Multi-storey Bamboo Structures in the Tropics

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For most of recent history, architecture in the urban regions of tropical Colombia has neglected principles of climate-sensitive design, thus leading to enclosed spaces relying heavily on mechanical climatization systems in order to obtain comfortable environments. This research investigates how to obtain comfortable indoor climate conditions throughout the year by responding to the environment with passive design strategies while establishing design guidelines for a construction system that integrates these principles and reconsiders the traditional construction culture into a contemporary vernacular system.

There are two different viewpoints to achieve comfortable conditions in buildings. Firstly, the building as a closed and active system (Thermos flask analogy), in which the enclosure of the building is regarded as an insulative barrier where there are minimal or virtually no exchanges between the natural and internal environment. Secondly, an open and passive system (The sieve analogy), that functions as an environmental filter and enables selective exchanges between the external climate and internal spaces (Yaeng, 1987). Each system requires the designer to follow entirely different and even opposite design criteria.

During the last two decades in Colombia's urban areas, the overwhelming implementation of closed building systems has led to a significant increase in heating, ventilating, and air-conditioning (HVAC) energy consumption. Reconsidering this approach and guiding the design towards an open and passive system has many advantages, such as lower energy usage and consequent reduction in greenhouse gas emissions, lower maintenance costs and the ability to provide a natural environment for the users (Wijewardane & Jayasinghe, 2008).

The main concern of climate-sensitive design in architecture and urban planning is creating a building (or urban structure) that provides a comfortable environment for the users while employing the least energy and technical equipment possible and ensuring that the building construction itself suffers no damage from the climate. (Lauber, 2005)

The decisive factor in the requirements made on the indoor climate is the user of the internal space. As people acclimatize naturally to their particular environment, thermal comfort is subjective to each individual. One study conducted by S. Wijewardanea and M. T. R.

Jayasinghe in Sri Lanka (similar climatic conditions to the coastal region of Colombia) indicated that temperatures between 27-29°C were reasonably comfortable without significant air movement for up to 80% of the population (Wijewardane & Jayasinghe, 2008). Once the comfort zones for a specific climate and users are available, the indoor climate can be purposefully influenced and determined to provide continuous comfort.

The external climate and the space's use can be considered 'disturbance variables' in terms of the interior climate. The degree of the variation is determined mainly by the flow of energy due to solar radiation, the emissions released by the use of the building, the thermal insulation of the buildings envelope, the heat storages capacity of the building's structure and finally, the airflow.

The interior can therefore be purposely influenced by design decisions made in the following areas:

Urban

- Choice of the micro-location
- Positioning of the building
- Orientation of the building

Design

- Floor plan solution
- Size and arrangement of windows
- The type, construction and arrangement of shading devices
- The shape of the roof
- Choice of Colour

Building Construction

- Building method, choice of materials
- Building mass
- Thermal insulation
- Construction of the building parts and elements

Utilization

- Airflow rates/ Ventilation
- Individual ventilation pattern of the users
- The period during which the building is used (Lippsmeier, 1969)

Extremes, both geographical and meteorological, characterize the tropical belt of the earth. This research focuses on warm, humid regions of the northern coast of Colombia. In such humid zones, the temperature constantly remains high with slight oscillation between the day and night as well as throughout the year, meaning no apparent seasons, although a rainy season between July and September, referred to as "*el fenómeno del niño*", are characteristic. Heavy rainfall results in abundant surface water, generating many water management issues and recurrent floods. Combined with high humidity levels, these conditions complicate the attainment of comfort levels in buildings. Therefore, it is crucial to consider that many of the design principles commonly used in construction, for example, high thermal mass or south and north-facing facades, are not ideal and tend to revert in a warm and humid climate. (See appendix A)

Historically architecture has been developed fundamentally to generate a habitable environment for human beings to shelter themselves from the weather and any other potential danger and create space in which they can coexist comfortably. The enormous diversity of environments in which humans have settled has led to a range of vernacular architecture, responding specifically within their context and availability of resources. However, the principles under which the vernacular architecture responds to its environment is rarely considered under the current urban development. This poses the question of how traditional tropical design principles can be employed to create buildings that, in a time of rapid urban growth, must be suited for industrial mass production and, in light of our technological age, must consider entirely new social aspirations?

Responding to the local climatic conditions, Colombian vernacular architecture typically involves a set of characteristics.

Given the minimal temperature oscillations, the inertia serves no significant climatic advantage in the building. This led to lightweight structures with high ceilings to stratify the warmer air. These structures are traditionally made from timber, native bamboo and other bio-based materials with low specific heat capacity that dissipate the heat as fast as possible.

Since the sun has a very high angle in this latitude, solar radiation is intense; the roof plane receives the most radiation, followed by the eastern and western facades. Therefore, it is critical to protect direct and diffuse radiation from entering the building as much as possible. The vernacular architecture developed particular elements such as large roof overhangs, various shading devices and veranda spaces to deal with these challenges. The orientation of the main façade is towards the North and South.

The most crucial climatization strategy for this context is ventilation. It helps dissipate the heat from the interiors and reduce humidity. Traditional urban settlements tend to be scattered, independent structures to avoid creating wind barriers that compromise the ventilation of other structures. The buildings have large openings that allow adequate cross-ventilation and are elevated on stilts to ventilate the building from underneath and reduce thermal contact with the ground. The elevation from the ground also protects them from insects, animals and potential floods, which can be recurrent in the tropical zones. (Serra Florensa & Cosh Roura, 2001) (see appendix A)

Considering the thermally adaptive comfort capacity of users in the tropics and with the correctly adjusted climatic design, it is possible to achieve a comfortable interior climate in warm and humid climates using only natural climate control, as many vernacular buildings prove.

Integrating these design principles into contemporary architecture is not an easy task. On the one hand, the building industry of this region, particularly in urban areas, is predominantly characterized by concrete, steel and structural masonry as their predetermined construction materials. They opt for a closed and active system that isolates them from the natural environment and leads them to consume vast amounts of energy to climatize the spaces. On the other hand, the typology of the vernacular types of settlements, which respond sensibly to their surroundings and environment, are limited to a low density. Moreover, their construction system is neither scalable nor suitable for prefabrication, rendering the traditional construction systems, as we know them, incompatible with a high density, rapid growing urban context.

In order to adjust the perspective of the building industry in Colombia towards a regional circular economy, the closed and active construction system must be substituted with an open and passive system that employs traditional design principles. To formulate an alternative construction system, specific design guidelines must be established that consider these principles while responding to the need for multi-storey structures in the urban context.

A simulation of the building envelope's layer structure and materials is conducted using the Ubakus 2D-FE method to determine and compare which construction system would be optimal to be employed in the tropical context. The results are properties of the tested component alone and do not make any statement about the heat protection of the entire room, but this still provides the information needed to compare the benefits and drawbacks of using each particular construction system. The envelopes proposed for this exercise are: on the one hand, structural masonry and plain reinforced concrete, which are the most commonly used construction materials in Colombia; on the other hand, a lightweight timber panel system with and without the use of insulation; these envelopes are chosen for the similarities with more traditional vernacular architecture found in the tropics.

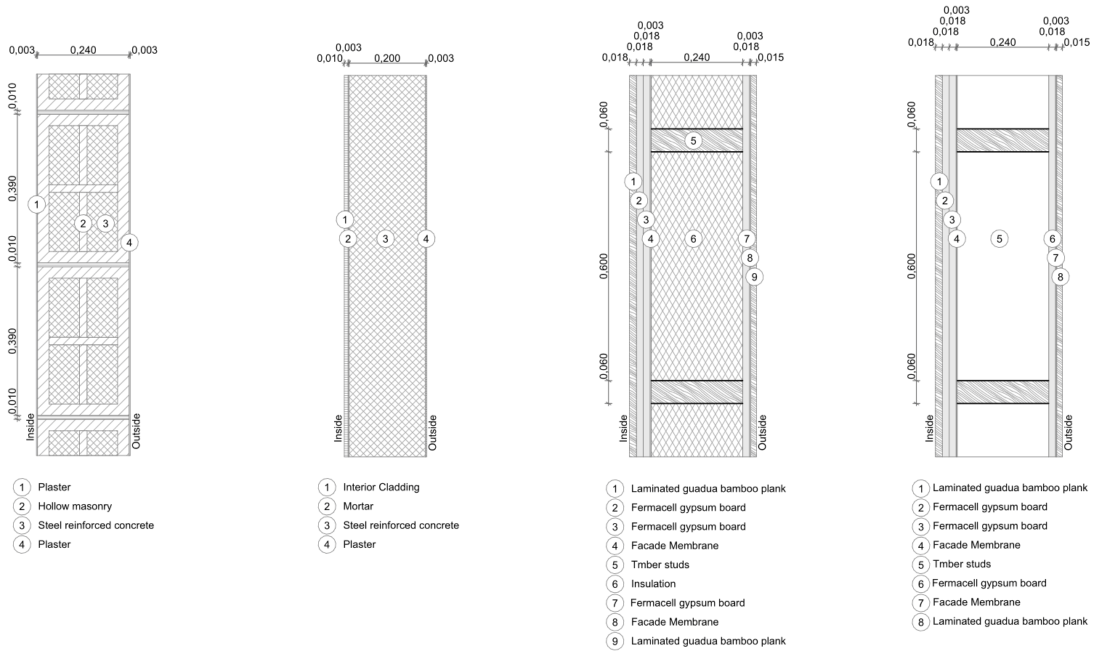


Figure 1. 4 Detailed facade compositions

The results indicate that the properties of the timber panel construction system are better suited climatically than the current construction systems but also provide a biobased alternative that could integrate the building industry as part of a circular economy (see appendix B). So, what <u>if the default antiquated construction systems currently used for tropical urban architecture in Colombia could be substituted for a hybrid multi-story building system centred on local material sourcing of standardized bamboo-based construction components?</u>

The panel construction system consists of various coordinated prefabricated building component layers and the use of minimal materials. The timber panels usually consist of a support structure of linear elements forming a stud frame and bracing planking on one or both sides. Further building component layers and infills may be added depending on requirements and the degree of prefabrication (Kaufmann, Krötsch, & Winter, 2018). However, this type of construction system tends to be limited to four or five storeys high, although several examples of specially designed hybrid panel frame constructions can go up to fourteen storeys high. Integrating bamboo as part of the structural components for a contemporary panel system is a way to adapt traditional Colombian architecture to the urban condition.

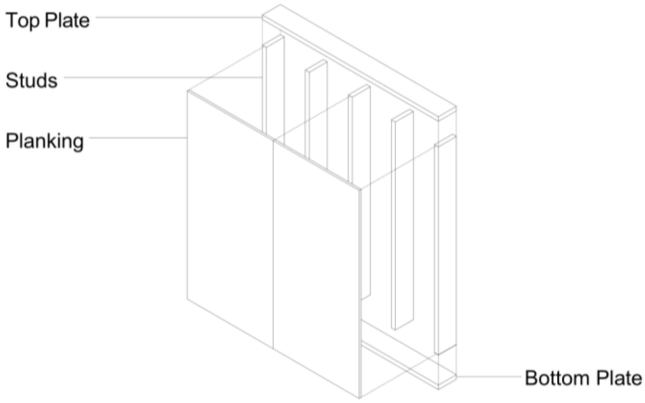


Figure 2. Conventional panel frame components

Guadua is a species of giant tropical bamboo native to Colombia. It is known among other species for its superior mechanical properties and durability, earning the nickname "*Acero vegetal"* (vegetative steel). With culms reaching 25 meters in height and diameters up to 22 centimetres in only three years of growth and attaining its maximum structural integrity in five makes it an alternative fast-growing low-carbon-footprint material to be used in construction. The know-how of working with this local material as a construction system has played a significant role in traditional Colombian architecture for centuries and continues to do so today.

The vernacular loadbearing bamboo construction is a plastered cane building system named '*Bahereque encementado'*. After witnessing its performance to several strong seismic events, Colombia normalized Guadua bamboo as a construction material in its NSR-10 construction codes. '*Bahereque encementado'* consists of round bamboo culms that form a frame. The top and bottom plates are preferably in timber due to the anisotropic characteristics of bamboo perpendicular to the grain. Flattened bamboo boards are used for the sheeting to which a steel wire mesh is nailed, and finally, the walls are plastered with cement mortar for weathering protection, structural integrity and improving fire performance. (Zea Escamilla, et al., 2018)

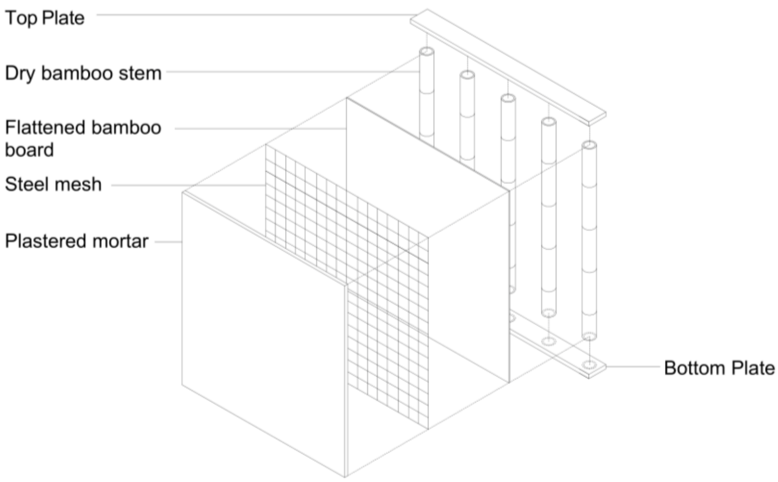


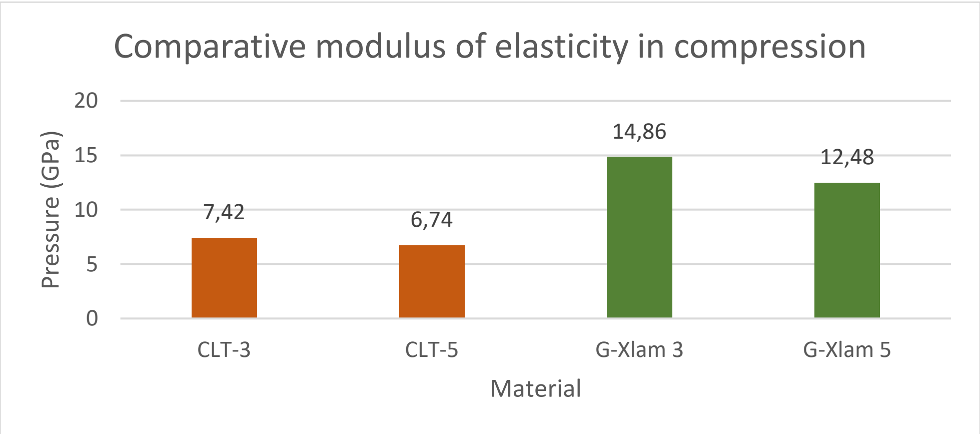
Figure 3. 'Bahareque encementado' components

However, a few main limitations render it unsuitable for multi-storey buildings. The construction system relies heavily on human labour, lacks scalability and can only be worked on-site with minimal possibilities for any degree of prefabrication. The material also struggles against technical difficulties and limitations that first must be studied and tested. The physical and mechanical constraints include the anisotropic tendency to split in the direction perpendicular to its fibres, the limited stiffness, the vulnerability in its mechanical connections to tensile stress, its reaction to external influences like fire, earthquakes and wind and the inhomogeneity of the raw bamboo culms, which complicate its standardized use as a construction material. It also relies on the significant use of cement, aggregates and steel for the reinforcement and plaster of the walls. There is also a lack of knowledge, practitioner expertise and confidence in its technology and potential. The construction system has a current maximum height limitation of two storeys for these reasons, despite the material's exceptional physical properties.

Even though bamboo has been used for centuries, the industrialization of giant Bamboo species commenced only in the 1990s. MosoBamboo in China has manufactured bamboo into multiple engineered construction products that undergo a process to minimize the material's inhomogeneity and anisotropy inherent in its raw state. These standardized products allow high performance, precisely calculatable planar building materials and range from flooring, façade cladding, panels to structural beams. (Lugt, 2017) Similarly, there is also interest in further processing bamboo in Colombia; the company Ecotableros for example processes bamboo into laminated bamboo boards. Unlike the traditionally flattened bamboo, this product has standardized structural integrity and can be used as the planking of a panel frame.

Despite increased research to define engineered bamboo's material behaviour and several successful applications, it is necessary to establish design guidelines and specifications for integrating traditional or engineered bamboo in a hybrid construction system.

Using glue-laminated bamboo enables higher levels of industrialization and standardization, thus making the material's properties more reliable and predictable. The studs are usually made of solid timber in a panel frame construction system, but replacing them with glue-laminated bamboo can enable the structure to bear greater loads. The comparison of the modulus of elasticity in compression of cross-laminated timber with cross-laminated bamboo shows that the properties of the bamboo are nearly twice as strong. (Archila, 2019; Zea Escamilla, et al., 2018) Therefore, this form of bamboo can reduce the element dimensions or even increase the number of potential storeys of the construction system (Zea Escamilla, et al., 2018).



Having said this, while bamboo in a raw state is significantly cheaper than timber, the process of manufacturing highly engineered bamboo products is expensive and generates a significant amount of material waste. This renders the use of the engineered material, on its own, non-competitive compared to alternative engineered timber products. Therefore, the optimal solution to create a cost-effective construction system is to combine each material's strengths and vulnerabilities into the components comprising the different elements for the panel construction system.

For instance, in the conventional panel frame, vertical loads are distributed from lintels to studs, which then transfer onto top plates. The crosspieces (top and bottom plates) are the weak points of vertical loadbearing, which is why few buildings are more than four storeys high. Raising the number of storeys requires special measures such as continuous studs or hardwood top and bottom plates. However, as previously shown, glue-laminated bamboo elements have superior mechanical properties to hardwood, meaning they can be used explicitly as crosspieces as an alternative in timber construction. (Kaufmann, Krötsch, & Winter, 2018) (see appendix C).

Integrating bamboo in its natural form into the panel construction as a reinforcement column could also be a means to exploit the full extent of the material's specific advantages: its affordability, renewability and mechanical strength while dealing with its vulnerabilities. Its placement between the studs and crosspieces allows conventional layering of additional panel components like standardized façade membranes (vapour and airtightness barriers), thermal insulation, fireproofing materials (e.g. Fermacell gypsum boards) and exterior cladding. These additional elements provide protective functions to the interior space and conceal the bamboo element's composure behind the planking.

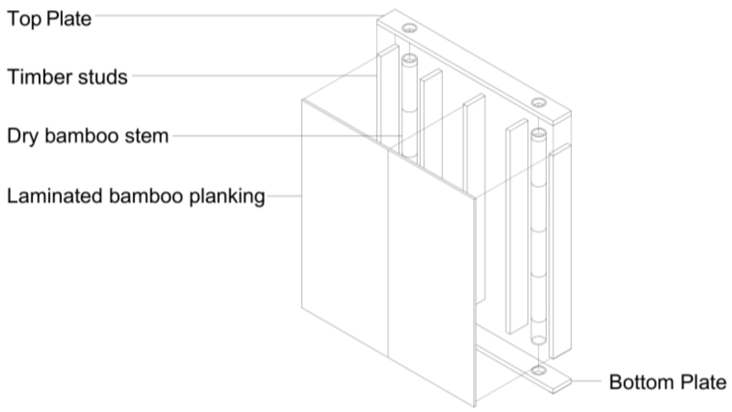


Figure 4. Hybrid Bamboo panel frame components.

Used as the main distributor for vertical loads, the panel benefits from the bamboo's compression properties parallel to its longitudinal axis. It also avoids its anisotropic liabilities and reduces the strain on the crosspieces and studs from vertical loads, which reduces the timber elements' section. The timber frame may then provide the additional stiffness required to deal with horizontal loads from high winds or seismic movements.

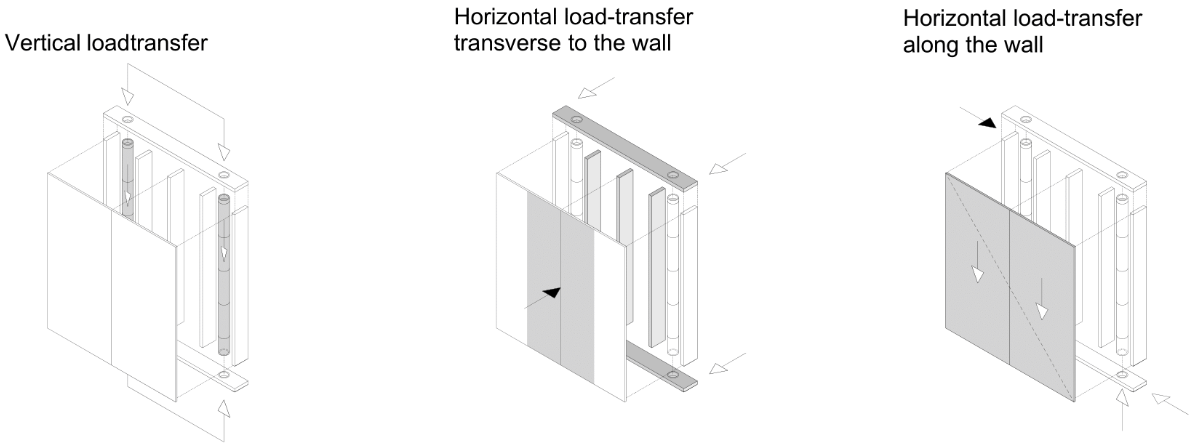


Figure 5. Vertical and horizontal load-transfer in a hybrid panel construction wall

Considering the potential of this loadbearing structure in a multi-storey building, the amount of bamboo stems integrated within each panel is adaptable from floor to floor, depending on the vertical loads each individual floor supports. This creates efficient use of material in the construction system.

The panel frame system could also fix-in a rear ventilated façade. Its main distinguishing feature is the air cavity that separates the exterior cladding from the insulation, which is drained and ventilated, thus protecting the insulation from driving rain while allowing evaporation of any built-in or diffusion-driven moisture. Further thermal benefits are achieved in a warm climate as the cladding prevents most heat gains from solar radiation, and the stack effect within the ventilated cavity aids the dissipation of heat. (Arregi, 2020)

Panel frame construction relies on a high degree of prefabrication. The integration of bamboo into a prefabricated timber frame element has positive aspects for the material. As it is sensitive to moisture, moving the completion of a sealed building envelope into a workshop shortens on-site construction and minimizes the dependency on weather conditions during assembly. Additionally, it also provides protected conditions that are ideal for manufacturing, improving the quality of the implementation and process control, along with the general efficiency of the construction.

Conclusion

To conclude, the default closed and active construction systems in Colombia's tropical context lack climate and environmental sensitivity considerations. Therefore, this approach makes them inadequate for their context producing an unnecessary consumption of energy and the isolation of the users from their natural environment. If they were reconsidered through open and passive design, remembering the traditional design principles of the tropics, a hybrid prefabricated panel construction system based on traditional or engineered bamboo elements provides a feasible alternative approach for the urban context. The system considers the historical use and material-culture identity of the native bamboo as a construction material but pushes it into a contemporary vernacular system that responds directly to its environment and the comfort needs of the users. The use of bio-based materials and the unique renewability and carbon sequestration capabilities of the bamboo plant also contemplates the possible integration of the construction industry into a circular economy. Colombia has a unique opportunity to further develop a bamboo-based construction system as a contemporary building material in architecture through further investigation.

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Appendix

Appendix A

The Tropical humid climatic conditions are taken from Santa Marta, a city on the Northern coast of Colombia that can be the base for other cities within similar climate conditions.

From the proximity of the location's latitude to the equator, the height angle of the sun remains high during the whole year and is not significantly disposed to the South nor North.

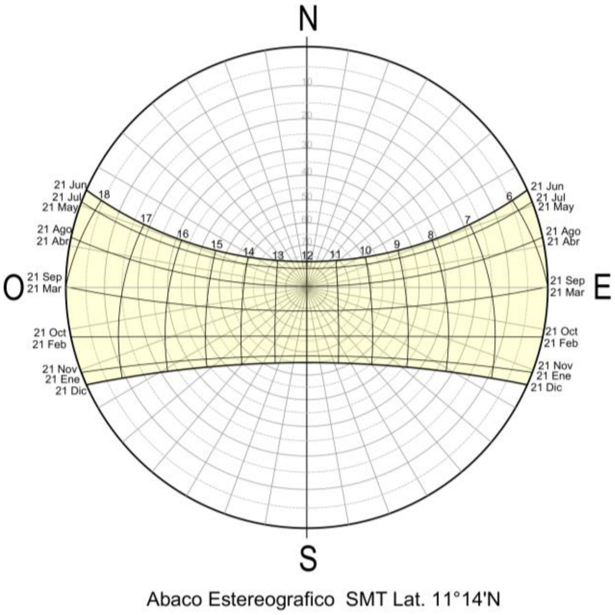


Figure 6. Stereographic diagram of Santa Marta. (Heliodon)

The psychrometric chart reveals how and which passive strategies can condition interior space's comfort level. Adding the data of Santa Marta, it becomes clear that the predominant strategy is ventilation and that control by inertia ceases to be as helpful under these climatic conditions.

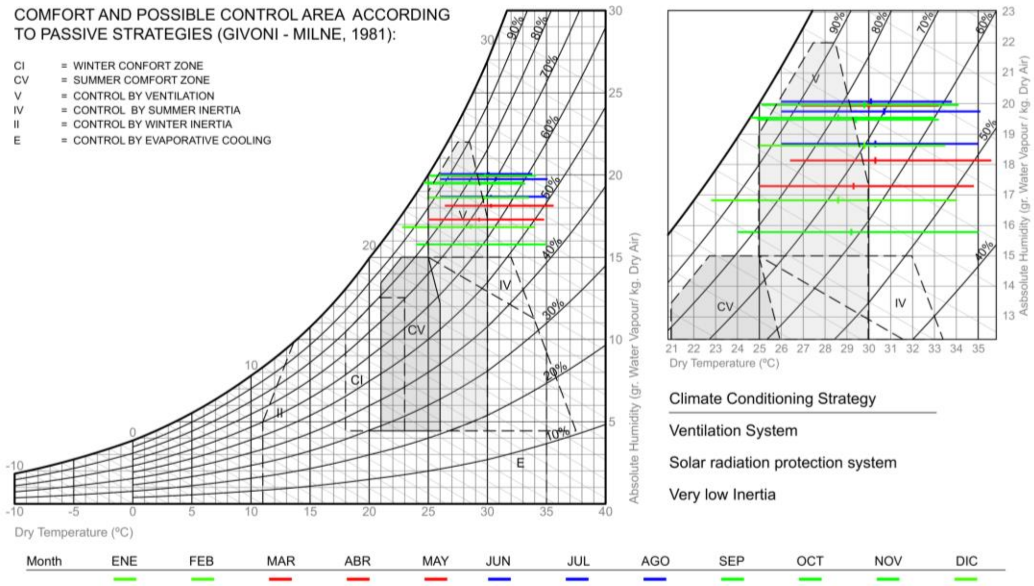


Figure 7. Psychrometric Chart detailed in Santa Marta.

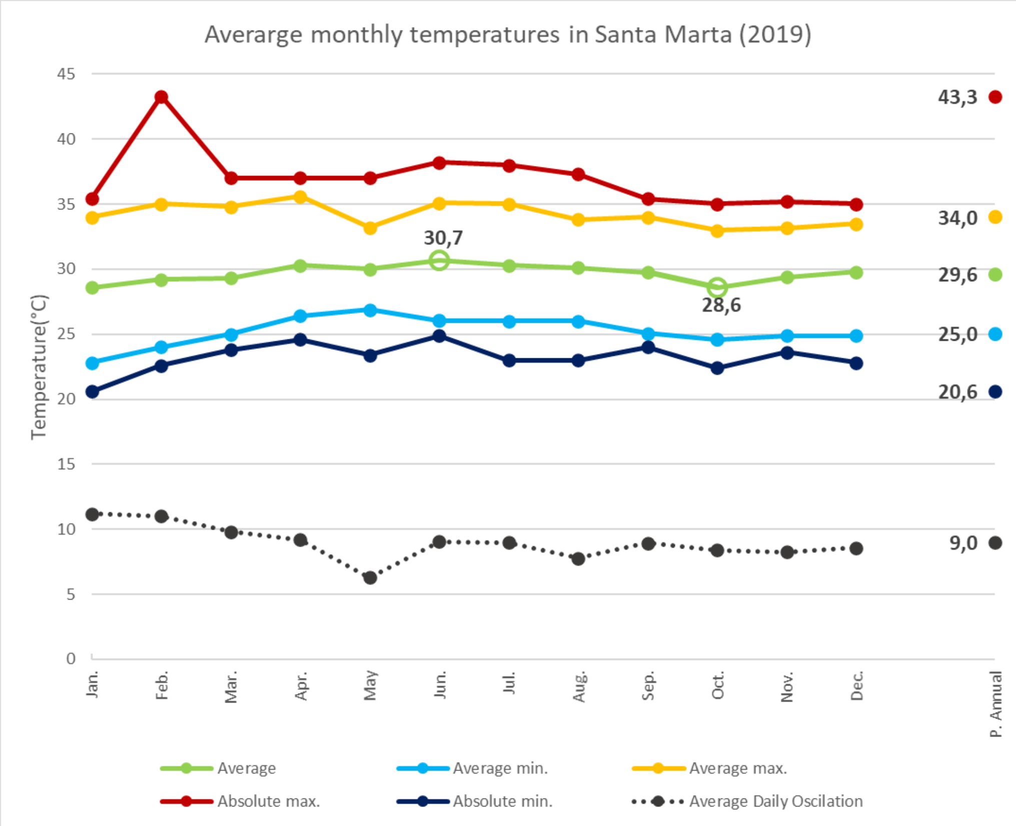


Figure 8. Average monthly temperatures in Santa Marta

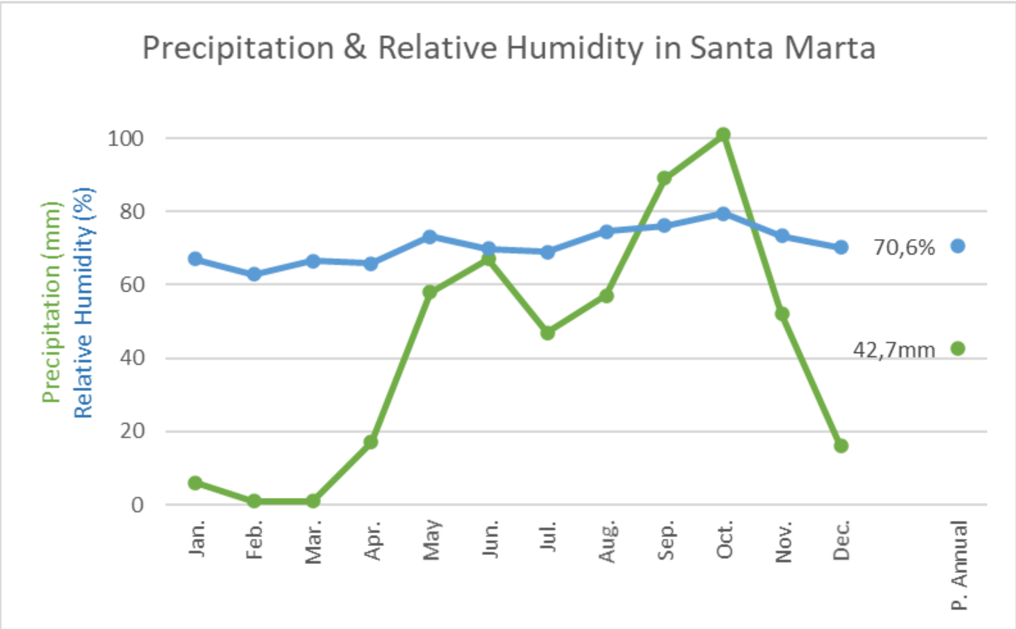
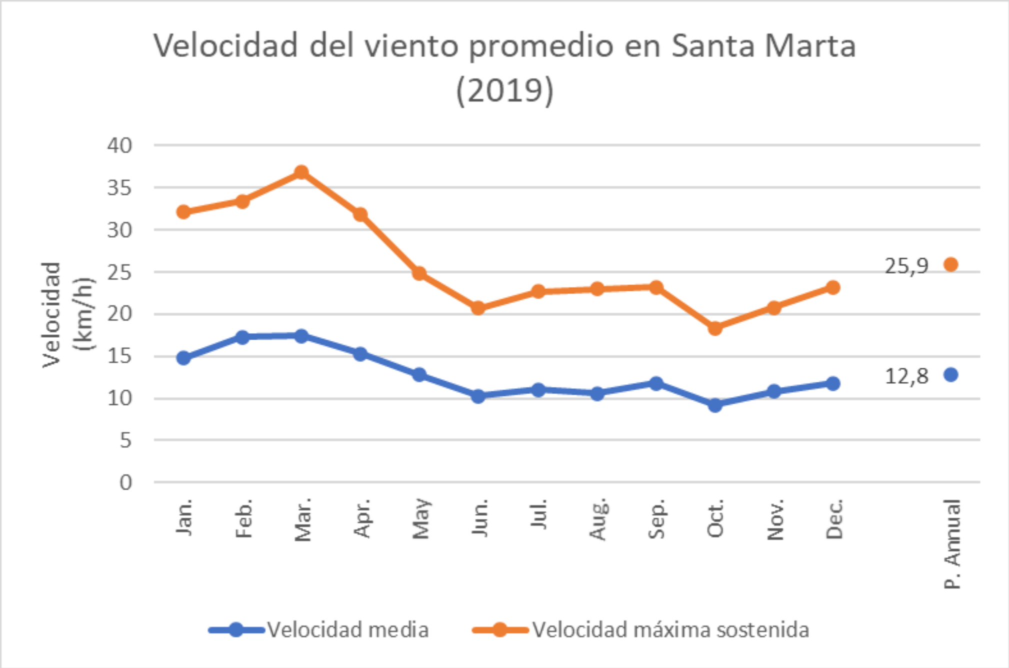


Figure 9. Ptecipitation & Relative Humidity in Santa Marte



Daily averages of global irradiation received for each month on the surfaces of a $1m^3$.

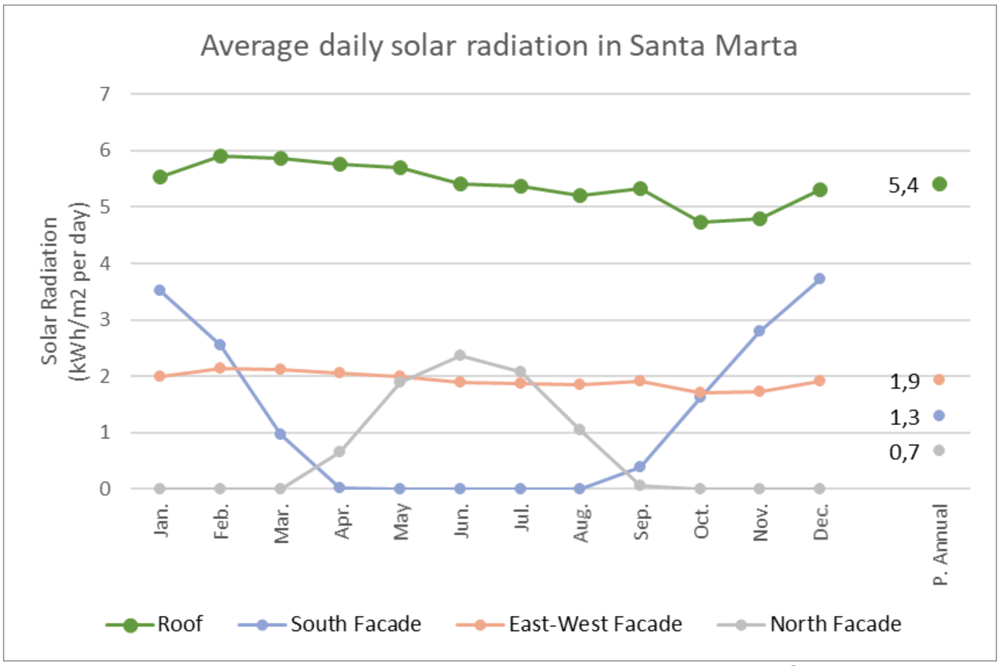


Figure 10. Daily averages of global irradiation received each month on the surfaces of a $1m^3$ cube (Heliodon).

Appendix B

Results of the comparison between

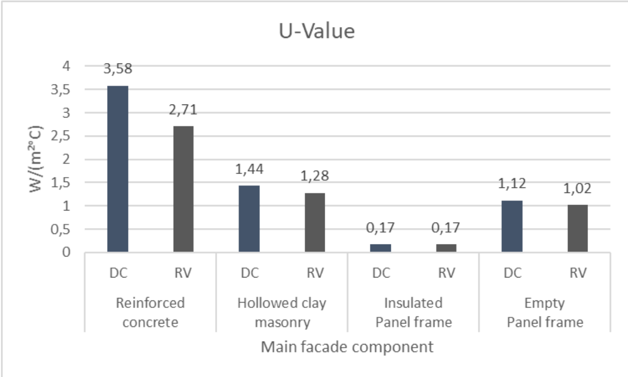


Figure 11. U-value

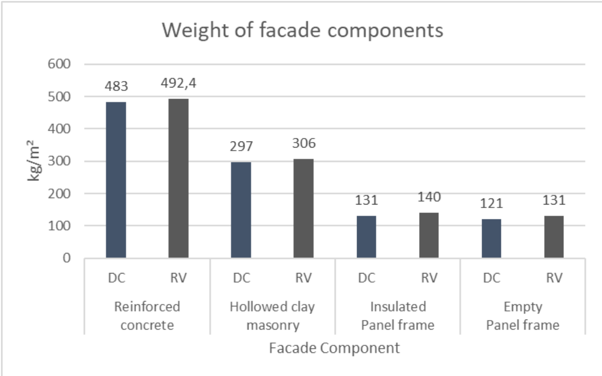


Figure 12. Weight of facade component

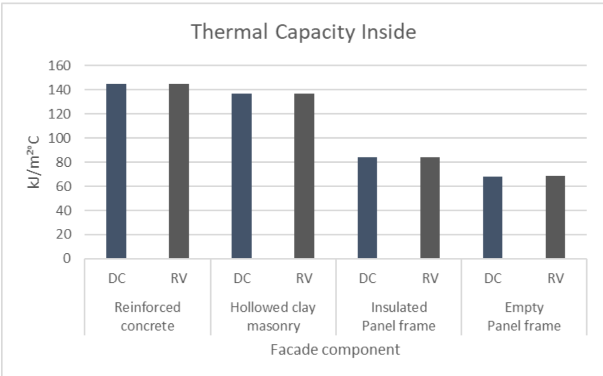


Figure 13.Thermal Capacity Inside

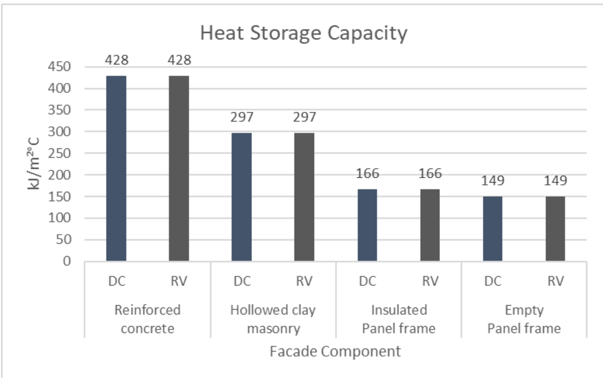


Figure 14. Heat storage capacity

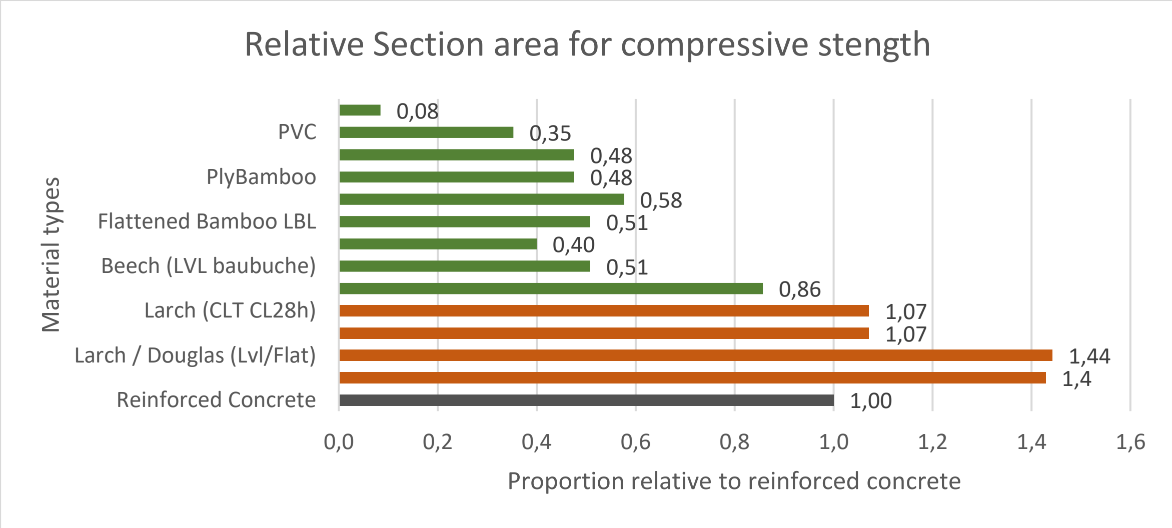


Figure 15. Relative area for compressive strength for various materials (Thomassen, 2019)

Appendix C

Panel frame system.

Figure 16. Panel frame variations of a wall element.

'Bahereque encementado' construction system.

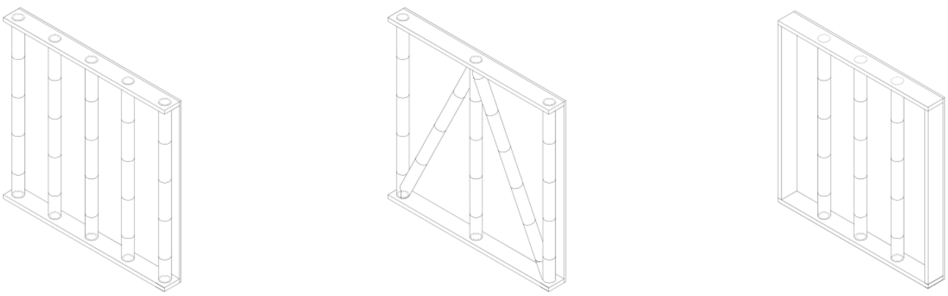


Figure 17. Baherque wall element frame variations

Figure 18. Bahareque Ecementado (NSR-10)

Variations to the hybrid panel frame construction system

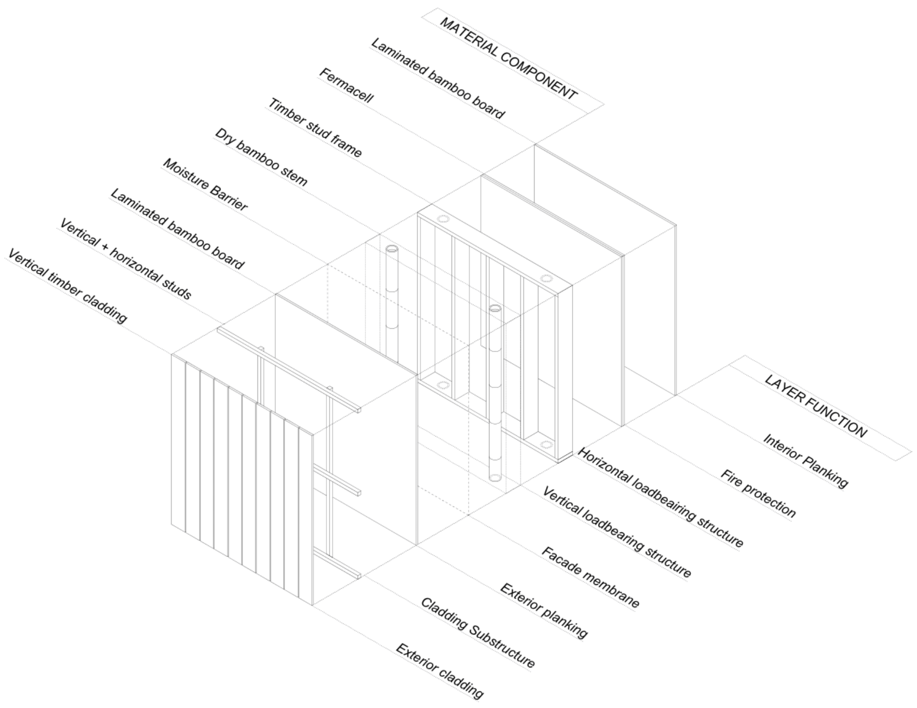


Figure 19. Hybrid bamboo panel frame facade separated by components and their function.

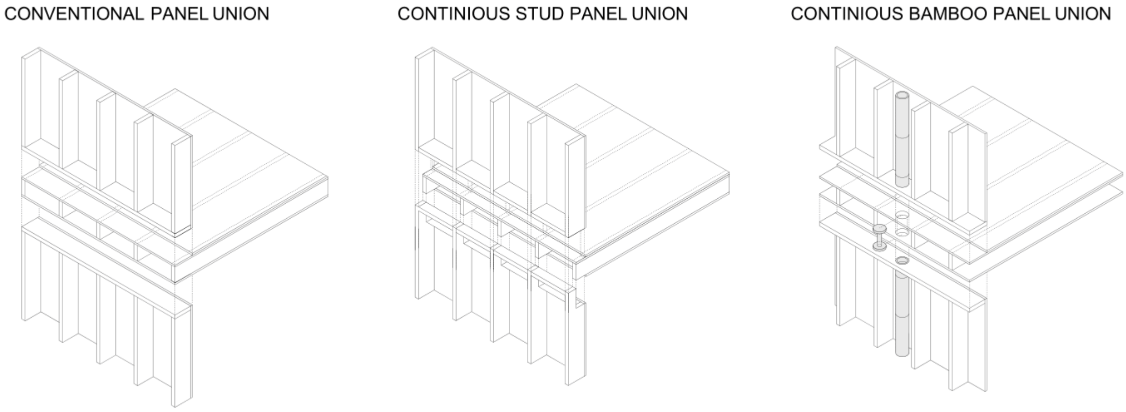


Figure 20. The union between panel floor and wall elements

Figure 21. Large openings for a hybrid bamboo panel frame

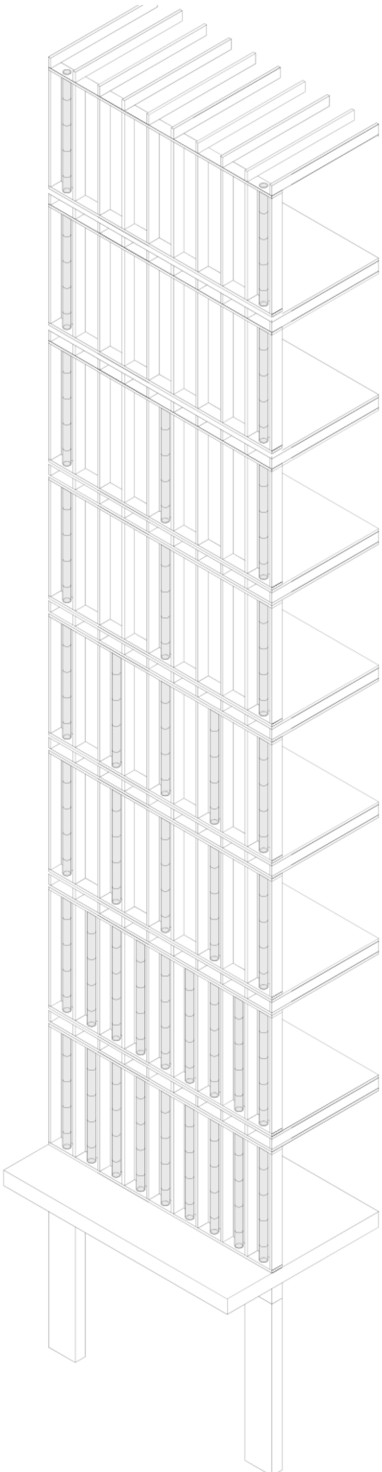


Figure 22. Multi-storey hybrid bamboo panel frame system with adaptable reinforcement column and concrete base.