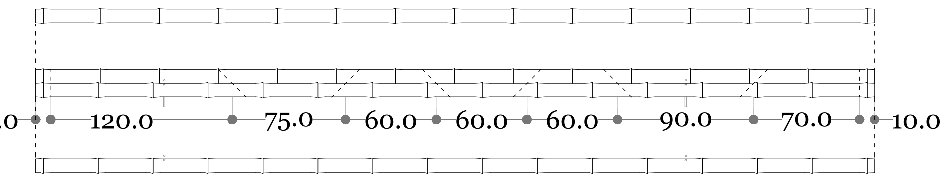


(a.) Floor beams [I-B.11]
(b.) Floor rafters [I-B.11]
(c.) Double bamboo laths, @30cm
(d.1) Flatten bamboo, 1st layer
(d.2) Flatten bamboo, 2nd layer
(d.3) Flatten bamboo, 3rd layer

BAMBOO FLOOR SLAB __I-B.12__



_019: Ø9 / L.5550

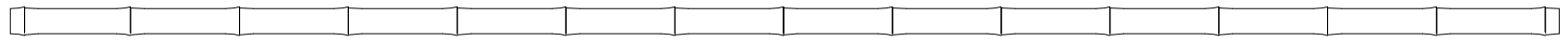


> Cutting list : **C - ROOF BEAM**

C.

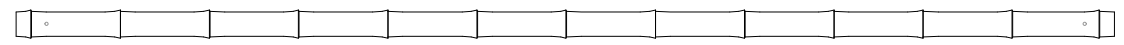
ROOF BEAM
6 un.

_019
Ø9 / L.5550
[S - S], 12 un.



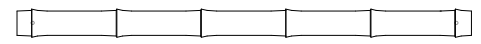
> Cutting list : **D - VERTICAL BRACING**

_020
Ø8 / L.3630
[S - S], 2 un.

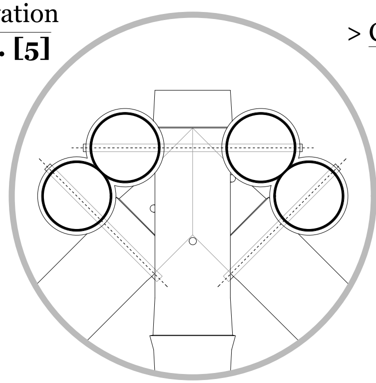


> Cutting list : **E - HORIZONTAL BRACING**

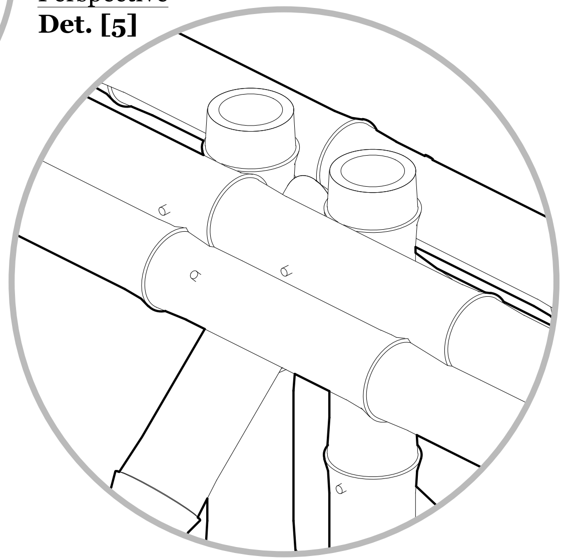
_021
Ø8 / L.1500
[S - S], 4 un.

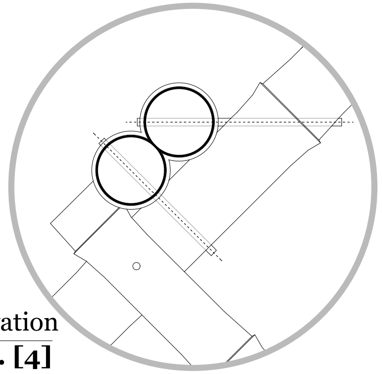


Elevation
Det. [5]



Perspective
Det. [5]





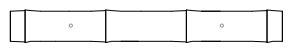
Elevation
Det. [4]

cm 100 200 400 e. 1/50

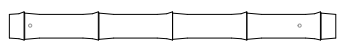
BRACING (vertic., 2 un.; horizont., 4 un.) / ROOF BEAMS, 6 un. **_I-B.13_**

_001
Ø10 / L.2600
[S - S], 8 un.

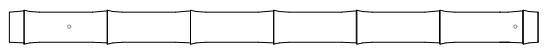
_002
Ø10 / L.900
[S - S], 8 un.



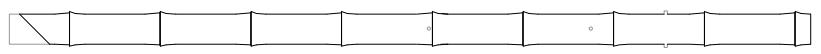
_003
Ø8 / L.1100
[S - S], 4 un.



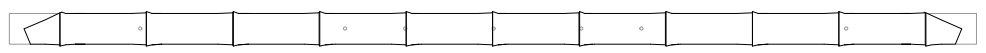
_004
Ø10 / L.1750
[S - S], 4 un.



_005
Ø10 / L.2650
[M - S], 4 un.

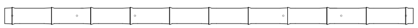


_006
Ø10 / L.3200
[F - F], 2 un.

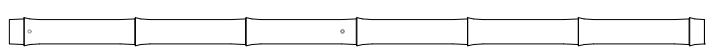


_007
Ø10 / L.900
[S - S], 2 un.

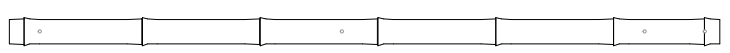
_007'
Ø10 / L.2700
[S - S], 2 un.



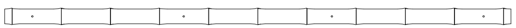
_008
Ø8 / L.2300
[M - S], 8 un.



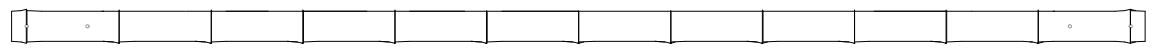
_009
Ø8 / L.2350
[S - S], 8 un.



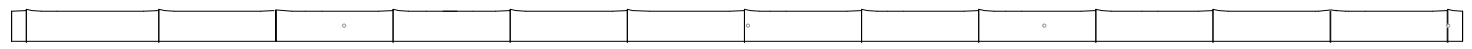
_010
Ø10 / L.3350
[S - S], 2 un.



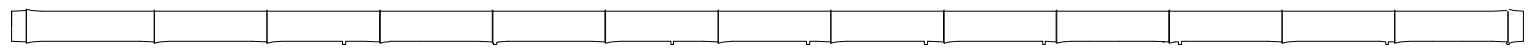
_011
Ø10 / L.3750
[S - S], 2 un.



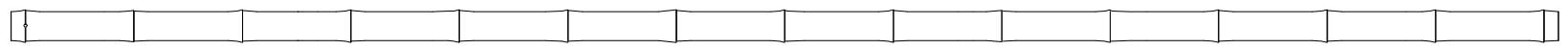
_012
Ø10 / L.4800
[S - S], 3 un.



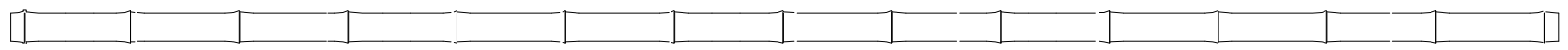
_013
Ø10 / L.5000
[S - S], 3 un.



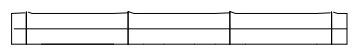
_014
Ø10 / L.5350
[S - S], 3 un.



_015
Ø10 / L.5550
[S - S], 3 un.



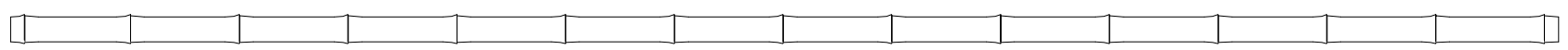
_016
Ø10 / L.1100
[S - S], 2 un.



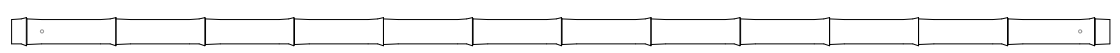
_017
Ø10 / L.2900
[S - S], 14 un.

_018
Ø10 / L.1800
[S - S], 1 un.

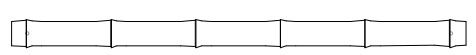
_019
Ø9 / L.5550
[S - S], 12 un.



_020
Ø8 / L.3630
[S - S], 2 un.



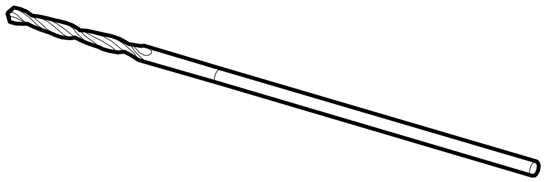
_021
Ø8 / L.1500
[S - S], 4 un.



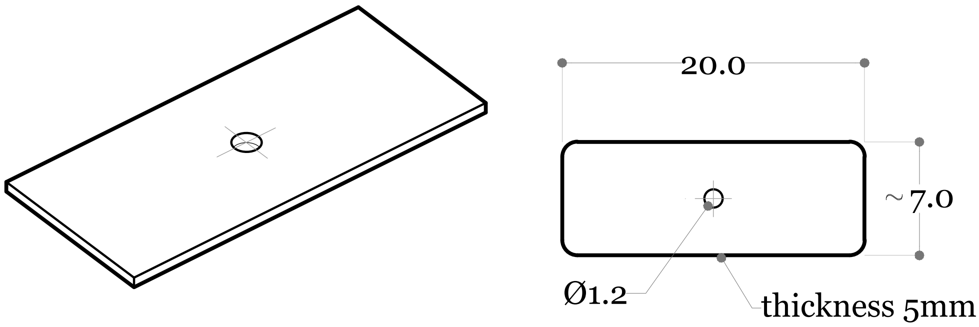
TOOL KIT - (A.) SPECIAL TOOLS

01. ELONGATED DRILL BIT FOR METAL

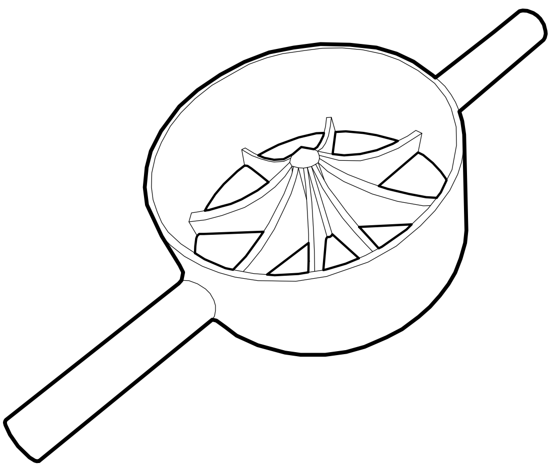
Drill bit for metal, **ø10 mm**, welded to a 25-cm-long, smooth (not-corrugated), steel bar, in order to reach at least **30-cm work length**

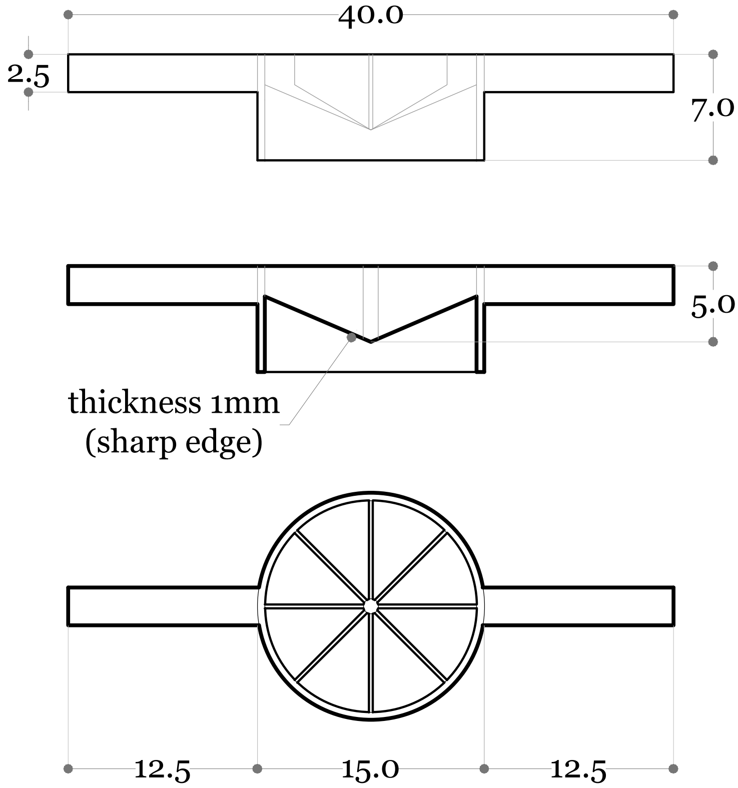


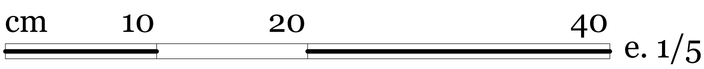
02. PEGS TEMPLATE



03. BAMBOO SPLITTER



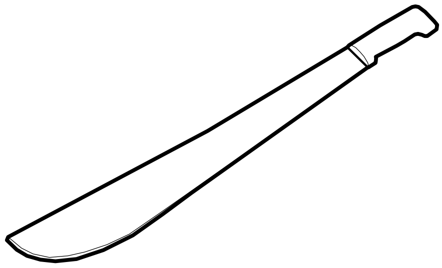




TOOL KIT - (B.) NORMAL TOOLS

At least 1 unit every 4 or 5 trainees.

04. MACHETE

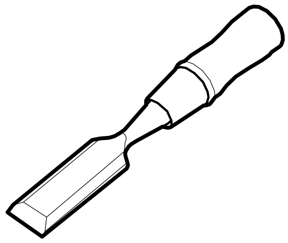


05. KNIFE

Size of the blade: 13 x 3,5 cm / 18 x 4 cm

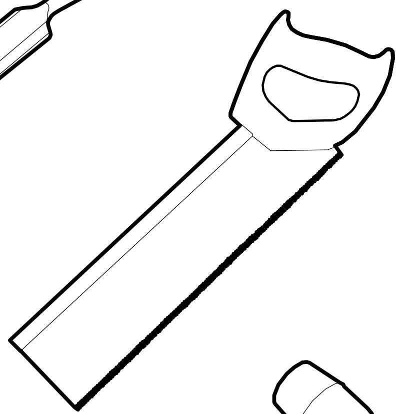
06. CHISEL

1 "



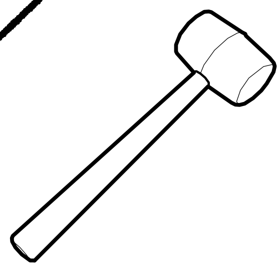
07. HAND SAW

Teeth pitch: 2,3 mm max. / 1,7 mm min.
TPI (teeth per inch): 11 minimun, 15 ideal



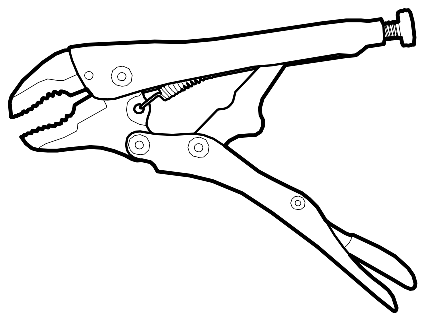
08. RUBBER MALLET

350 - 500 grams



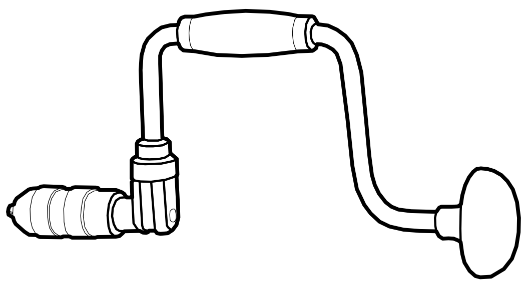
09. LOCKER PLIERS / PRESSURE CLAMP

5 - 7 "



10. MANUAL HAND DRILL

To host **ø10 mm** drill bits (normally 8-13mm)



11. DRILL BIT FOR METAL

Standard drill bits **ø10 mm** for metal

TOOL KIT - (C.) OTHER TOOLS
At least 2 or 3 units per building site.

12. MEASURING TAPE
5 m long or longer

13. SHARPING STONE

14. PLIERS

TOOL KIT - (D.) INDIVIDUAL PROTECTION EQUIPMENT

15. HELMET
Adjustable

16. SAFETY GOGGLES
Adjustable, with side protection

17. GLOVES

18. SAFETY SHOES
With safety toecap

19. SAFETY VEST

TOOL KIT - (E.) BUILDING SITE EQUIPMENT
At least 1 unit per building site.

20. SQUARE

21. PLUMB BOB

22. WHEELBARROW

23. MALLET
To break stones in smaller pieces

24. COMPACTOR

25. SHOVEL

26. PICK and/or HOE

27. LEVEL HOSE
Transparent, ø 0,5 "

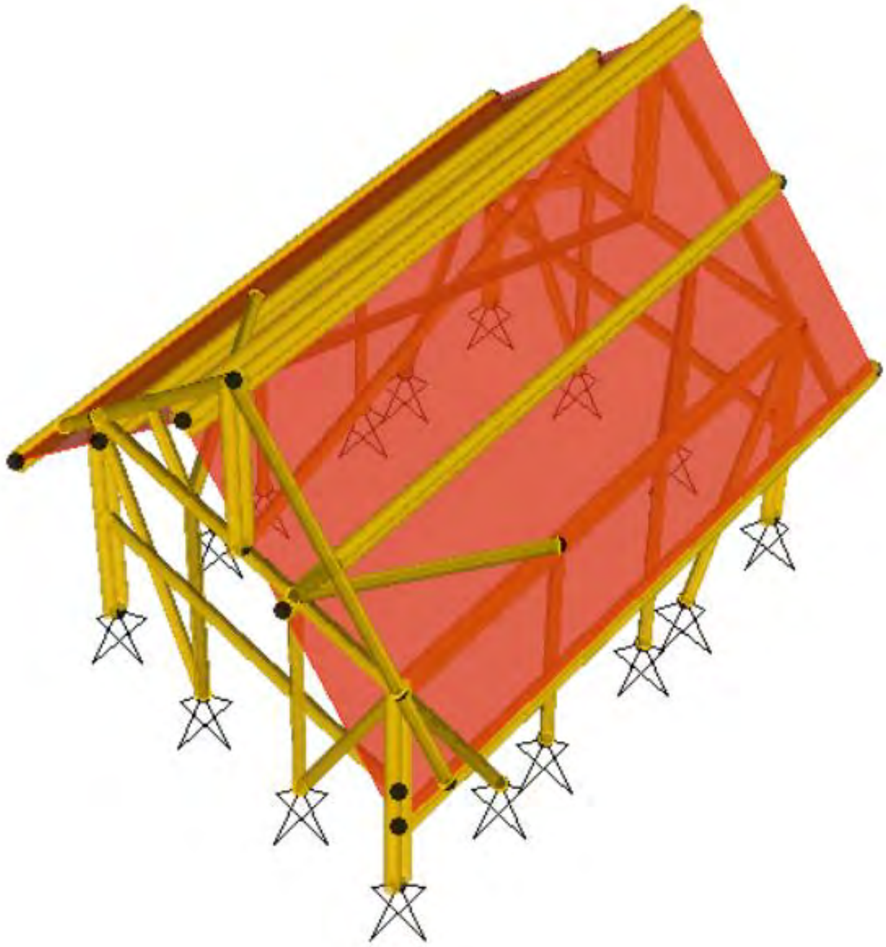
28. LADDER
Highest working height required: 4.25m / Ladder height: 3.60m

Madagascar

North-East of Madagascar

Maroansetra and surroundings

MEMORIA DE CÁLCULO “CASA MADAGASCAR”



PROYECTO : CASA MADAGASCAR.

UBICACIÓN : MADAGASCAR

RESPONSABLE : ING. LUIGI GUEVARA CERVERA – R.C.I.P. 202105

FECHA : ABRIL DE 2025

ÍNDICE

DEFINICIONES

Capacidad de un elemento estructural: Es la máxima fuerza axial, fuerza cortante y momento flector que es capaz de resistir un elemento o componente estructural

Capacidad modificada de diseño: La capacidad de un elemento o componente estructural afectada por los coeficientes de modificación.

Cargas: Fuerzas aplicadas a un elemento o estructura.

Coeficiente de modificación: Son los coeficientes por los cuales se afecta a los esfuerzos admisibles y a los módulos admisibles de elasticidad, para tener en cuenta las condiciones de uso particular de un elemento o componente estructural y así obtener los valores modificados que pueden ser usados en el diseño estructural.

Columna: Elemento cuyo trabajo principal es a compresión:

Columna compuesta: Columna formada a partir de dos o más piezas individuales de bambú, unidas entre sí para funcionar como una sola.

Diafragma: Subsistema estructural encargado de la transmisión y resistencia de las fuerzas horizontales principalmente por acción en su plano. Los diafragmas pueden ser horizontales (entrepisos y cubiertas), verticales (muros de corto) o inclinados (cubiertas).

Entramado: Conjunto de elementos estructurales como vigas y viguetas en entrepisos y cubiertas o como pies derechos en muros, que se encargan de dar soporte al material de revestimiento.

Esfuerzo admisible: Son los esfuerzos de compresión paralela, compresión perpendicular, corte paralelo, flexión, tracción paralela y tracción perpendicular, que resisten los elementos estructurales de bambú.

Mortero: Mezcla de arena, cemento y agua, que es utilizada para llenar los entrenudos en conexiones, también se utiliza para pegar ladrillos y pañetar muros o techos.

Sección: Perfil o figura que resulta de cortar una pieza o cuerpo cualquiera por un plano.

Sección compuesta: Sección formada por la unión de dos o más bambúes.

Sección transversal: Es aquella sección que resulta de cortar un bambú en sentido perpendicular a las fibras

Solicitación: Fuerza interna (axial, cortante, momento flector o tracción) que actúa en una sección determinada de un elemento o componente estructural.

Viga: Pieza cuyo trabajo principal es la flexión.

Viga de sección compuesta: Viga conformada por dos o más bambúes conectados de tal forma que se garantice el trabajo en conjunto.

Vigueta: Pieza cuyo trabajo principal es la flexión, pero que hace parte de un conjunto de elementos que trabajan juntos.

RESUMEN

El presente documento contiene la propuesta estructural para el proyecto denominado “Casa Madagascar”. El análisis y diseño de las estructuras se han realizado de acuerdo a lo establecido en las normas de estructuras peruanas e internacionales vigentes.

“Casa Madagascar” es un módulo de bambú de un solo nivel que tiene un ancho de 2.7 m, largo de 3.8 m y una altura máxima de 3.7 m; está constituido por columnas y vigas bambú, arriostrados con diagonales de bambú. La cubierta está soportada por las vigas de bambú que transmiten las cargas hacia las columnas de bambú, que a su vez transmiten las cargas hacia la cimentación de concreto simple. Las columnas de bambú se conectan a la cimentación a través de acero corrugado cubierto de mortero, lo cual ayuda a rigidizar la unión columna de bambú - cimentación.

1. OBJETIVOS

El presente documento tiene por objeto detallar el modelamiento, análisis y diseño estructural para la construcción de proyecto denominado “Casa Madagascar”.

2. MODELO ESTRUCTURAL

El proyecto “Casa Madagascar”, es módulo de bambú de un solo nivel que tiene un ancho de 2.7 m, largo de 3.8 m y una altura máxima de 3.7 m; según se muestra en la siguiente figura.

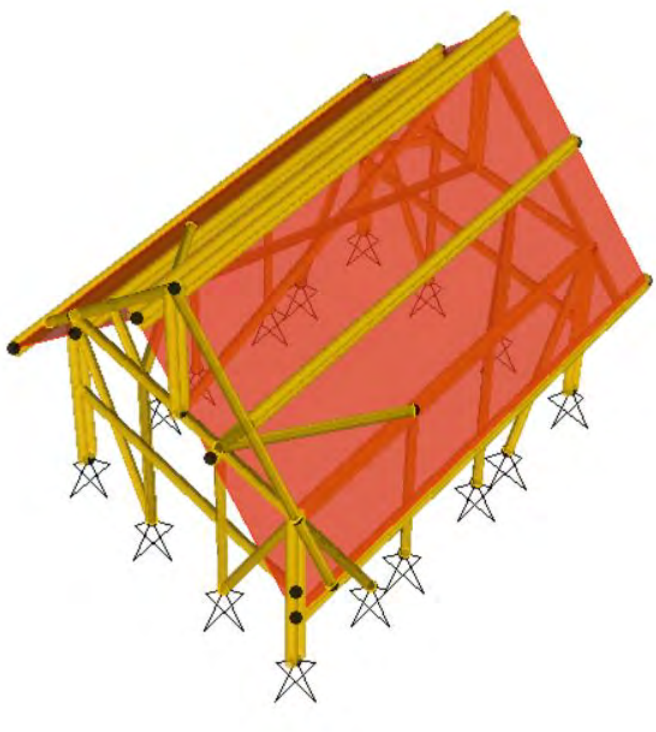


Figura 1: Modelo 3D SAP2000.

El modelo estructural del proyecto “Casa Madagascar” se elaboró en el programa SAP2000 v22.1.0, considerando materiales isotrópicos con comportamiento de deformación de tipo lineal. Los elementos de bambú como columnas, vigas y diagonales, se modelaron a base de elementos "frame[1]" (analizados como elementos articulados). Las columnas se consideraron como elementos apoyados[2] en la cimentación.

2.1. MATERIALES

Para la implementación del modelo estructural se utilizaron las propiedades del bambú[3] que se muestran en la siguiente tabla:

Tabla 1: Propiedades del bambú.

Propiedades del bambú	
Esfuerzo admisible a la flexión (f_m)	150.00 kgf/cm²
Esfuerzo admisible a la tracción (f_t)	180.00 kgf/cm²
Esfuerzo admisible a la compresión paralela (f_c)	140.00 kgf/cm²
Esfuerzo admisible a la compresión perpendicular (f_{cp})	14.00 kgf/cm²
Esfuerzo admisible al corte (f_v)	12.00 kgf/cm²
Módulo de elasticidad promedio 0.5 ($E_{pro0.5}$)	95000 kgf/cm²
Módulo de elasticidad promedio 0.05 ($E_{pro0.05}$)	75000 kgf/cm²
Módulo de elasticidad mínimo (E_{min})	73000 kgf/cm²
Coeficiente de Poisson (ν)	0.35
Módulo de Corte (G)	27777.78 kgf/cm²
Peso específico (γ_c)	900 kgf/m³

Las propiedades del bambú han sido extraídas de la NSR-10[4] Capítulo G.12 – Estructuras de guadua (numeral G.12.7.3 – Esfuerzos admisibles y Módulos de Elasticidad), salvo el E_{min} que corresponde a la Norma E.100[5] Bambú del Reglamento Nacional de Edificaciones (RNE) (numeral 8.5 Módulo de Elasticidad).

2.2. SECCIONES

Para el modelamiento de la estructura de "Casa Madagascar" se han planteado las secciones[6], que se muestran en las figuras y tablas siguientes:

---

[1] El elemento Frame utiliza una formulación viga-columna general, tridimensional que incluye los efectos de flexión, torsión, la deformación axial y deformación por corte.
[2] No se permite la translación en ninguno de sus tres ejes, pero si se admite rotación en cualquiera de ellos.
[3] Se utilizará la especie *Dendrocalamus Giganteus.*
[4] Norma colombiana
[5] Norma peruana
[6] Dichas secciones han sido verificadas luego mediante el diseño estructural.

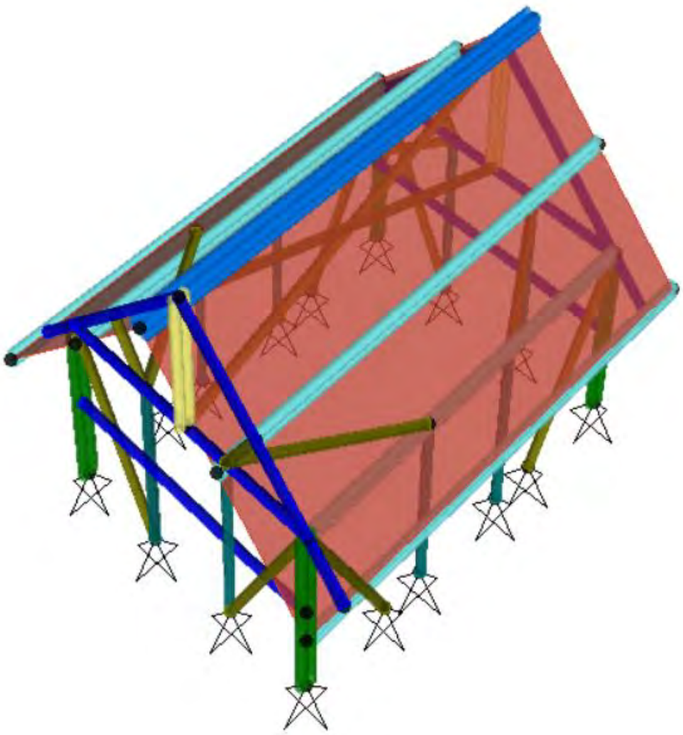


Figura 2: Vista 3D **“Casa Madagascar”** (Secciones)

Tabla 2: Secciones de Bambú

Nomenclatura	Bambúes	Elemento	Diámetro (cm)	Espesor (cm)	Color
C1	1	COLUMNA	10	1.2	
C2	2	COLUMNA	10	1.2	
V1	1	VIGA	10	1.2	
V2	2	VIGA	10	1.2	
V4	4	VIGA	10	1.2	
D1	1	DIAGONAL	10	1.2	
D2	2	DIAGONAL	10	1.2	

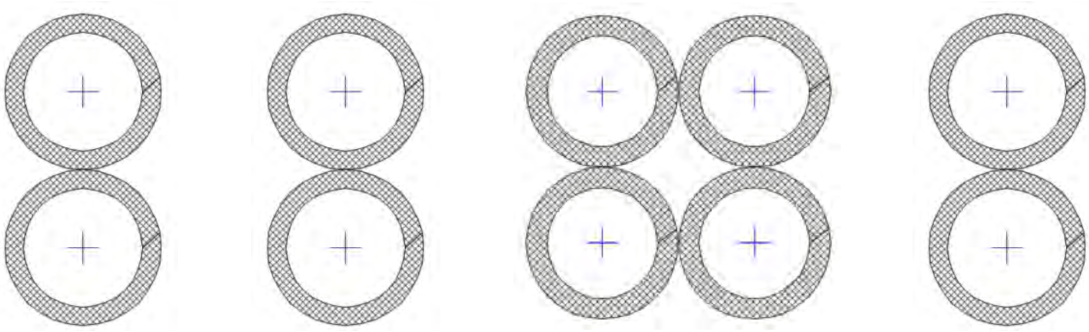


Figura 3: Secciones bambú

Tabla 3: Propiedades de Secciones de Bambú

Sección	D (cm)	t (cm)	A (cm^2)	I_x (cm^4)	r_x (cm)	S_x (cm^3)	I_y (cm^4)	r_y (cm)	S_y (cm^3)
C1	10.00	1.20	33.18	327.11	3.14	65.42	327.11	3.14	65.42
C2	10.00	1.20	66.35	2312.98	5.90	231.30	654.22	3.14	130.84
V1	10.00	1.20	33.18	327.11	3.14	65.42	327.11	3.14	65.42
V2	10.00	1.20	66.35	2312.98	5.90	231.30	654.22	3.14	130.84
V4	10.00	1.20	132.70	4625.95	5.90	462.60	4625.95	5.90	462.60
D1	10.00	1.20	33.18	327.11	3.14	65.42	327.11	3.14	65.42
D2	10.00	1.20	66.35	2312.98	5.90	231.30	654.22	3.14	130.84

2.3. CARGAS PERMANENETES

Las cargas gravitacionales permanentes que se considera para el análisis de la estructura comprenden a la carga debido al peso propio de la estructura (DEAD), la sobrecarga debido al peso propio de los elementos no estructurales (SC). Además, se considera la carga viva (LIVE) de acuerdo a lo estipulado en la Norma E.020[7] Cargas del RNE, el resumen de las cargas[8] ingresadas al modelo se muestra a continuación:

Tabla 4: Cargas gravitacionales

Nivel	SC (D) (kgf/m^2)	LIVE (L) (kgf/m^2)
Primer nivel	30	30

Para cubierta de la estructura, se ha establecido un peso propio máximo de 30 kgf/m^2. Por otro lado, el Artículo 7 "Carga viva del techo" de la Norma E.020 Cargas del RNE, establece: *"d) Para techos con coberturas livianas de planchas onduladas o plegadas, calaminas, fibrocemento, material plástico, etc., cualquiera sea su pendiente, 0,30 kPa (30 kgf/m^2)".*

2.4. MASA SÍSMICA

Para el cálculo de las masas sísmicas se deben considerar las cargas permanentes más un porcentaje de la sobrecarga de uso, que no puede ser inferior a 25 % en construcciones destinadas a la habitación privada o al uso público donde no es usual la aglomeración de personas o cosas, ni a un 50% en construcciones en que es usual esa aglomeración.

En nuestro caso se está considerando las cargas permanentes más 25% de la sobrecarga de uso (DEAD+SC+0.25LIVE).

2.5. CARGAS DE VIENTO

Los elementos exteriores expuestos a la acción del viento, serán diseñados para resistir las cargas (presiones y succiones) exteriores e interiores debidos al viento, suponiendo que éste actúa en dos direcciones horizontales perpendiculares entre sí. En la estructura la ocurrencia de presiones y succiones exteriores serán consideradas simultáneamente.

De acuerdo a la Norma E.020 Cargas del RNE, la edificación en estudio se clasifica como Tipo 1. Edificaciones poco sensibles a las ráfagas y a los efectos dinámicos del viento, tales como edificios de poca altura o esbeltez y edificaciones cerradas con cobertura capaz de soportar las cargas sin variar su geometría, para este caso la velocidad de diseño del viento hasta 10 m de altura será la velocidad máxima

[7] Norma peruana.
[8] Las cargas se han ingresado sobre la cubierta del primer nivel tanto para SC, como para LIVE.

adecuada a la zona de ubicación de la edificación, se asumirá un valor de 250 km/h (según velocidades registradas en Madagascar).

La velocidad de diseño del viento en cada altura de la edificación mayor a 10 m se obtendrá de la siguiente expresión.

$$V_h = V\left(\frac{h}{10}\right)^{0.22}$$

Donde:
$V_h =$ velocidad de diseño en la altura h en km/h.
$V =$ velocidad de diseño hasta 10 m de altura en km/h
$h =$ altura sobre el terreno en metros

En ese sentido la carga exterior del viento (presión o succión) se supondrá estática y perpendicular a la superficie sobre la cual actúa. Se calculará mediante la siguiente expresión:

$$P_h = 0.005CV_h^2$$

Donde:
$P_h =$ presión o succión del viento a una altura h en kgf/m^2.
$C =$ factor de forma adimensional indicado.
$V_h =$ velocidad de diseño en la altura h en km/h

Tabla 5: Factores de Forma (C)

Construcción	Barlovento	Sotavento
Superficies verticales de edificios	+0,8	-0,6
Anuncios, muros aislados, elementos con una dimensión corta en la dirección del viento	+1,5	
Tanques de agua, chimeneas y otros de sección circular o elíptica	+0,7	
Tanques de agua, chimeneas, y otros de sección cuadrada o rectangular	+2,0	
Arcos y cubiertas cilíndricas con un ángulo de inclinación que no exceda 45°	+0,8	-0,5
Superficies inclinadas a 15° o menos	+0,3-0,7	-0,6
Superficies inclinadas entre 15° y 60°	+0,7-0,3	-0,6
Superficies inclinadas entre 60° y la vertical	+0,8	-0,6
Superficies verticales ó inclinadas (planas ó curvas) paralelas a la dirección del viento	-0,7	-0,7
* El signo positivo indica presión y el negativo succión.		

En el caso del módulo en estudio, se considera un factor de forma de +0.7 para Barlovento y de -0.6 para Sotavento, para lo cuales se presenta las siguientes cargas de viento:

Tabla 6: Cargas de Viento

Estructura	Altura máxima (m)	$\boldsymbol{V_h}$ (km/h)	$\boldsymbol{P_h}$(kgf/m^2) Barlovento	$\boldsymbol{P_h}$ (kgf/m^2) Sotavento
Casa Madagascar	3.70	250.00	218.75	-187.50

3. ANÁLISIS SÍSMICO Y DE VIENTO

3.1. ESPECTRO SÍSMICO

Para el análisis sísmico se determinó la aceleración espectral definida por:

$$S_a = \frac{ZUCS}{R} g$$

Donde:
$Z =$ factor de zona, es la aceleración máxima horizontal en el suelo con una probabilidad de 10% de excedencia en 50 años.
$U =$ factor de uso o importancia, definido por la categoría de las edificaciones
$C =$ factor de amplificación sísmica, de acuerdo a las características del sitio.
$S =$ factor de suelo
$R =$ coeficiente de reducción de las fuerzas sísmicas.
$g =$ aceleración de la gravedad

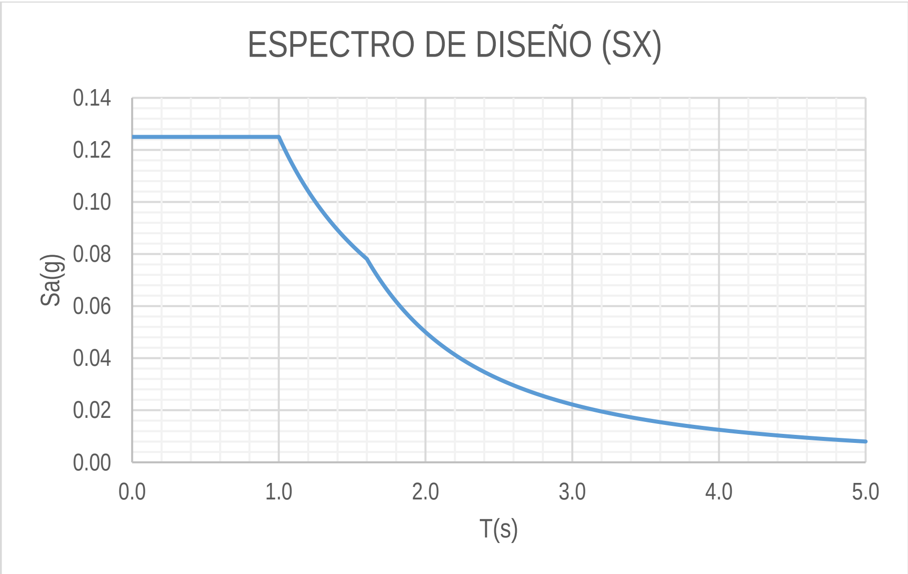
Los parámetros para el espectro de diseño[9] de la estructura se muestran en la siguiente tabla:

Tabla 7: Parámetros para el espectro de diseño.

Parámetro	Factor/Coeficiente
Factor de zona (Z)	0.25
Factor de uso (U)	1.00
Factor de amplificación sísmica (C)	2.50
Factor de suelo (S)	2.00
Coeficiente de reducción de fuerzas sísmicas (R[10])	7

El factor Z, corresponde a una zonificación 2 (Sismicidad baja); el factor U corresponde a una edificación común, cuya falla no acarrea peligros adicionales de incendios o fugas de contaminantes; el factor S corresponde a un tipo de suelo S3, de donde se obtiene que T_P =1.0 segundos, y T_L =1.6 segundos; el factor C corresponde a los valores de T_P y T_L señalados. y el factor R es igual a 7.

Luego se obtiene el siguiente espectro para ambas direcciones:



[9] El espectro de diseño se ha construido de acuerdo a lo indicado en la Norma E.030 Diseño Sismorresistente del RNE (Norma Peruana).
[10] El sistema de estructural de bambú, no está contemplado en la Norma E.030 Diseño Sismorresistente, por lo que se utiliza un valor R =7, correspondiente al sistema estructura de madera que al igual que el bambú se diseña por esfuerzos admisibles. Es importante mencionar que se considera una estructura regular.

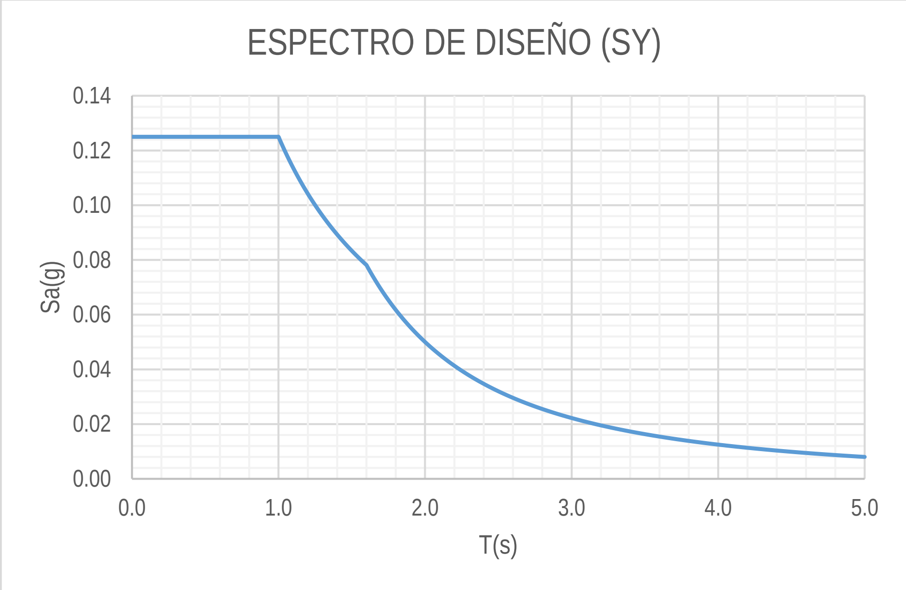


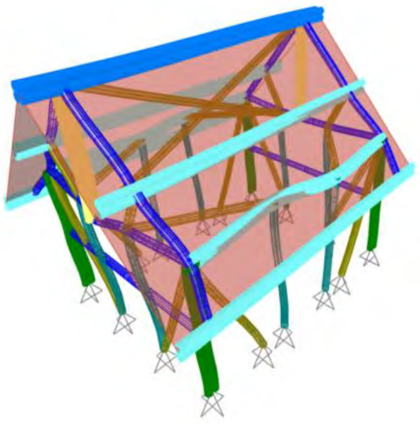
Figura 4: Espectros de diseño SX y SY

3.2. MODOS Y PERIODOS

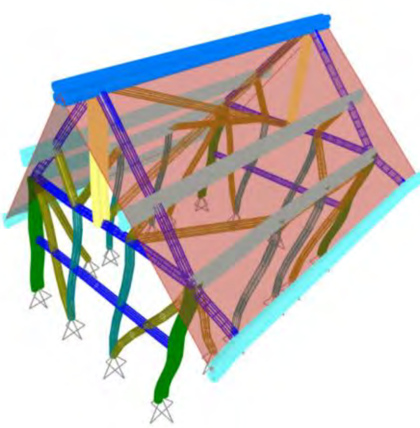
Se realizó el análisis modal usando un caso de Modal-Eigen Vectors en SAP2000, en cada dirección se consideran aquellos modos de vibración cuya suma de masas efectivas sea por lo menos el 90% de la masa total, pero se toma en cuenta por lo menos los tres primeros modos predominantes en la dirección de análisis, para nuestro caso se obtuvo las respuestas correspondientes a los 6 primeros modos, el detalle de los periodos y las masas modales principales para cada uno de los modelos se muestra en la tabla siguiente:

Tabla 8: Periodos y masas modales.

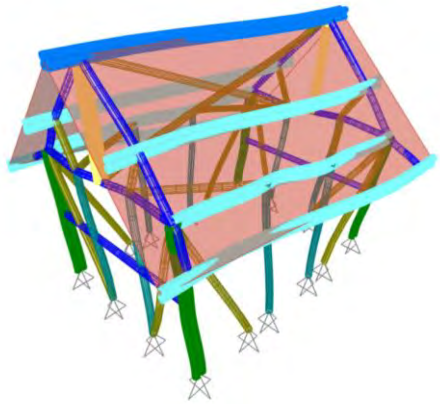
Modo	Periodo (seg)	UX (%)	UY (%)	RZ (%)	**∑UX (%)**	**∑UY (%)**	**∑RZ (%)**
1	0.133	91.40%	0.00%	0.00%	91.40%	0.00%	0.00%
2	0.131	0.00%	97.90%	0.00%	91.40%	97.90%	0.00%
3	0.112	0.00%	0.00%	72.70%	91.40%	97.90%	72.70%
4	0.091	0.00%	0.00%	21.00%	91.40%	97.90%	93.70%
5	0.084	3.40%	0.00%	0.00%	94.70%	97.90%	93.70%
6	0.081	0.00%	0.00%	0.00%	94.70%	97.90%	93.70%



Modo 1



Modo 2



Modo 3

Figura 5: Formas modales.

El periodo principal es 0.133 s, con una forma modal predominantemente traslacional en X.

3.3. DESPLAZAMIENTOS POR VIENTO

Los desplazamientos máximos por viento se muestran en la tabla siguiente:

Tabla 9: Distorsiones por viento (W)

Joint	X (m)	Y (m)	Z (m)	H (m)	Desp. X (m)	Desp. Y (m)	Desp. Z (m)	**Δ/H**	Estado (<0.010)
90	4.20	3.15	1.63	1.63	0.000000	0.001849	0.001091	0.001131	OK
91	-0.40	3.15	1.63	1.63	0.000000	0.001849	0.001091	0.001131	OK

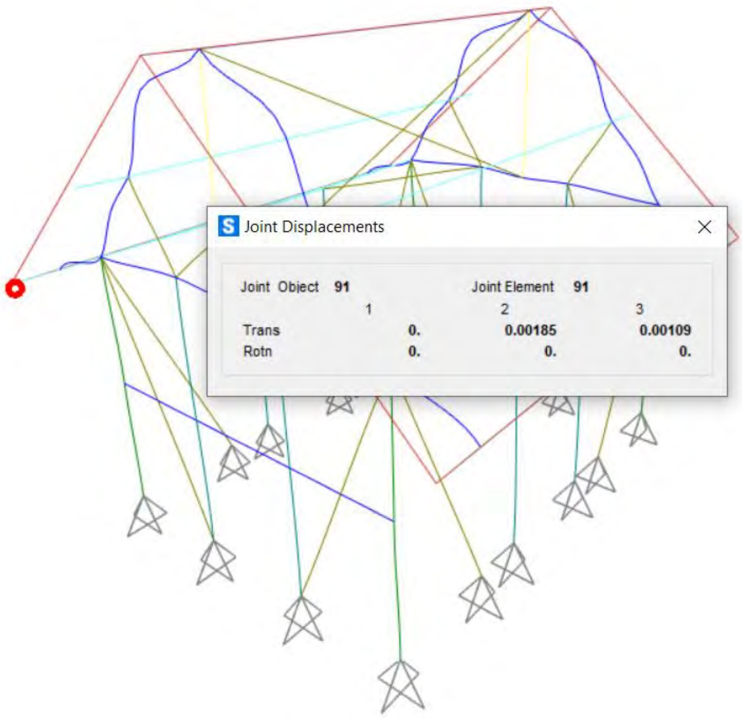


Figura 6: Nodos con mayores distorsiones por viento (W).

Las distorsiones por cargas de viento son más mayores en el sentido Y (0.001131), las cuales se presentan en los puntos extremos de la cubierta, y no exceden en ningún caso el valor límite de 0.01 (1% de la altura del piso) establecido en la Norma E.020 Cargas del RNE.

3.4. FUERZAS POR VIENTO

Las fuerzas por viento (Barlovento y Sotavento) aplicadas en las superficies de la estructura se muestran a continuación:

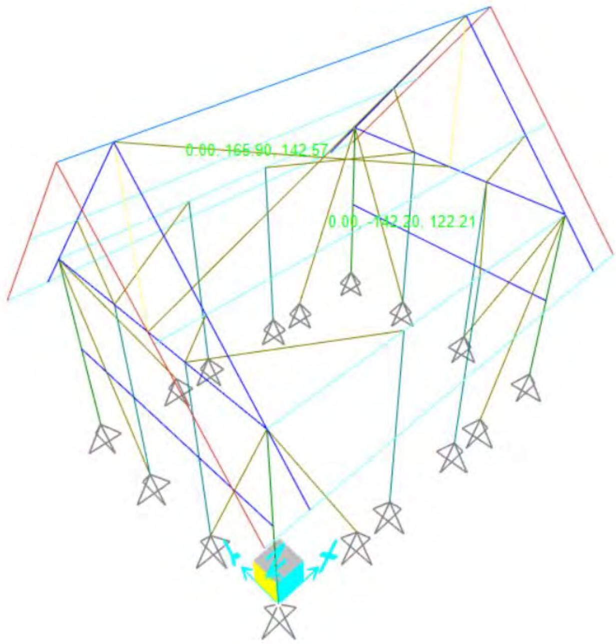


Figura 7: Fuerzas por viento (W).

Se observa que las fuerzas calculadas en la tabla 6, se han descompuesto en fuerzas en los ejes Y – Z

Tabla 10: Descomposición de fuerzas por viento (W)

Tipo	P_h(kgf/m^2)	Fy	**Fz**
Barlovento	218.75	165.90	142.57
Sotavento	-187.50	-142.20	122.21

Es de precisar que las fuerzas de viento, generan reacciones en los puntos de cimentación (apoyos), según se muestra

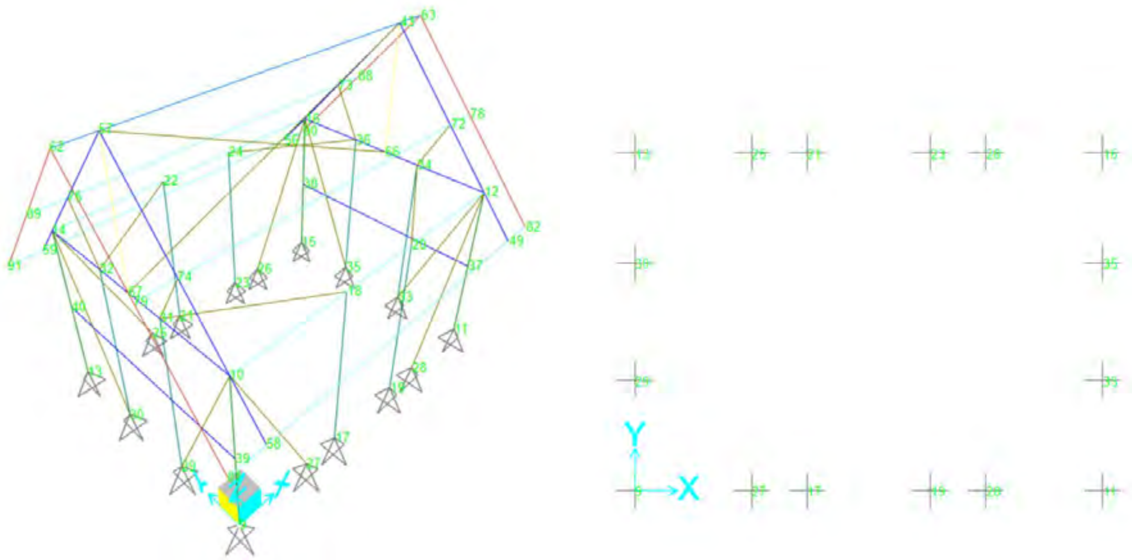


Figura 8: Puntos de cimentación (apoyos) de la estructura.

Tabla 11: Reacciones por fuerzas por viento (W)

TABLE: Joint Reactions								
Joint	OutputCase	CaseType	F1	F2	F3	M1	M2	M3
Text	Text	Text	Kgf	Kgf	Kgf	Kgf-cm	Kgf-cm	Kgf-cm
9	W	LinStatic	4.43	130.9	1044.95	0	0	0
11	W	LinStatic	-4.43	130.9	1044.95	0	0	0
13	W	LinStatic	-5.91	130.49	-1388.09	0	0	0
15	W	LinStatic	5.91	130.49	-1388.09	0	0	0
17	W	LinStatic	0.04301	16.7	27.41	0	0	0
19	W	LinStatic	-0.04301	16.7	27.41	0	0	0
21	W	LinStatic	-0.05782	16.11	-40.83	0	0	0
23	W	LinStatic	0.05782	16.11	-40.83	0	0	0
25	W	LinStatic	222.87	12.34	-494.45	0	0	0
26	W	LinStatic	-222.87	12.34	-494.45	0	0	0
27	W	LinStatic	-167.8	13.11	372.28	0	0	0
28	W	LinStatic	167.8	13.11	372.28	0	0	0
29	W	LinStatic	0.35	787.59	-2082.27	0	0	0
30	W	LinStatic	-0.42	674.21	1030.06	0	0	0
33	W	LinStatic	-0.35	787.59	-2082.27	0	0	0
35	W	LinStatic	0.42	674.21	1030.06	0	0	0
Total			0	3562.90	-3061.88	0	0	0

Se observa que la sumatoria de las reacciones por fuerzas de viento en el eje X es 0 kg, en el eje Y es de 3562.90 kg y en el eje Z es de -3061.88 kg; asimismo, no se presentan momentos en los apoyos.

De otro lado, el peso de la cimentación considerando concreto y terreno es:

$$Peso\ cimentación\ =\ Peso\ de\ concreto\ +\ Peso\ de\ terreno$$

$$Peso\ cimentación\ = (3.8*2*0.3*0.6+2.15*2*0.3*0.6)*2300\ +\ (3.2*2.15*0.6)*1600 = 4926.6+6604.8$$

$$Peso\ cimentación\ = 11531.4\ kg$$

En ese sentido, las fuerzas del viento son menores que el peso de la cimentación, por lo que no se espera que ocurra volteo de la estructura por las acciones del viento.

3.5. DESPLAZAMIENTOS SÍSMICO

El máximo desplazamiento relativo de entrepiso, calculado según el artículo 31 de la Norma E.030 Diseño Sismorresistente[11], no excede la fracción de la altura de entrepiso (distorsión) que se indica en la tabla siguiente:

Tabla 12: Limites para distorsión de entrepiso.

Material Predominante	$\boldsymbol{\Delta/h}$
Concreto Armado	0.007
Acero	0.010
Albañilería	0.005

[11] Aprobada mediante Resolución Ministerial N° 355-2018-VIVIENDA de 23.10.2018.

Material Predominante	Δ/h
Madera	0.010
Edificios de concreto armado con muros de ductilidad limitada	0.005

El sistema estructural de bambú, no está contemplado en la Norma E.030 Diseño Sismorresistente, por lo que se utiliza un valor $\Delta/h = 0.010$, correspondiente al sistema estructural de madera que al igual que el bambú se diseña por esfuerzos admisibles. Para estructuras regulares, los desplazamientos laterales se calculan multiplicando por 0,75 R los resultados obtenidos del análisis lineal y elástico con las solicitaciones sísmicas reducidas. El detalle se muestra a continuación:

Tabla 13: Distorsiones sísmicas en X.

Joint	X (m)	Y (m)	Z (m)	H (m)	Desp. Relativo Elástico (m)	Desp. Relativo Inelástico (m)	**Δ** (m)	**Δ/H**	Estado (<0.010)
58	0.00	-0.40	1.63	1.63	0.000441	0.002315	0.002315	0.001416	OK
59	0.00	3.15	1.63	1.63	0.000441	0.002315	0.002315	0.001416	OK
90	4.20	3.15	1.63	1.63	0.000442	0.002321	0.002321	0.001420	OK
91	-0.40	3.15	1.63	1.63	0.000442	0.002321	0.002321	0.001420	OK

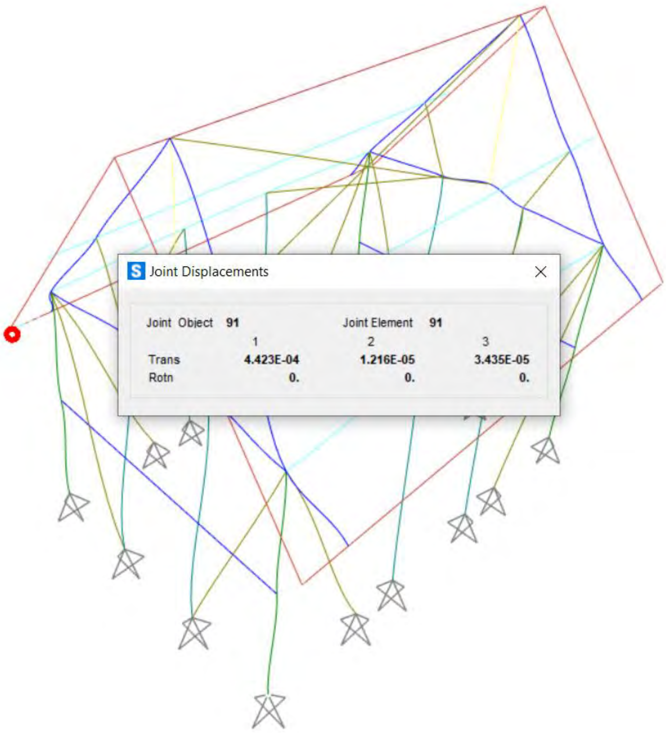


Figura 9: Nodos con mayores distorsiones sísmicas X.

Tabla 14: Distorsiones sísmicas en Y.

Joint	X (m)	Y (m)	Z (m)	H (m)	Desp. Relativo Elástico (m)	Desp. Relativo Inelástico (m)	**Δ** (m)	**Δ/H**	Estado (<0.010)
81	-0.40	-0.40	1.63	1.63	0.000591	0.003103	0.003103	0.001898	OK
82	4.20	-0.40	1.63	1.63	0.000591	0.003103	0.003103	0.001898	OK
90	4.20	3.15	1.63	1.63	0.000591	0.003103	0.003103	0.001898	OK
91	-0.40	3.15	1.63	1.63	0.000591	0.003103	0.003103	0.001898	OK

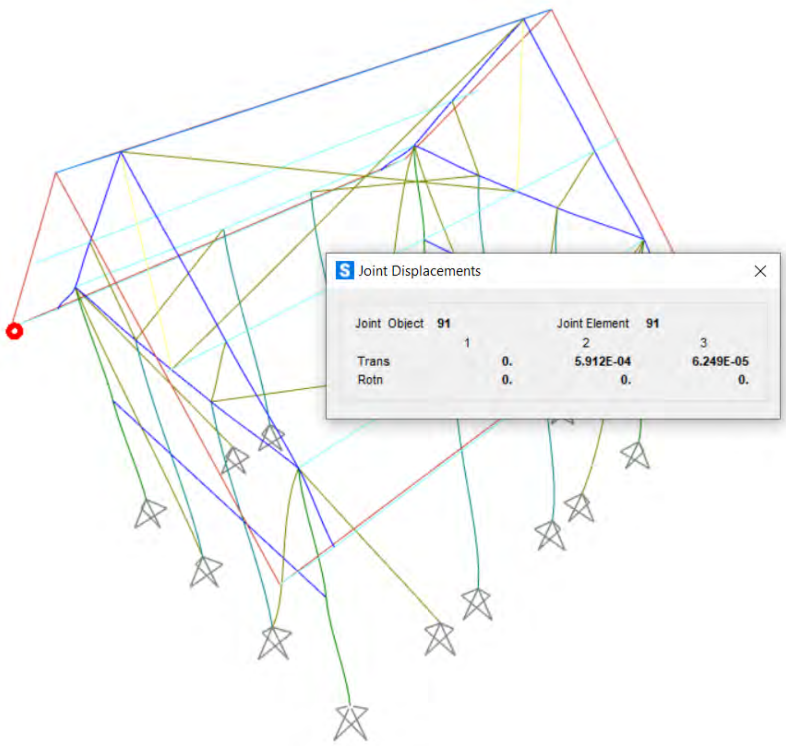


Figura 10: Nodos con mayores distorsiones sísmicas Y.

Las distorsiones sísmicas son más altas en el sentido Y (0.001898) que en el sentido X (0.001420), las cuales se presentan en los puntos extremos de la cubierta, y no exceden en ningún caso el valor límite de Δ/h= 0.010 establecido en la Norma E.030 Diseño Sismorresistente del RNE.

Es preciso indicar que, se han calculado las distorsiones considerando los apoyos a nivel del cimiento, dado que este es muy rígido, y sus desplazamientos son despreciables en relación a la estructura de bambú; esto permite obtener valores de masa efectivas de por lo menos el 90% de la masa total, y por tanto resultados más confiables.

4. DISEÑO

4.1. DISEÑO POR ESFUERZOS ADMISIBLES

Para el diseño de los elementos estructurales, los esfuerzos admisibles han sido modificados por los coeficientes de modificación establecidos en la Norma E.100 Bambú (numeral 8.4 Esfuerzos admisibles), de acuerdo al caso en diseño, según se muestra:

$$f_i' = f_i C_D C_L C_T$$

Donde:
f_i' = esfuerzo admisible modificado.
f_i = esfuerzo admisible de solicitación i.
C_D = coeficiente de modificación por duración de cargas.
C_L = coeficiente de modificación por estabilidad de vigas.
C_T = coeficiente de modificación por distribución de esfuerzos.

Para el diseño se han utilizado los siguientes valores admisibles modificados:

Tabla 15: Propiedades modificadas del bambú[12].

Propiedad	Coeficiente/Esfuerzo
C_D	1.00
C_L	0.95
C_T	1.10
Esfuerzo admisible a la flexión (f'_m)	156.75 kgf/cm^2
Esfuerzo admisible a la tracción (f'_t)	198.00 kgf/cm^2
Esfuerzo admisible a la compresión paralela (f'_c)	154.00 kgf/cm^2
Esfuerzo admisible a la compresión perpendicular (f'_{cp})	15.40 kgf/cm^2
Esfuerzo admisible al corte (f'_v)	13.20 kgf/cm^2

Además, los esfuerzos actuantes de momento flector, fuerza axial, entre otros, en los elementos estructurales se han extraído del modelo elaborado en SAP2000.

4.2. COMBINACIONES DE CARGA

Las combinaciones de carga para el diseño por esfuerzos admisibles están dadas por la Norma E.020 Cargas del RNE, se considerará que actúan en las siguientes combinaciones:

(1) D
(2) D+L
(3) D + (W ó 0,70 E)
(4) D + T
(5) α[D + L + (W ó 0,70 E)]
(6) α[D + L +T]
(7) α[D + (W ó 0,70 E) + T]
(8) α[D + L + (W ó 0,70 E) + T]

D = Carga muerta
L = Carga viva
W = Carga de viento
E = Carga de sismo, según NTE E.030 Diseño Sismorresistente.
T= Acciones por cambios de temperatura, contracciones y/o deformaciones diferidas en los materiales componentes, asentamientos de apoyos o combinaciones de ellos.
$\alpha =$ Factor que tendrá un valor mínimo de 0.75 para las combinaciones (5), (6) y (7); y de 0.67 para la combinación (8). En estos casos no se permitirá un aumento de los esfuerzos admisibles.

En nuestro caso la combinación aplicable más desfavorable seria la (5), con viento y sismo en ambas direcciones.

4.3. DISEÑO DE COLUMNAS

Diseño compresión

La longitud efectiva es la longitud teórica de una columna equivalente con articulaciones en sus extremos. La longitud efectiva de una columna puede calcularse con la fórmula:

[12] Los valores de las propiedades del bambú han sido tomadas de la Norma NSR-10 Capitulo G.12 – Estructuras de Guadua y la Norma E.100 Bambú del RNE.

$$l_e = l_u k$$

Donde:
$l_u =$ longitud no soportada lateralmente del elemento.
$k =$ coeficiente de longitud efectiva, según las restricciones en los apoyos.

Nota: Si bien es cierto para nuestras condiciones de apoyo del módulo, el valor k es mayor a 1, de manera conservadora para este diseño se asumirá $k = 1$.

En columnas de bambú, la medida de esbeltez está dada por la fórmula:

$$\lambda = \frac{l_e}{r}$$

Donde:
$\lambda =$ relación de esbeltez del elemento.
$l_e =$ longitud efectiva del elemento.
$r =$ radio de giro de la sección.

En el diseño de elementos solicitados a compresión constituidos por dos (2) o más culmos la medida de esbeltez será calculada usando el radio de giro r calculado con la siguiente expresión:

$$r = \sqrt{\frac{I}{A}}$$

Donde:
$I =$ inercia de la sección calculada.
$A =$ área de la sección transversal.
$r =$ radio de giro de la sección.

Según su relación de esbeltez, las columnas de bambú rollizo se clasifican en cortas, intermedias o largas.

Tabla 16: Clasificación de columnas.

Columna	Esbeltez
Corta	$\lambda < 30$
Intermedia	$30 < \lambda < C_k$
Larga	$C_k < \lambda < 150$

Donde:

$$C_k = 2.565\sqrt{\frac{E_{0.05}}{f_c'}} = 2.565\sqrt{\frac{75000}{154}} = 56.60$$

Donde:
$C_k =$ límite entre las columnas intermedias y las columnas largas.
$E_{0.05} =$ módulo de elasticidad percentil 5.
$f_c' =$ esfuerzo admisible en compresión paralela a las fibras modificado.

El esfuerzo máximo de compresión paralela a la fibra actuante (f_c) sobre cualquier sección de bambú rollizo en columnas, no debe exceder el valor del esfuerzo de compresión paralela a las fibras admisibles (f_c') modificado por los factores correspondientes.

$$f_c = \frac{N}{A_n} \le f_c' \qquad Corta$$

$$f_c = \frac{N}{A_n\left(1 - 0.4\left(\frac{\lambda}{C_k}\right)^3\right)} \leq f_c' \qquad Intermedia$$

$$f_c = 3.3\frac{E_{0.05}}{\lambda^2} \leq f_c' \qquad Larga$$

Donde:
f_c = esfuerzo de compresión paralela a la fibra actuante.
f_c' = esfuerzo de compresión paralela a la fibra admisible modificado.
A_n = área neta de la sección transversal.
N = fuerza de compresión paralela a la fibra actuante.
λ = esbeltez.
C_k = esbeltez que marca el límite entre columnas intermedias y largas.
$E_{0.05}$ = módulo de elasticidad percentil 5.

No se permiten columnas con esbeltez mayor a 150.

Diseño de sección con mayor ratio de demanda capacidad (D/C).

Tabla 17: Diseño a compresión de columnas con mayor D/C

Frame	Sección	Longitud (cm)	Radio (cm)	λ	TIPO	P (kgf)	A (cm)	fc (kgf/cm2)	f'c (kgf/cm2)	D/C
6	C2	210.00	3.14	66.88	LARGA	-396.52	66.35	55.33	154	0.359
7	C2	210.00	3.14	66.88	LARGA	-396.52	66.35	55.33	154	0.359
8	C2	210.00	3.14	66.88	LARGA	-396.52	66.35	55.33	154	0.359
9	C2	210.00	3.14	66.88	LARGA	-396.52	66.35	55.33	154	0.359

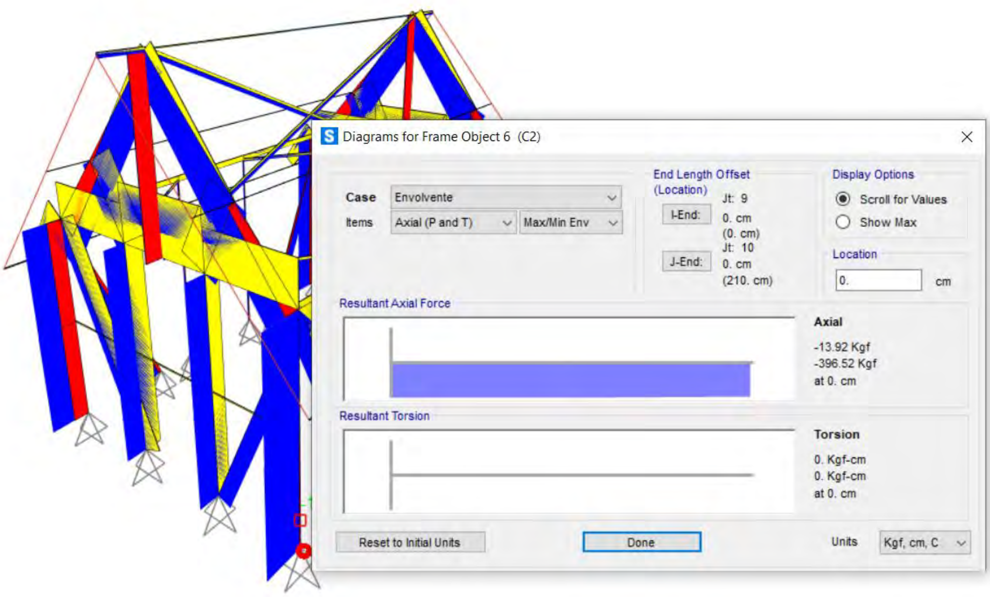


Figura 11: Columnas con mayores D/C.

Las columnas no exceden valores de D/C = 0.36, y los mayores valores de D/C provienen de columnas tipo largas propensas a pandeo, ubicadas en las esquinas del módulo de bambú, por lo tanto, las secciones de las columnas propuestas de las estructuras se consideran adecuadas tanto para esfuerzos de compresión como de pandeo.

4.4. DISEÑO DE VIGAS

Diseño flexión

El esfuerzo de flexión actuante (f_m) sobre cualquier sección de bambú rollizo, no debe exceder el valor del esfuerzo a flexión admisible (f'_m) modificado por los coeficientes correspondientes:

$$f_m = \frac{M}{S} \leq f'_m$$

Donde:
f_m = esfuerzo de flexión actuante
M = momento actuante sobre el elemento
f'_m = esfuerzo admisible modificado
S = módulo de sección

Diseño de sección con mayor ratio de demanda capacidad (D/C)

Tabla 18: Diseño a flexión de vigas con mayor D/C

Frame	Sección	Longitud (cm)	M (kgf.cm)	S (cm3)	fm	f'm	D/C
38	V1	61.37	-5264.31	65.42	-80.47	156.75	0.513
45	V1	61.37	-5264.31	65.42	-80.47	156.75	0.513
47	V1	61.37	-5264.31	65.42	-80.47	156.75	0.513
49	V1	61.37	-5264.31	65.42	-80.47	156.75	0.513

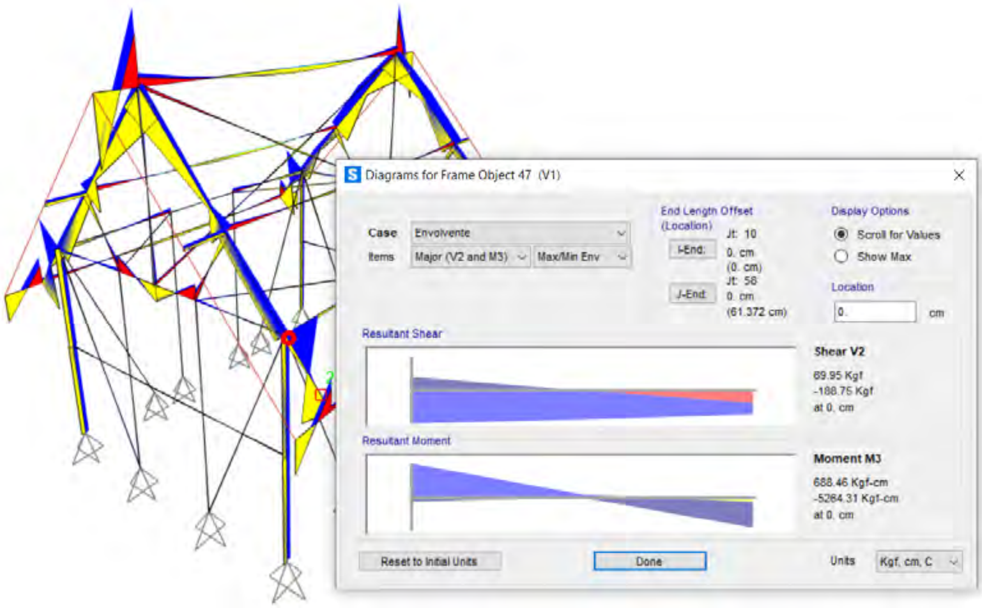


Figura 12: Vigas con mayores D/C.

Las vigas no exceden valores de D/C = 0.52, las cuales esta ubicadas en los extremos del módulo de bambú; por tanto, las secciones de las vigas propuestas de las estructuras se consideran adecuadas.

4.5. DISEÑO DE CIMENTACIONES

De acuerdo al numeral 9.3.1 de la Norma E.100 Bambú los cimientos, sobrecimientos, losas y pisos se regirán por lo establecido en la Norma E. 050 Suelos y Cimentaciones del RNE. Se debe construir un sobrecimiento de una altura mínima de 20 cm sobre el nivel del terreno natural para recibir todos los elementos estructurales verticales de bambú (columnas y muros estructurales).

En nuestro caso se está utilizando al cimiento de 60 cm, sobre el cual se apoyan las columnas de bambú; esta altura es suficiente para proteger a los elementos de bambú de la humedad del suelo, lluvias, inundaciones, entre otros.

Asimismo, se recomienda anclar las columnas de bambú al cimiento, con varillas de ϕ ½" cubiertas de mortero, y una longitud embebida en el cimiento de al menos 50 cm; lo cual ayudará a rigidizar la unión columna de bambú - cimentación.

5. CONCLUSIONES Y RECOMENDACIONES

- Los elementos de bambú (columnas y vigas) no exceden valores de D/C = 0.52 para los diferentes esfuerzos a los que son sometidos considerando una envolvente de carga muerta, viva, viento y sismo según lo establecido en la Norma E.020 Cargas del RNE; por lo tanto, las secciones de bambú propuestas para las estructuras se consideran adecuadas.

- Las distorsiones por cargas de viento no exceden en ningún caso el valor límite de 0.01 (1% de la altura de piso) según lo establecido en la Norma E.020 Cargas del RNE; en ese sentido, la estructura se considera adecuada ante cargas laterales de viento.

- Las distorsiones sísmicas no exceden en ningún caso el valor límite de $\Delta/h= 0.010$ según lo establecido en la Norma E.030 Diseño Sismorresistente del RNE; en ese sentido, la estructura se considera adecuada ante cargas laterales de sismo.

- Se sugiere utilizar un cimiento de 60 cm, esta altura es más que suficiente para proteger a los elementos de bambú de la humedad del suelo, lluvias, inundaciones, entre otros.

- Se recomienda anclar las columnas de bambú al cimiento, con varillas de ϕ ½" cubiertas de mortero, y una longitud embebida en el cimiento de al menos 50 cm; lo cual ayudará a rigidizar la unión columna de bambú – cimentación.