Structural Adequacy of Traditional Bamboo Housing in Latin America

Jorge A. Gutiérrez

National Laboratory for Materials and Structural Models, Civil Engineering Department, University of Costa Rica

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Most of the photographs included in this publication are those taken by the author during his field trips to the Guadua culture region of Colombia and Ecuador, except Figs. 9 (by Arch. Jorge Morán), 10 (by Eng. Rafael Bejarano), and 49a, 49b and 57 (from the book *Bambusa Guadua* by Marcelo Villegas). Some figures and graphs were taken from the references indicated.

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Jorge A. Gutiérrez

Foreword

Physically, bamboo appears tailor-made for use as a building component – round, straight, smooth, strong and beautiful. These favorable aspects could not have escaped the notice of our ancestors in search of materials to explore and extend their construction skills. Hence, one of the earliest substantive uses of bamboo might have been in housing construction.

The extensive use of bamboo in Asia has been recorded in a large number of documents, both ancient and modern. Although there is evidence that bamboo was equally important to some ancient cultures in the Americas (bamboo housing components that are about 4 500 years old have been found in Ecuador), documentation of the ways and means by which it was put to use is sparse. Part of the Americas is home to one of the largest bamboos known – Guadua. In recent years, there has been a revival of interest on the ways in which Guadua can be used, and it was but natural that housing construction lead this bamboo renaissance.

One of the most remarkable and successful attempt to revive bamboo housing, albeit with modern aspects, happened in Costa Rica, a place that did not have any Guadua! The National Bamboo Project of Costa Rica proved beyond doubt that the choice of bamboo for a building material by millions of people in Colombia and Ecuador is sensible – in terms of economics, convenience, safety and aesthetics. Dr Jorge Gutiérrez, who has been actively involved in the Costa Rican project, was invited by INBAR to examine the present day relevance of the traditional bamboo housing construction in Latin America. The result of that in-depth study is being presented here as an INBAR Technical

Report for the benefit of all – policy makers and practitioners alike – involved in the field of housing construction.

I.V. Ramanuja Rao	Ian R. Hunter
Programs Coordinator, INBAR	Director General, INBAR

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Chapter One

Introduction

As a construction material, bamboo is widely used in all parts of the world where it grows. In many places, its use is restricted almost exclusively for low-cost housing, usually built by the owners themselves. For this and other reasons, bamboo is customarily regarded as "poor man's timber" and used as a temporary solution to be substituted as soon as improved economic conditions allow.

However, there is a large region of Colombia and Ecuador in South America where bamboo, even if regarded as a second class material by some, has been extensively used in houses that are 50-100 years old. Most of these houses have been built in very difficult construction sites like very steep hills, earthquake-prone regions or swampy coastal areas that are frequently inundated. This region has an authentic bamboo culture with a strong tradition of bamboo housing.

The problem with traditions is that they are usually transmitted from generation to generation with hardly any changes and without any transfer outside of the region where they were developed. The consequence is that they are often at peril with the advent of new materials and technologies, and tend to gradually disappear. Hence, there is a need to study the traditional design and construction techniques that have been locally developed for bamboo housing in the bamboo culture region of South America, so that the knowledge is closely examined and recorded.

For this purpose a research project was submitted to the International Network of Bamboo and Rattan (INBAR), with the following general objective:

"To study the traditional design and construction techniques that have been locally developed for bamboo housing in three Latin-American countries, and to analyse them through the lens of existing scientific knowledge and sound engineering practice, in order to highlight their adequacies and identify their pitfalls."

The three countries originally proposed as study areas were Colombia, Ecuador and Peru. However, Peru was later excluded because the bamboo used for house construction in the northern part of the country is brought from Guayaquil, Ecuador, and there are no original construction techniques. To study the traditional bamboo houses of Colombia and Ecuador, visits were arranged to the city of Guayaquil, the largest in Ecuador (2.5 million inhabitants). The smaller Colombian cities of Manizales (500 000 people), Pereira (380 000) and Armenia (270 000) – the capitals of the Departments of Caldas, Risaralda and Quindío, respectively, and comprising what is known as “Antiguo Caldas” – were visited. The study team also found time to visit several smaller towns and their surrounding countryside in both countries.

There are obvious limitations in studies of this kind. In the first place, the time available is always inadequate to fully grasp the complex realities and diverse housing solutions, particularly to someone who is not part of that environment: qualified local professionals do have a more complete understanding of the social and technological environment. Another difficulty arises because the study is intended for a general public and not for specialized structural or earthquake engineers: all aspects have to be viewed from a more general and less technical level. It should also be stated here that analytical theories are of little use for the types of traditional housing that this study deals with because it is practically impossible to produce a reliable mathematical model that could predict their behavior. And, facts are more reliable than theories. The success of many of the bamboo structures has adequately proved their capacity to resist the passage of time and to survive natural calamities, such as the earthquakes that frequent the region. It is in the empirical evidence of their behavior through the years, and not in theoretical results obtained from complex analytical models, that the adequacy of bamboo structures becomes evident.

The report has been organized in several sections. A conceptual framework, developed by the author as a tool to evaluate the quality of traditional or engineered structural designs, is presented first. A fragmented approach does not allow an understanding of the integral structural forms, which are much more than a collection of structural and constructional details. It is hoped that this conceptual system will become a useful methodology for similar studies in other regions where bamboo or other type of traditional houses merit similar evaluations.

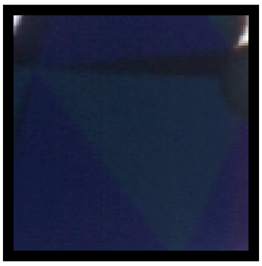
Second, the characteristics of Guadua, the specific bamboo exclusively used for these dwellings, are presented. The particular region of Colombia and Ecuador where it is extensively used is described in terms of its environmental, cultural and socio-economic conditions.

The different housing prototypes existing in the region are discussed next, in terms of their evolution and response to the specific conditions. Particularly significant is the construction technique known as bamboo *bahareque*, not only because of its aesthetics and widespread presence in the region, but also because of its proven durability and success against lateral forces such as earthquakes. The houses are analysed from the perspective of their structural systems and components, describing the use of materials, structural shapes, construction details and building techniques. Their performance during service conditions – daily regular loads and weathering exposure – as well as extreme conditions – severe earthquake and strong winds – are considered. The study examines, in particular, the behavior of bamboo *bahareque* dwellings located in the epicenter area of the Colombian earthquake on 25 January 1999 that struck the Department of Quindío. The need for adequate technology transfer procedures is stated and illustrated with a successful experience.

The study concludes with a summary of the most important characteristics, those that deserve special attention because they significantly contribute to the structural soundness and durability of the houses.

Chapter Two

Structural Adequacy:



a Conceptual Framework

After visiting a few hundred bamboo houses built under different settings, with quite diverse shapes, use of the material, construction details and structural behavior, both under daily service conditions as well as extreme situations, a question arises: what makes a structural solution adequate? To answer this question – which is of great importance not only for this report but also for the general field of structural design – a conceptual framework is proposed. This framework will be applied to the particular conditions of this study. It is hoped that it will prove valuable also for more general tasks.

In his seminal work about the process of architectural design, Christopher Alexander (1964) presented the **design process** as an interplay between the two dialectical concepts of **form** and **context**, the last containing everything that does not belong to the first and, in consequence, completing the universe of our interest:

> Every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem. In other words, when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context. Good fit is a desired property of this ensemble which relates to some particular division of the ensemble into form and context.
>
> The form is a part of the world over which we have control, and which we decide to shape while leaving the rest of the world as it is. The context is that part of the world that puts demands on this form; anything in the world that makes demands on the form is context. Fitness is a relation of mutual acceptability between the two. In a problem of design we want to satisfy the mutual demands which the two make on one another. We want to put the context and the form into effortless contact or frictionless coexistence.

The difficulties of the design process (the creation of the form) arise from the fact that a precise mathematical description of the context is impossible for all but a few simple cases. Inasmuch as the context is not precisely known, the question of achieving fitness, or adequacy as we prefer to call it, seems also an impossible task unless we choose to define it in negative terms: by pointing out those conditions of the form that could be identified as lack of fitness or inadequacy in their specific context – “those specific kinds of misfits which prevent good fit”.

It is clear that these concepts can be borrowed from the theory of architectural design, where they were originally formulated, and applied to other design processes. In fact, these ideas have been applied to the dynamic but apparently unrelated field of computer programming with considerable success (Gamma et al. 1995). They, however, have remained unknown to the much closer field of structural design. In the following paragraphs, these concepts will be elaborated into a theoretical scheme that will provide a useful methodology for the evaluation of fitness or adequacy of existing or proposed structural designs. The methodology can be used for the study of traditional dwellings, created by the type of cultures that Alexander calls “unselfconscious” (Alexander 1964). These cultures do not get involved in the self-conscious process that is proper of architecture or engineering design. There simply is a right way to build, and this is transmitted from generation to generation with little modifications (such modifications usually represent clever adaptations to changes occurring in their context). Obviously, the methodology is also applicable to the self-conscious or engineered structural design process.

The concept of form was known to the philosophers of the classical Greece, where it was introduced to characterize the process of human creation, whether artistic or technical. Form is composed of **intention** and **materiality**. The first – **intention** – represents the ideal conditions that, consciously or unconsciously, are to be satisfied by the created form. The second – **materiality** – represents the material resources available for that purpose. It is clear that these two terms constitute another dialectic pair, with intention pulling upwards, as an aspiration of perfection, while materiality holds the process downwards in the ground. The creation of a form constitutes a dialectic synthesis of these two opposites. It can be regarded as an extension of the myth of man as a dialectic synthesis of spirit and matter, an animal creature with a divine glow, that is deeply implanted in the philosophy and theology of western civilization.

In the search for the components of intention, we may borrow from the Roman architect Vitruvius, who in the first century BC defined what became the desiderata for the next two thousand years for the creation of architectural and structural forms. He established the three requisites for any successful architectural work: *venustas, firmitas* and *utilitas*. Some English translations (Vitruvius 1960) refer to these as beauty, durability and convenience, but we will translate them as delight, firmness and service.

From the structural point of view, the most important component of the form is **firmness**. It can be defined as the capacity of a structure to resist its own weight and other loads and actions produced by its use and existence – such as ground settlements, temperature changes or eventual extreme actions like earthquakes or strong winds – while keeping the response of the components and the entire structure under prescribed limits.

Three characteristics are essential for a firm structure:

- **Strength** or the capacity to withstand the specific loads and other actions defined by the context, while keeping the internal forces of its structural components under prescribed limits.
- **Stiffness** or the capacity to keep the displacements and internal deformations under tolerable limits while resisting the specific loads and actions.
- **Stability** or the capacity of the structure to return to its original equilibrium state after the application of minor perturbations and to resist the external loads without local or global buckling.

Next in importance is **service**, which involves two important aspects because a structure requires a functional form that is in harmony with the context. It is obvious, although not always well understood, that the structure is conceived and constructed to perform a series of functions and that a failure to satisfy any of those constitutes a failure of the structure, even if it remains firm on the ground. The effects of a functional structure should not affect the context, which is usually referred to as “the environment”, beyond tolerable limits that must be clearly defined and enforced. This concept applies not only to large industrial facilities but to individual dwellings and small structures as well.

The last but not the least is the concept of **delight** or beauty, erroneously left to the sole care of architects and aestheticians (and a source of frequent contention among them). It should be an important concern to all engineers and professionals involved in the design process, and also to the public at large. Every structural design should explicitly consider aesthetics as a fundamental component. Similar to what was mentioned earlier in relation to service, delight involves both the form and its context, because the beauty of a particular structure is not only due to itself but also to the way it relates, either by integration or by contrast, to its surroundings. The concern for delightful structures has been explicitly considered in some recent large engineering projects, where cost overruns of up to 15% were accepted in lieu of less pleasant solutions.

For illustrative purposes, the three nodes of an equilateral triangle can represent the three Vitruvian components of intention (Fig. 1). The equal sides refer to their equivalent

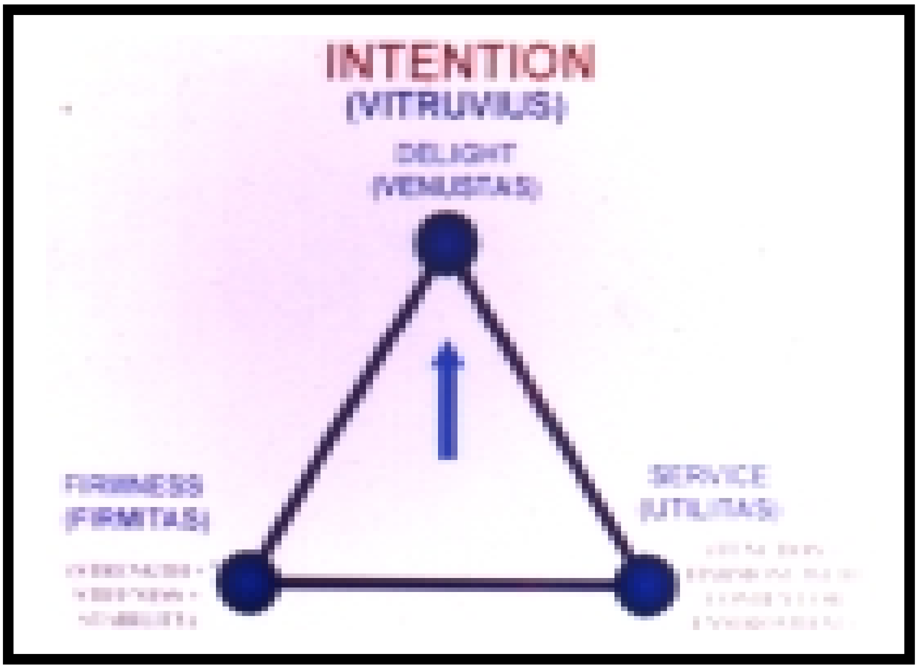


Fig. 1: *Equilateral triangle representing Vitruvian components of intention*

importance, but delight is located in the upper node because it is related to the higher spiritual goals of human beings.

However, an important fourth component is missing – **economy**. Incidentally, Vitruvius included it in his famous book, but under a different heading. Economic considerations are at the base of the creation of practically all structural forms. At least three different conditions should be evaluated:

a) Construction (materials, labor and equipment);

b) operation; and

c) maintenance.

When economy is added to the illustration in Fig. 1, it turns into a four-node figure. To maintain an equilateral figure with interactions between all the nodes, a three-dimensional tetrahedral representation is appropriate (Fig. 2).

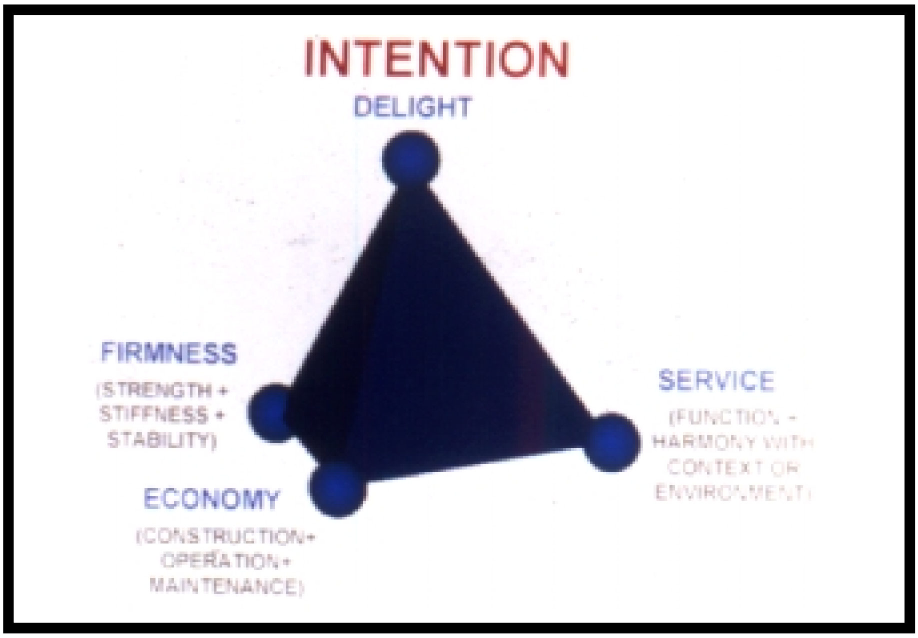


Fig. 2: *The tetrahedral representation of intention*

In **materiality** – the element that restricts our intentions in the creation of a structural form – the **materials** themselves define the first component. Since the dawn of civilization, many materials have been used to build structures: vegetable fibers, adobe, timber, stone, brick and natural concrete were predominant in historic times and artificial concrete, iron and steel in the last two centuries. A proper understanding of the materials – their strengths and weaknesses, their advantages and constraints, and the opportunities they offer and the threats they pose – is essential to accomplish the **intention** of the **form** in the structural design process. There are no good or bad materials; there are only materials more suitable for specific purposes. What is important is to understand their behavior to take advantage of their strengths while avoiding their weaknesses. When comparing and evaluating materials, different parameters will rate them differently. Unit cost and availability at a particular site or energy consumption required for their production could be, in some cases, as important as strength or rigidity. This is a key concept for the evaluation of the traditional bamboo housing in Colombia and Ecuador, which is the subject of this study, and for the evaluation of other types of traditional dwellings as well.

Closely related to structural materials is structural **shape**. Sometimes shape gets defined by the structure itself. For example, a flexible rope forming a parabolic shape to resist uniformly distributed vertical loads: the shape of the cables of a modern steel suspension bridge, the longest free-spanning structures ever built. This is a typical example of what is known as an active shape structure. The same shape, when inverted upwards, forms the arch. It resists by compressive internal forces what in the flexible rope is resisted by tension. Roman engineers understood this basic principle and used the shape of arch to build marvelous stone or brick masonry structures that have survived to our days (stones and bricks are quite durable and strong in compression but extremely weak in tension).

Two other components complete the **materiality** of the structural form. One is the **dimensioning** and **detailing** of the structural elements to provide the required strength, stiffness and stability to the individual components and guarantee effective joints among themselves. The other is the **construction technology** that makes it possible to build the conceived form.

The four components of the **materiality** mentioned above are all equally important and can be represented by another tetrahedron, with each component representing a node and the structural **materials** occupying the lowest position (Fig. 3).

As mentioned earlier, the intention and materiality of the form constitute a dialectical pair with the first corresponding to the thesis and the second to the antithesis. Their synthesis would be the **structural design**, a creative process demanding a satisfactory solution to their dynamic interplay, with the intention pulling upwards and the materiality holding downwards. Hence, the optimum synthesis may be represented by the eight-node, three-dimensional star, *Stella Octangula*, formed by the two original tetrahedrons symmetrically penetrating each other (Fig. 4). This beautiful shape aptly represents the artistic process involved in the creation of structural forms that we call design.

Form and context, as explained before, represent another dialectical pair with one affecting the other. In structural theory, the effects of the context upon the form are

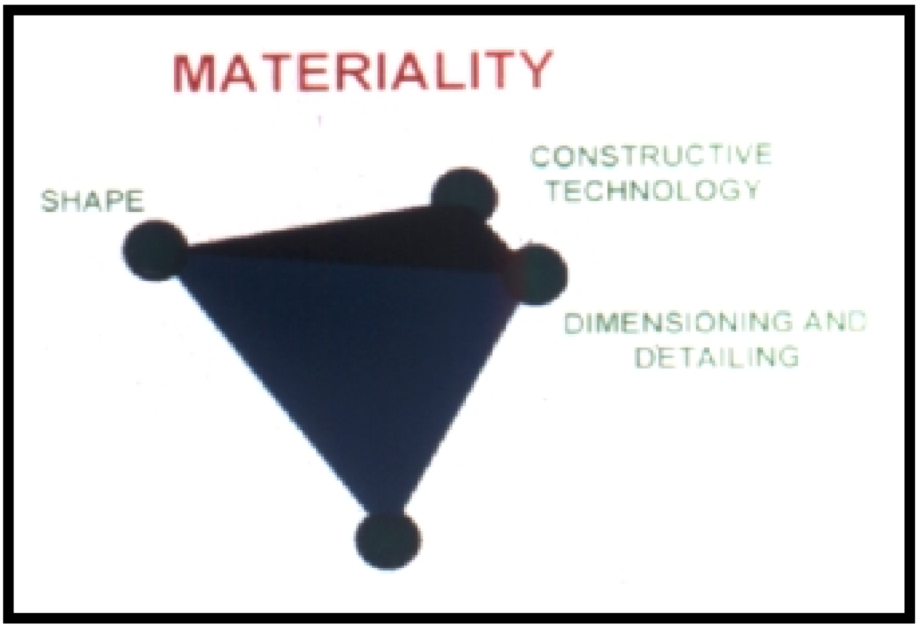


Fig. 3: *The tetrahedral representation of materiality*

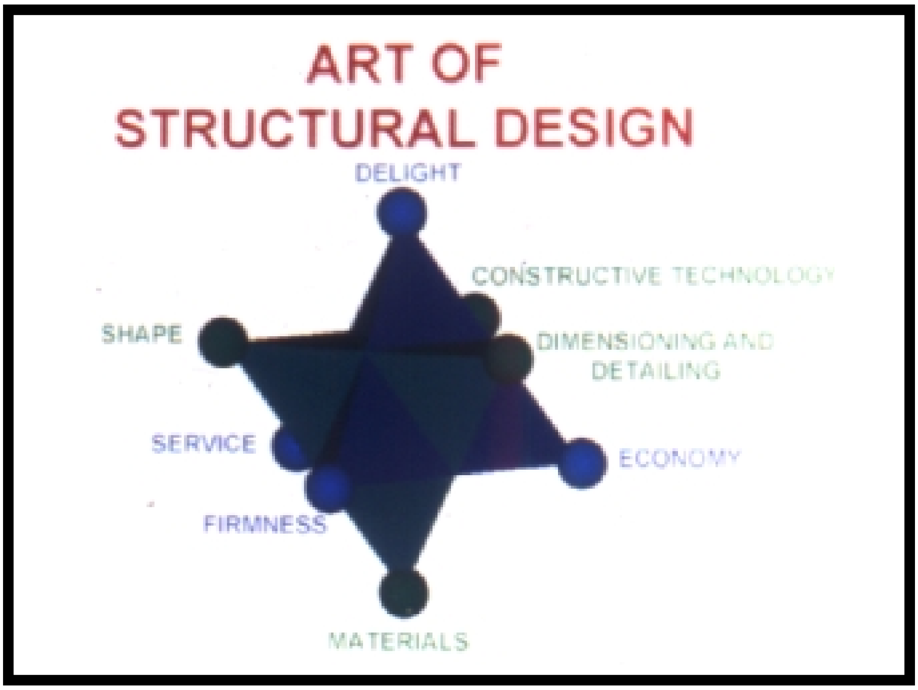


Fig. 4: *The synthesis of structural design* – Stella Octangula

called **loads** or, more generically, **actions**. These actions must be defined with a certain degree of precision and reliability. For some of them, like the gravitational loads owing to the weight of the structural materials themselves, this is relatively easy. However, it may become very difficult in the case of extreme effects, such as a large earthquake or a strong hurricane, which can only be defined in probabilistic terms.

Associated with the effect of actions upon the structure is the concept of fitness or adequacy of the form in its specific context. It is impossible to define this concept in positive terms. It can be defined in negative terms specifying whatever constitutes a misfit or unacceptable behavior and defining specific limits of tolerance for each possible misfit. The structure will be considered unfit or inadequate if any of these predefined limits is violated. This scheme of what constitutes an adequate behavior for each particular combination of actions is known as **limit state design**. When specific expected performances of the structural behavior are defined for particular levels of loads, the scheme is called **performance-based design**.

It must be emphasized that the entire process of creation of a structural form is context-dependent – historically, culturally and geographically – or, in synthesis, dependent on

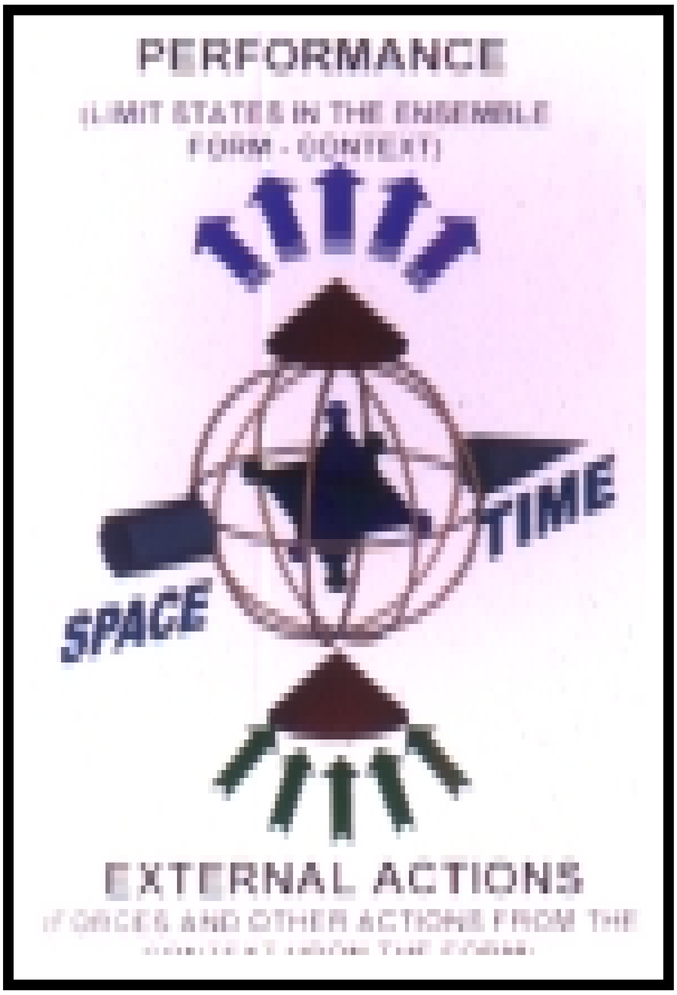


Fig. 5: *Actions derived from the context and adequate form-context behavior*

time and space. Hence, when evaluating the fitness or adequacy of a particular solution, it is essential to place the evaluation in the particular historic, cultural, socio-economic and climatic conditions of the context. These considerations are graphically represented in Fig. 5.

A theoretical framework as set forth here is essential for any attempt at a rational evaluation of the adequacy of structural forms. In its absence, all studies of structural and constructive fitness will end up being a catalog of construction details; without a set of criteria to identify what constitute adequate solutions worth disseminating and reproducing. As already mentioned, the conceptual framework is equally applicable to what Alexander calls **self-conscious** process of design, as performed by architects or engineers, or to **unselfconscious** processes resulting from traditional ways of construction that repeat proven solutions, without major changes, generation after generation.

Chapter Three

The Guadua Culture Region

# of Colombia and Ecuador

The bamboo houses, both traditional and non-traditional, of South America are built almost exclusively with one particular species of bamboo: the elegant, large, woody and straight *Guadua angustifolia* Kunth (Fig. 6), belonging to the genus *Guadua* (Soderstrom 1985, Soderstrom and Ellis 1987). According to McClure (1993), "Among the bamboos native to the Western Hemisphere, *Guadua angustifolia* is outstanding in the stature, mechanical properties (strength and workability) and durability of its culms, and in the importance their many uses have given this species in the local economy wherever it is available." Without doubt, *Guadua angustifolia* (termed Guadua hereafter, unless otherwise specified) is the most extensively used and economically important bamboo native to the New World (Judziewicz et al. 1999).

Many authors from different times and origins have provided vivid accounts of the history, the geography and the environmental conditions of the regions of Colombia and Ecuador where Guadua grows naturally. James J. Parsons, an emeritus professor of geography at the University of California, Berkeley, is the author of the excellent synthesis (Parsons 1991) that follows:

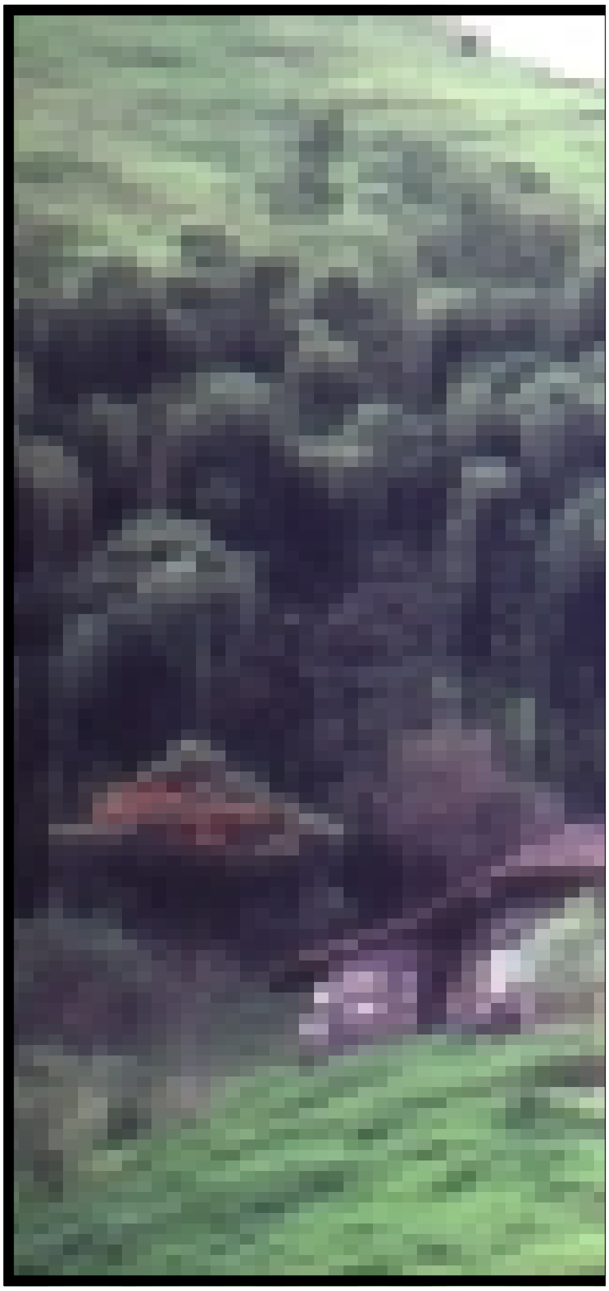


Fig. 6: Guadua angustifolia *in the Antiguo Caldas, Colombia*

The first Europeans to enter the western part of modern Colombia and Ecuador were struck by the extraordinary abundance and luxuriance of the tall, graceful, clump-forming “canes” that are known today as the giant American bamboo (*Guadua angustifolia* Kunth; *Bambusa guadua* Humboldt and Bonpland) or simply *caña* or *caña Guadua*. “Thick as a man’s thigh”, the bamboo prospered best on the well-watered volcanic and alluvial soils of the Ecuadorian coastal lowlands and the middle Cauca Valley in Colombia.

Early chroniclers were awed by the immensity and the extent of these canebrakes and by the diversity of uses that the native people made of the joined culms or stems. To Pedro Cieza de León, the first Spaniard to describe the Quindío region, domain of the sophisticated Quimbaya culture, the close bond between the native inhabitants and the widely distributed Guaduales was an indication of a large Indian population in past times. “All of this province”, he wrote, “is full of big and dense canebrakes that one only can move through with great effort”. In no part of the Indies had he seen canes of such size and abundance. The entangling stands were so dense that one could easily become lost in them. From the Río Cauca to the primitive Spanish settlement of Cartago (modern Pereira) the thickets of this majestic wild bamboo, known to the natives as Guadua, extended unbroken for some ten leagues and hid the small town from view until a traveller was upon it.

Alexander von Humboldt passed through the canebrakes in 1801 on his descent from the Quindío Pass across the Cordillera Central to the foothills of the Cauca Valley. He wrote in his narrative of the journey that “of all vegetation forms between the tropics the bamboo and the tree fern make the most powerful impression upon the imagination of the traveller”. In his time, the Quindío, a zone of rolling hills mantled by recent ash from the nearby volcanoes, was almost unpopulated, the aborigines having long since been decimated by war and European diseases.

Today the remaining groves of these elegant canes embellish a humanized landscape dominated by coffee, sugarcane and improved pasture from the

> department of Caldas southward beyond Popayán within the Río Cauca drainage in Colombia. Their extent is undoubtedly much reduced, as it likewise must be in coastal Ecuador, where shade-grown cacao is also part of the cropping complex. There, specifically in the rainier foothills of the Río Guayas basin north of Guayaquil, the handsome Guaduales must have been no less impressive, but early accounts are few. The denser Indian populations, and consequently the focus of Spanish interests, were in the drier areas along the coast and in the lower Guayas valley in environments lacking sufficient precipitation to support Guaduales. Nonetheless, the easy access by river to the bamboo forests facilitated the integration of the versatile giant cane into the material culture of the people of the littoral and has done so for at least five millennia, as is demonstrated by evidence of its use at the earliest archaeological sites.

Parsons even terms the regions of Colombia and Ecuador where the plant grows naturally as a Guadua culture region, stating “so closely is this striking plant linked to virtually every aspect of life and vernacular culture” (Parsons 1991). This region (Fig. 7) consists of two different areas separated by unpopulated parts of the middle and lower Río Patía drainage of southernmost Colombia. The northern area belongs to Colombia and corresponds to the region of the Antiguo Caldas comprising the Departments of Caldas, Risaralda and Quindío (whose capital cities are Manizales, Pereira and Armenia, respectively). This area is located in the high mountains of the Cordillera Central, bordered by the valleys of the Cauca and Magdalena Rivers. Some mountains reach 5 400 meters above sea level, although the Guadua rarely grows at altitudes higher than 1 700 meters. The southern region belongs to Ecuador and comprises the lowland coastal Provinces of Esmeraldas, Manabí and Guayas (the capital of Guayas being Guayaquil, the largest city of Equador and of the entire Guadua culture region). The climate is hot and very humid and the land is flat and prone to inundation. In both regions the annual rainfall exceeds 1 500 mm, which is excellent for the plant. The whole area is seismically active because of complex geotectonic processes, which are also responsible for the volcanism of the region.

For a systematic study of the typology of the traditional bamboo dwellings of this region, specific cultural, social and technological issues must be considered in addition to the already mentioned climatic and environmental factors.

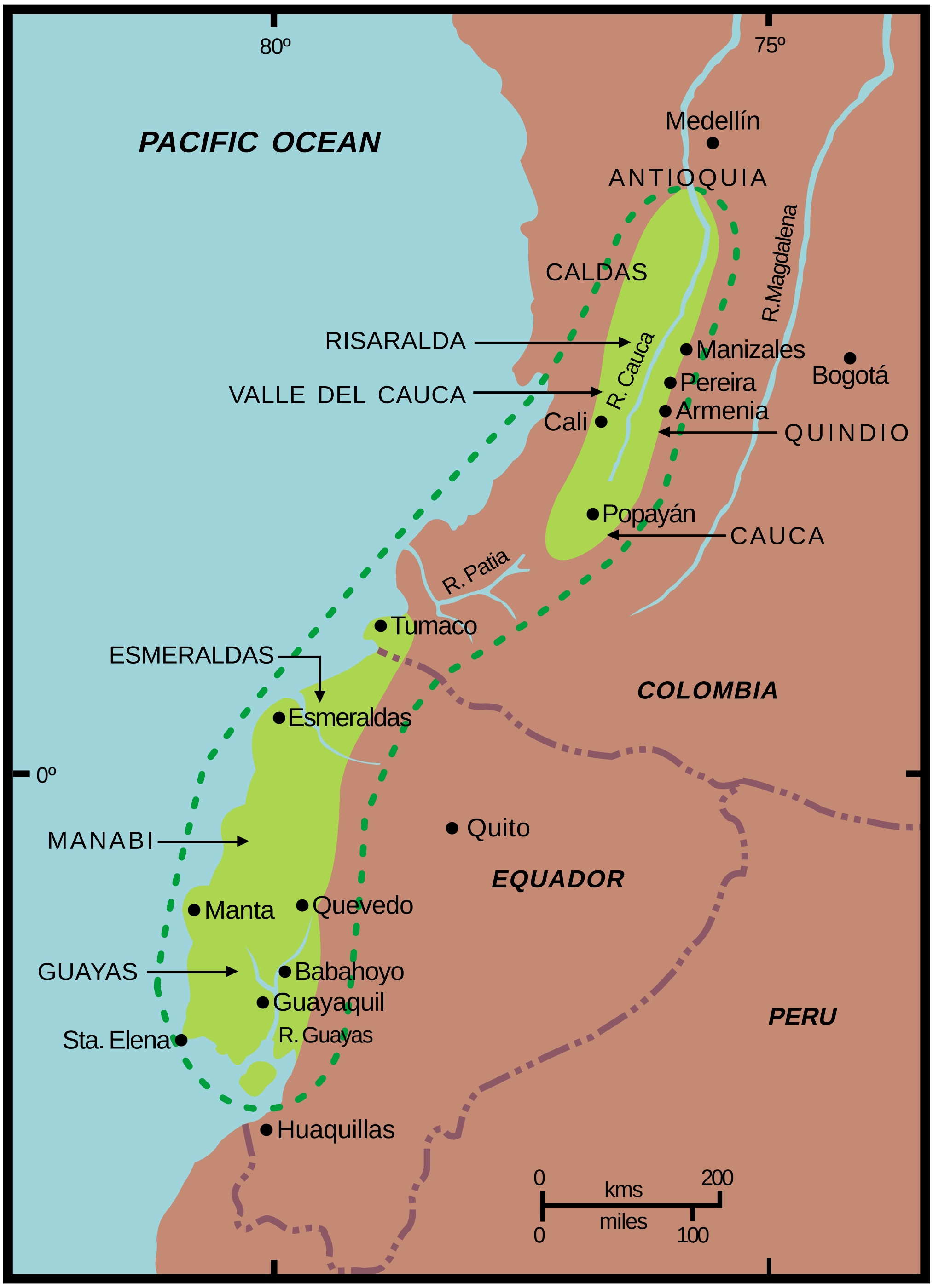


Fig. 7: *The Guadua culture region of Colombia and Ecuador (After Parsons 1991)*

Chapter Four

Types of Bamboo Houses in the Guadua Culture Region

For the purpose of this report, a bamboo house will be any house where bamboo is an important structural material, although other structural materials such as timber, adobe, mortar or vegetable fibers may also be used in the construction. In all parts of the world where woody bamboo grows naturally, it has played an important role as structural material for dwellings and other types of structures. However, the way it is combined with other structural materials varies considerably because house form is essentially a result of social, cultural, climatic and technological factors (Rapoport 1969).

The typologies of the houses of the Guadua culture region of Colombia and Ecuador present a very complicated blend of cultural and technological influences that do not necessarily represent the most adequate response to climatic or other local conditions. This situation also occurs with other structural materials in most of the traditional rural and urban centers of Latin America. The conquering European culture that was established in the early 16th century in this subcontinent apparently destroyed the indigenous culture, and imposed its religion, language and law. However, in the tension between the illusions and the facts of the conquest, a new culture started emerging from the very beginning of the process. Three oppressed main groups – the defeated indigenous populations, the mestizo*s* (a crossbreed of Europeans and indigenous Americans) and the introduced black African slaves – initiated what may be called the counter-conquest of Latin America: the cultural conquest of the conquerors by the defeated (Fuentes 1994). As a result, a new multiracial and multicultural society emerged. This autochthonous Latin American culture has received the name *El Mestizaje* or The Crossbreed. Many cultural manifestations, including traditional house forms, cannot be understood unless viewed from this perspective.

In the region of this study, the native Guadua bamboo was being used as a construction material for housing and other applications much before the arrival of the Spaniards (Parsons 1991, Robledo 1996). The material was ingeniously adopted later, as a substitute for timber, in house forms that earlier had European influence but eventually adapted to the new reality. Commercially, Guadua is widely available in the market as structural poles for the structure of walls, floors and roofs or as split *esterilla,* which is obtained by longitudinally cutting, flattening and removing the softer interior of the culms, and is used in walls and ceilings (Fig. 8).

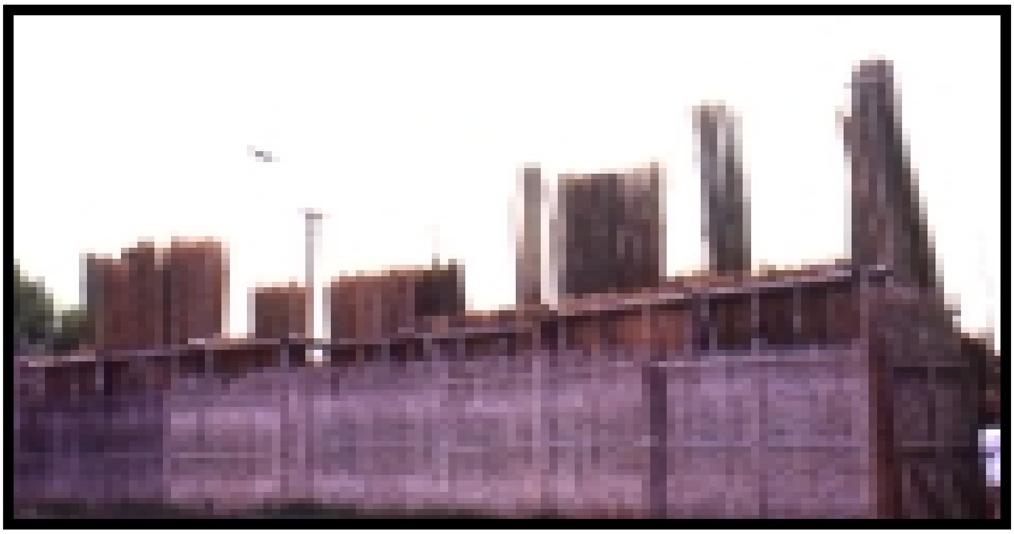


Fig. 8: *A yard for selling bamboo poles and split bamboo* (esterilla) *in Manizales, Colombia*

For the purpose of this study, four social categories will be defined, each one with different housing prototypes corresponding to their particular situations:

- **Rural**, built by peasants in small towns, large haciendas or small plots of land in the countryside. Bamboo is well accepted by most of these groups and new constructions continue reproducing the traditional techniques which, in some cases, are a synthetic blend of pre-Columbian and Spanish traditions.
- **Urban traditional**, corresponding to buildings and dwellings located in the downtown areas of the main cities (Guayaquil, Manizales, Pereira and Armenia) and larger towns. They were usually built in the first half of the 20th century, before cultural changes led to their rejection and the introduction of masonry, reinforced concrete and other modern materials. Many of these houses are still in use and very well preserved.
- **Urban marginal**, built in the large slum areas of the cities using whatever is available. Bamboo, being the cheapest material, is widely used but it is culturally rejected and regarded as a temporary solution.

- **Urban engineered**, the result of the efforts of architects and engineers who are totally convinced of the extraordinary potential of Guadua as a construction material, and are using it in housing projects for low- and middle-income groups (some use Guadua even in luxury houses for the very rich).

The solutions for each particular social category may have significant differences depending on their location in the two different climatic and environmental conditions – (a) the lowland coastal regions of Ecuador, or (b) the high-altitude, hilly Colombian region of the Antiguo Caldas. Housing types and construction techniques for each social category and, when applicable, for each climatic region are covered in the following section.

Rural Housing

In the coastal lowlands of the Guadua culture region of Ecuador, rural houses are made, almost exclusively, of vegetable material – bamboo poles for most of the structure, *esterilla* for walls and floors, palm leaves or grass for the roof and, where flooding is frequent, timber poles for elevating the floor from the ground. Owing to the hot climate, the *esterilla* of the walls, which in Ecuador is always placed in a vertical position, is left uncovered. This allows for the passage of breeze and produces an extremely light structure (Fig. 9). The houses may easily last over two decades, with the *esterilla* of the walls and the cover material of the roof being replaced every 4-5 years.[1] In Babahoyo, one can see houses built on top of balsa logs floating on the river, facilitating the mobility of their owners (Fig. 10).

In the rural areas near the urban populations, the houses maintain their basic features but the roof is usually corrugated iron (Fig. 11). The reason for this is that corrugated

[1] *This concept of "durability through substitution", though alien to the Western man, is strongly ingrained in the Oriental mind. For instance, in Japan and China, timber and bamboo have been extensively used for temples and palaces; the components are periodically replaced, preserving the ancient buildings with renewed materials. In some cases, the building is entirely rebuilt after a period of time as part of a religious ceremony, like the famous Japanese Shinto shrine of Ise in the south coast of Honshu, which is entirely rebuilt every 20 years (since AD 690), using timber from trees planted as part of the previous ceremony.*

Fig. 9: *A rural house in the lowlands of Ecuador (note uncovered* esterilla *walls)*

Fig. 10: *The floating houses of Babahoyo, Ecuador*

Fig. 11: *A rural house near Guayaquil, Ecuador, with corrugated iron roof*

Fig. 12: *A rural house near Manizales, Colombia, with tiled roof*

iron is relatively cheap, lasts longer and is easier to replace and more efficient against rain, although it is less pleasant as it causes the temperature inside the house to increase significantly.

The use of the *esterilla* is different in the rural houses of the Antiguo Caldas, Colombia. There, because of the cool mountain climate, the *esterilla* of the walls is placed in double layers – at both sides of the timber or bamboo poles – and then plastered. The plaster was originally made with a mixture of mud and horse dung, called *cagajón.* Later on, when it became commercially available, Portland cement became the choice mortar material. The roof is usually made out of bamboo and covered with clay tiles, resulting in a house with an entirely different appearance (Fig. 12).

The house described above is a typical example of a construction technique that is extensively used in many countries of Latin America since the colonial times, and still in use in the region of this study: the *bahareque.* It is a wattle-and-daub technique that normally uses timber poles for the wall structural frames and two different procedures for the walls. The first – known as *bahareque macizo* or solid *bahareque* – uses spaced horizontal canes or bamboo laths whose purpose is to hold the mud, sometimes combined with broken tiles, that is placed in the interior. The second – known as *bahareque hueco* or hollow *bahareque* – uses a double layer of horizontal bamboo *esterilla* (in some places, closely spaced small diameter horizontal canes) as a supporting surface for the mortar, which is plastered on both outer faces (Figs. 13a & 13b). As will be explained later, this second procedure, when plastered with cement mortar, results in a very effective structural component.[2]

As mentioned, these construction techniques are used also in other Latin American countries like Guatemala (Nino 1998) and Costa Rica where FUNBAMBU, the well-known institution that introduced bamboo for social housing in that country, uses a very rational and economical variation with a light, non-hollow, single layer (Gutiérrez 1998).

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[2] *For this reason, whenever the structural properties or behavior of* bahareque *is referred to in this report, the reference is to hollow* bahareque*.*

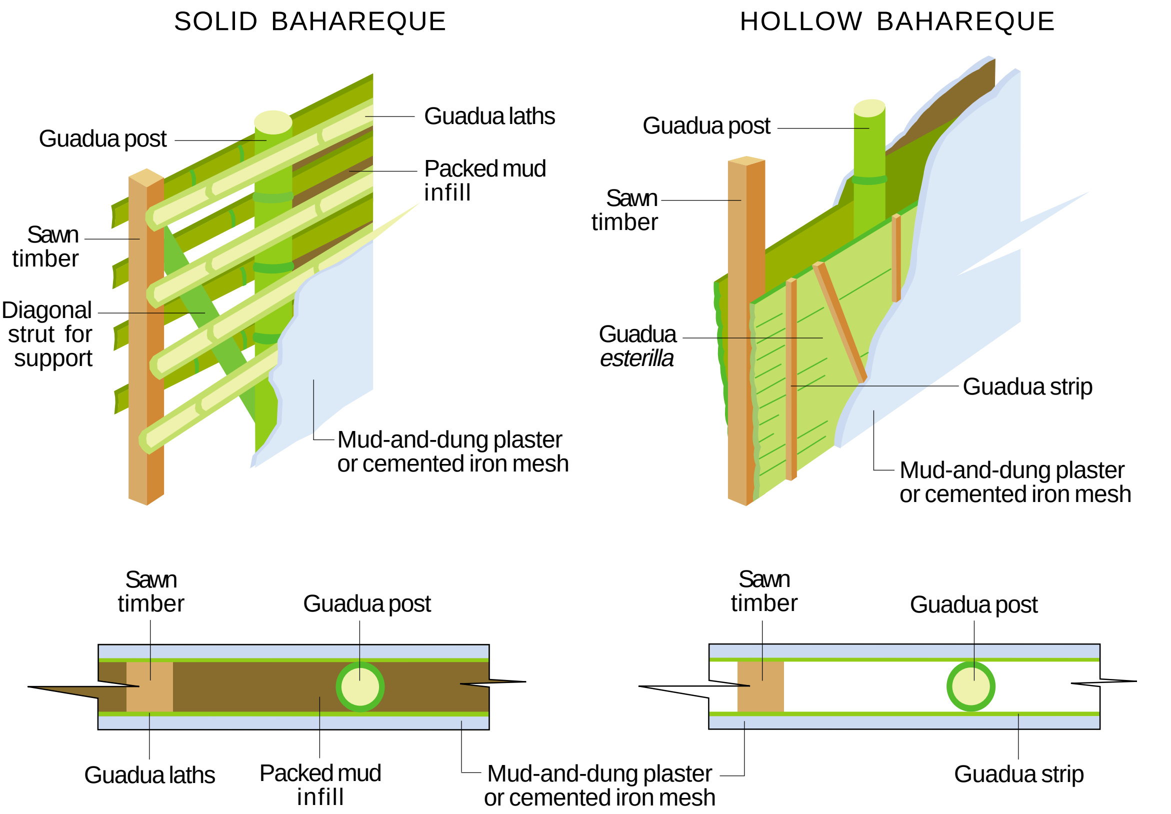


Fig. 13a: *The solid (left) and hollow (right)* bahareque *techniques (Robledo 1996)*

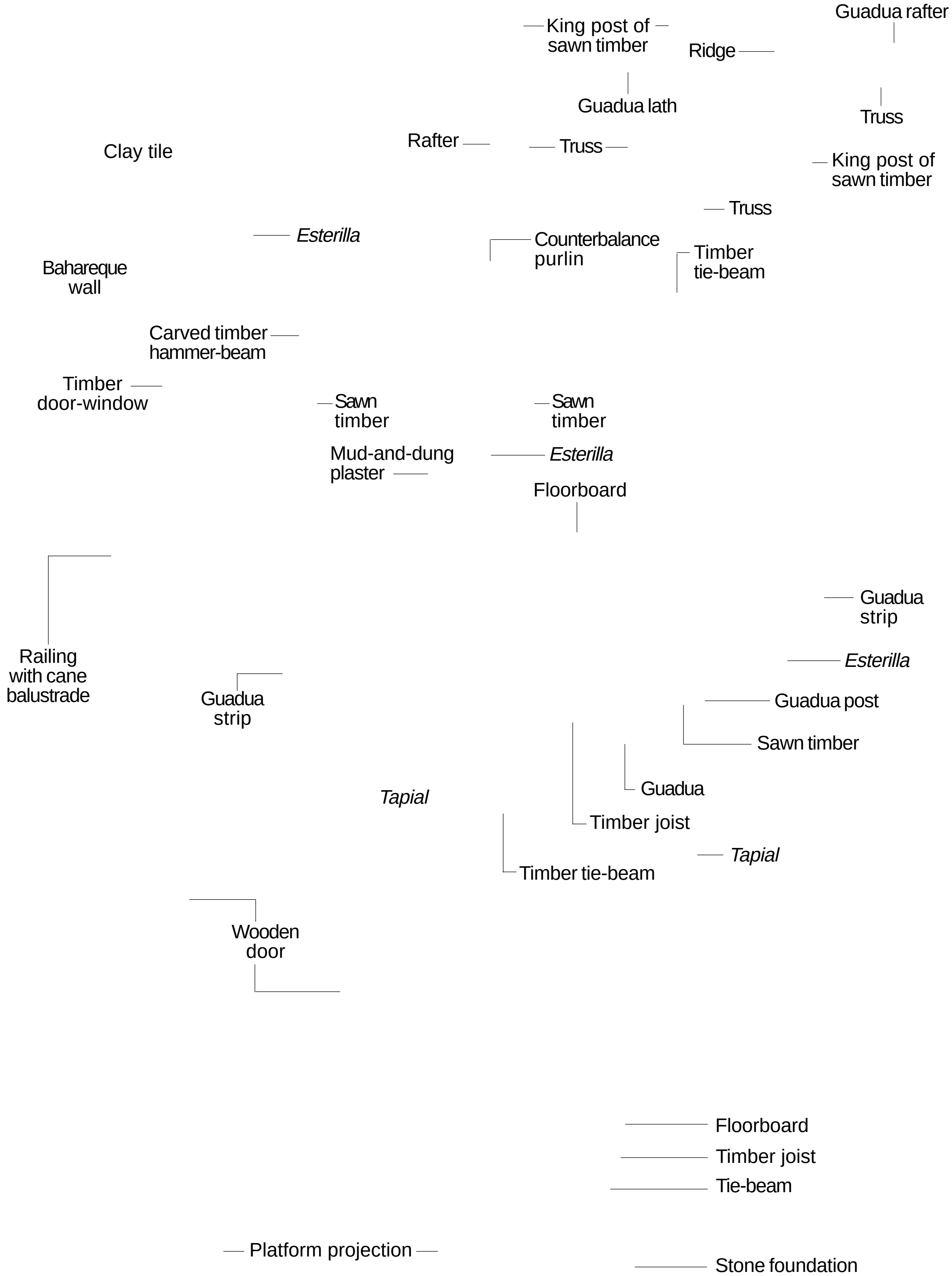
Fig. 13b: *A wall built using the solid* bahareque *technique*

The interesting thing about *bahareque* construction in the Antiguo Caldas is that the original settlers, who came from nearby Medellin in the second half of the 19th century, were culturally fixed to the construction technique of rammed earth walls, known in Spanish as *tapial.* In this technique, brought from Europe by the early Spanish settlers, very thick walls are built by earth filled into a formwork in layers of up to 10 cm and thoroughly compacted to a thickness of 6-7 cm with a ramming tool. When the formwork is full with compacted earth, it is dismantled and moved to the next position, fixing it firmly over the previously completed row. In this way the building goes up gradually, layer by layer (Stulz and Mukerji 1988). Needless to say these are very massive and heavy walls with almost nil tension capacity, and are very vulnerable to even minor earthquakes. As a consequence, the socially rejected but technologically superior *bahareque* gained its place when the frequent earthquakes convinced the settlers that there was no other choice, and a *temblorero* or earthquake-proof style emerged. Around 1884, a hybrid method was introduced. It used the elegant but weak *tapial,* or sometimes brick, in the first story and the lighter but stronger *bahareque* in the second (Fig. 14). By 1917, *bahareque* was firmly established as the construction technique for the complete building (Robledo 1996).

It is interesting to note that the *temblorero* style using Guadua inside the hollow *bahareque* was initiated in the city of Manizales, but eventually found its way to the rural houses and *haciendas* of the Antiguo Caldas, providing the region with a distinct personality (Fig. 15). Unlike in the cities, the people of the rural areas regard bamboo housing in high esteem. This is also true for the lighter bamboo houses of the rural areas of Ecuador.

Urban Traditional Housing

For the reasons already cited, there is an evident and logical similarity between the rural and the urban traditional houses of the Antiguo Caldas – especially the old houses built in the small villages and towns which have survived the frenzy of urban renewal. In towns like Salamina or Neira, to mention some of the most representative, it is still possible to see houses that have the basic features previously discussed, but in a larger



Guadua rafter
King post of sawn timber
Ridge
Guadua lath
Truss
Clay tile
Rafter
Truss
King post of sawn timber
Truss
Esterilla
Counterbalance purlin
Timber tie-beam
Bahareque wall
Carved timber hammer-beam
Timber door-window
Sawn timber
Sawn timber
Mud-and-dung plaster
Esterilla
Floorboard
Guadua strip
Esterilla
Railing with cane balustrade
Guadua strip
Guadua post
Sawn timber
Guadua
Tapial
Timber joist
Tapial
Timber tie-beam
Wooden door
Floorboard
Timber joist
Tie-beam
Platform projection
Stone foundation

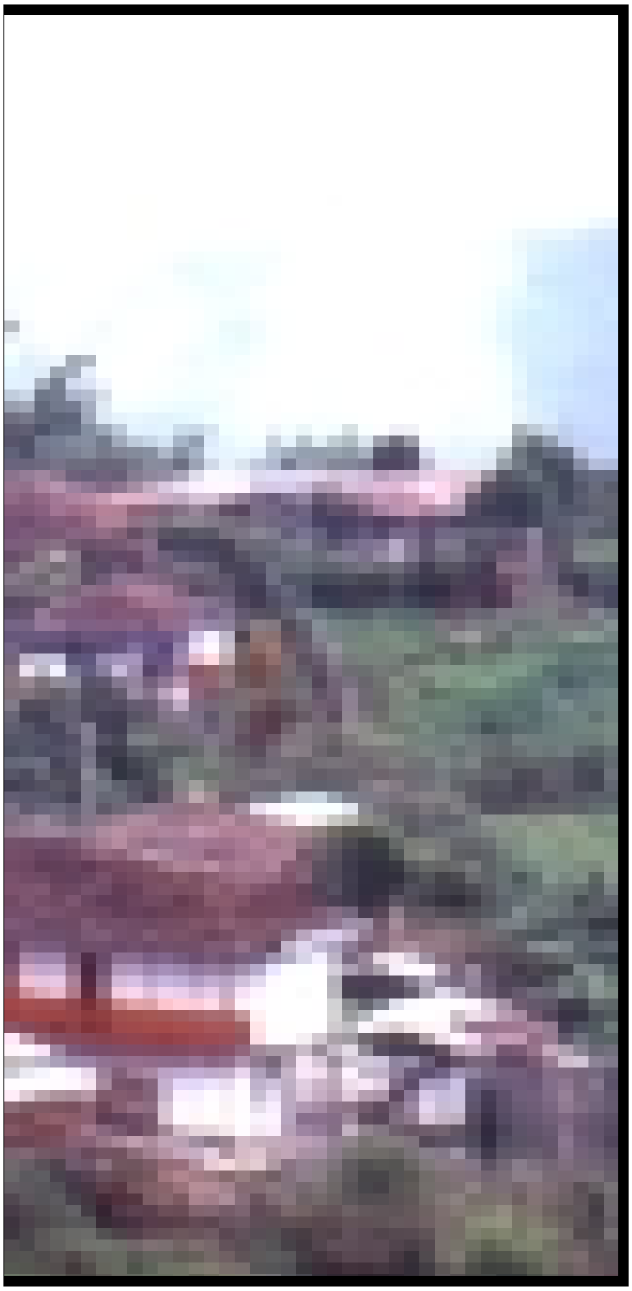
and taller scale (Fig. 16). Many of those houses, which are more than a century old, are in excellent condition (Fig. 17), giving a clear indication of the capacity of the bamboo *bahareque* to resist not only the weathering but also the moderate and strong earthquakes that frequently strike the region.

Although the towns of Antiguo Caldas were originally initiated in the upper and flatter parts of the mountains, they spread down the steep hills as they grew (Fig. 18). This condition creates extremely difficult construction problems that the early settlers learned to tackle with great success. The people of the hilly villages and cities of the Antiguo

(previous page)

Fig. 14: *The* temblorero *(hybrid* tapial-*and*-bahareque*) construction (based on Robledo 1996)*

Fig. 15a *(below)* **& b** *(following page)***:** *The* temblorero *houses in Antiguo Caldas*



Caldas became real experts in the art of constructing houses and other buildings on steep lands (Fig. 19). Even the builders of marginal houses exhibit this specialized knowledge, as will become apparent in the next section.

From the structural point of view, these dwellings and buildings have the basic characteristics to be firm in a seismic region. One, they are quite regular in height, and have exterior mortar walls that are continuous from the base to the top to avoid unnecessary setbacks. Two, they are light because of the hollow *bahareque* of the walls and the timber floors. Three, they have a timber-and-bamboo structural frame, which is built to provide the necessary continuity to the vertical, horizontal and diagonal structural elements for the transmission of vertical gravitational forces and horizontal seismic or wind forces, from their point of application to the ground. They even possess some clever architectural protective devices against wear from weather – like the generous roof eaves that protect the walls against the frequent rains of the region, and the brick or stone foundations that raise the timber and bamboo of the walls to separate them from the moisture of the ground.

In the larger cities of the Antiguo Caldas (like Manizales, Pereira and Armenia), the status of

Fig. 16: *Old urban-traditional housing in Antiguo Caldas (Salamina, Colombia)*

Fig. 17: *A bamboo* bahareque *house in Salamina, Colombia*

Fig. 18: *A bamboo* bahareque *town on a hill: Salamina, Colombia*

bamboo *bahareque* construction may be less evident but it is equally important. As mentioned earlier, in the city of Manizales, the socio-economic conditions and the earthquakes created a need for the *temblorero* style based on the *bahareque.* However, bamboo was not the first choice for *bahareque*; it was the last. The first choice naturally was sawn timber, for structural walls, floors and even roofs. Owing to the scarcity and the consequent high price of timber, a second alternative was found in *arboloco* (literally "crazy tree"), a straight, hollow, woody plant, which grows naturally in the area (Fig. 20). It is mechanically very strong, very resistant to insects and fungi, and has excellent characteristics for poles (and even beams) such as thick walls and high strength under transverse compressive forces (Fig. 21). Only when timber and *arboloco* were not available, Guadua was used as a structural component (Robledo 1996).[3]

[3] This may explain the social rejection of bamboo as a construction material among the upper and middle classes of the larger cities.

Fig. 19: *Some bamboo buildings built on a slope in Salamina, Colombia*

(opposite page)

Fig. 20: Arboloco *in the surroundings of Manizales, Colombia*

Fig. 21: Arboloco *as a structural joist in a* bahareque *construction*

The frequent and devastating fires that destroyed large portions of these cities also contributed to the rejection of Guadua. The city of Manizales was severely damaged by large fires in 1922, 1925 (229 buildings in 32 blocks destroyed) and 1926 (Robledo

Fig. 22a *(above)* **& b** *(opposite page): Bamboo* bahareque *in modern constructions (Manizales, Colombia)*

1996). The fires were basically due to unsafe conditions in the electric power distribution system and in the electrical installations inside the buildings, as well as to the absence of efficient fire departments.

However, when the city was rebuilt, adopting and adapting the canons of modernism, bamboo *bahareque* continued as a predominant construction technique for a long time. Entire buildings in the downtown area are still bamboo buildings, although the elaborate shapes of their facades may confuse all but the very knowledgeable (Fig. 22). In some cases these buildings present a very elaborate facade, whereas the lateral and even the back sides are of exposed *esterilla* (Fig. 23). Modernism also extended to the new neighborhoods built in the early 1930s, as can be seen in many beautiful surviving examples built using bamboo *bahareque* covered with cement mortar (Fig. 24).

The key aspects of the urban traditional houses built on the mountains of the Antiguo Caldas can be seen also in the houses in the low, hot and humid city of Guayaquil, Ecuador. It is evident that bamboo *bahareque* with cement mortar was introduced there

for cultural and technological reasons, regardless of climatic considerations – the technique allows the construction of elegant and varied shapes acceptable to the upper and middle classes. One can find many *bahareque* houses and buildings in downtown Guayaquil (Fig. 25). In the old quarter of Las Peñas – a hilly, rocky place near the downtown area – there are many old *bahareque* constructions which, because of the sloping site and construction characteristics, resemble Manizales (Fig. 26).

The impressive old building of the University of Guayaquil (Fig. 27) is made of bamboo and is currently being restored using the same original construction techniques

Fig. 23a & b: *A* bahareque *building with exposed* esterilla *walls at the back and sides (note that the steep site allows five stories in the back to the two in the front)*

Fig. 24: *A modern* bahareque *house in Versalles (Manizales, Colombia)*

Fig. 25: *A bamboo bahareque building in downtown Guayaquil*

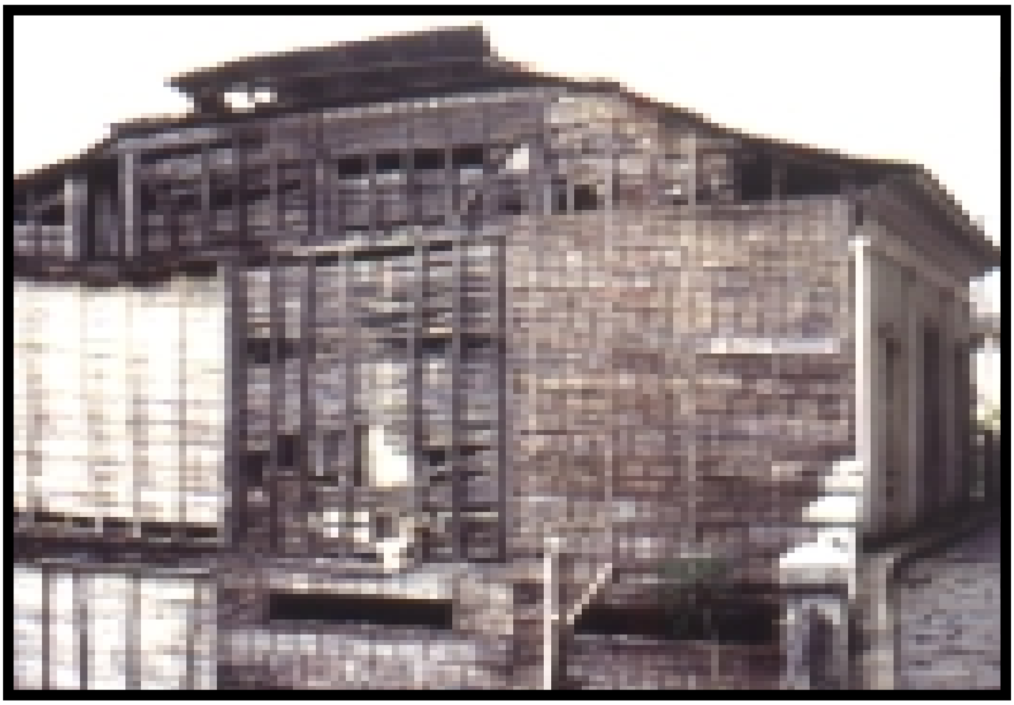


Fig. 26: Bahareque *construction in Las Peñas, Guayaquil*

Fig. 27: *The facade of University of Guayaquil building*

Fig. 28: *University of Guayaquil building – detail of interior restoration*

(Fig. 28). The restoration work presents the opportunity to admire the quality of workmanship displayed in the assembling of the timber structure (Fig. 29). It reminds one of the construction traditions of the old timber-framed houses with wattle-and-daub infill built in England (Harris 1993) and other European countries – such as

Fig. 29: *University of Guayaquil building – workmanship of the timber framework*

Germany, France and Spain – during Medieval and Renaissance times. In the case of Guayaquil, this high quality of timber workmanship is generally attributed to the presence of an important shipyard tradition existing since colonial times. However, the evidence of a technological transfer from Europe in the timber *bahareque* traditions of Latin America cannot be downplayed; Guadua would then be a new material for an old construction tradition.

Urban Marginal Housing

Perhaps nowhere in the Guadua culture region of Colombia and Ecuador is the ingenuity of man in the use of bamboo as a construction material more evident than in the vast extensions of slums, crowded with informal marginal houses, that surround most of the larger cities. There, in sites steep enough to be in permanent risk of landslides and in lowlands inundated with contaminated water, lives a large part of the population in vast slums that keep growing at rates much higher than those of formal construction. Most of the inhabitants are recent migrants from the rural areas, lured by the mirage of better opportunities in the city. In these slums bamboo is the construction material. But as in slums all over the world, here too it is regarded as "poor man's timber" and held in low esteem.

It is an extremely difficult task to describe housing types so numerous and varied, but a selection of the most conspicuous can be presented.

The slums having the worst conditions in the entire Guadua culture region are those found in the outskirts of Guayaquil. Hundreds of thousands of squatters live here in unstable landfills or flooded areas under extremely deprived conditions (García-Rios 1992, CEAFAX 1997). An organization named "Viviendas Hogar de Cristo", founded and run by Jesuit priests, has been producing low-cost bamboo houses in this area. The cost of a two-room basic house is $360, usually sold with significant subsidies for the very poor. The organization has a large manufacturing plant to produce a few basic types of prefabricated bamboo panels made out of bamboo *esterilla* and laths (Fig. 30). Seven of these panels can be assembled to produce the basic two-room house, which can then be roofed with corrugated iron or similar materials. The output capacity of the

Fig. 30: *Viviendas Hogar de Cristo plant for manufacturing bamboo panels*

plant is 15 prefabricated houses a day. More than 23 000 units have been produced in a 25-year period (CEAFAX 1997). The basic house – composed of the seven panels, the roof, the timber floor and the base poles necessary to raise it from the ground – is sold as a package. It is usually assembled by the owner, with the help of some hired skilled labor. A more elaborate two-story model, with concrete masonry in the first floor and bamboo panels in the second, is displayed at the entrance to the plant (Fig. 31).

Even if these slum houses do not look as neat as the model house displayed in the manufacturing plant (Fig. 32), there is no doubt that the situation would have been much worse (Fig. 33), and perhaps more expensive, without this alternative. The different individual tastes are evident in some of the improvements and changes introduced to these simple houses (Fig. 34). In one particular case, the cultural fixation with masonry as the ideal construction material became evident in the painting of concrete blocks in the facade of the *esterilla* wall (Fig. 35). Without technical supervision, however, real masonry work can sometimes lead to disaster (Fig. 36).

The situation is less dramatic in the slums of Manizales. The site conditions are healthier and safer than in the flooded lowlands of Guayaquil, and the population much smaller and their economic conditions less critical. Although the slums are built on steep hills

Fig. 31: *A two-story bamboo-and-concrete house made by Viviendas Hogar de Cristo*

Fig. 32: *Viviendas Hogar de Cristo bamboo housing in the Bastión Popular slum in Guayaquil*

Fig. 33 *(above & below)*: *Different types of bamboo housing in the Bastión Popular slum*

Fig. 34: *Expression of individual tastes in bamboo houses in the Bastión Popular slum*

Fig. 35: *"Rejection" of bamboo* – esterilla *wall painted over as concrete masonry*

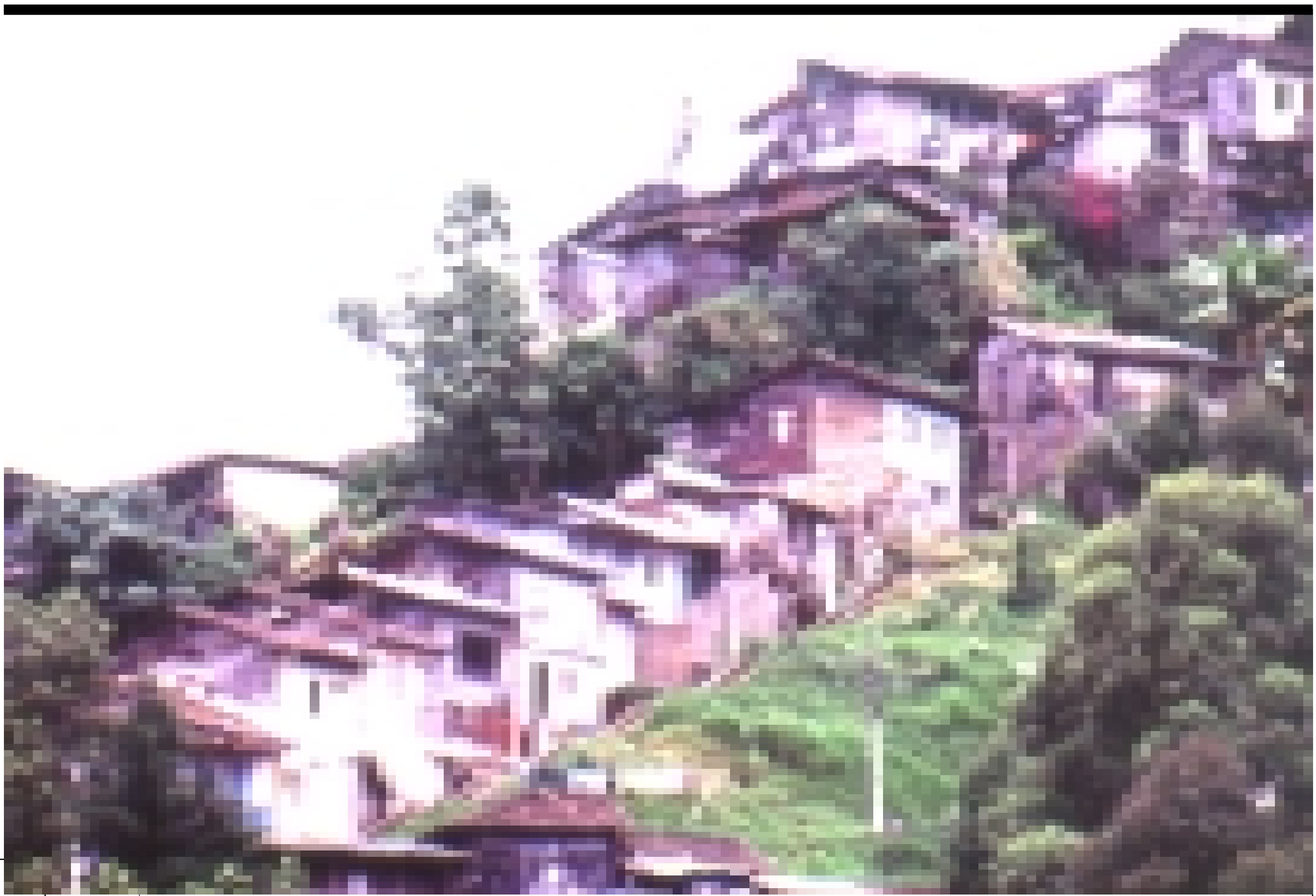
Fig. 36: *Failure of masonry house built without technical supervision in the Bastión Popular slum*

that have not seen any urbanization attempt (Fig. 37), the topographic conditions are not very different from most of the recently urbanized land. Bamboo is again the predominant material, used as structural posts, beams and *esterilla,* producing an extremely light structure (Fig. 38). The houses literally hang from the top of the hills

Fig. 37: *Slums of Manizales*

Fig. 38: *Light bamboo housing in Manizales: (a-previous page) general view; (b-above) detail*

Fig. 39: *Bamboo houses of a Manizales slum clinging on to a steep hill*



forming a continuous structure, built using techniques learned since the colonization of the region (Fig. 39).

The main problem of these constructions lies in the cultural rejection of bamboo as a construction material. Most people inhabiting these houses aspire to live in a masonry house. As a consequence, when their income allows them, much heavier masonry walls gradually substitute the lighter bamboo walls. Quite frequently, these new walls are not properly attached to the remaining original ones or to the structural elements, resulting in additional unnecessary masses and weights placed in completely unstable conditions. The combined effect of these conditions has proved fatal in the event of earthquakes, which usually topple the walls, endangering lives and damaging the rest of the structure in the process. This unfortunate situation was quite evident during the recent Quindío earthquake (25 January 1999), and was responsible for much of the damage suffered by the bamboo houses (discussed later in this book).

Urban Engineered Housing

In the last decades, as a result of the work of early pioneers (Hidalgo 1974, Castro 1985), an ever-growing number of architecture and engineering professionals, living and practicing in the Guadua culture region, have assumed the challenge of using bamboo as a construction material for low-income housing, providing engineered solutions to house designs. The term “urban engineered housing” is used in this report to characterize this promising trend that could eventually incorporate Guadua as an engineering construction material, overcoming its negative social connotations.[4] Some architects are even using the material for luxury houses, built for the very rich, in a deliberate attempt to accelerate its social acceptance (Villegas 1989).

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[4] The houses fabricated by the Viviendas Hogar de Cristo belong, in principle, to this category. However, most of them are usually assembled by the owners who are not aware of the technical aspects. For instance, they have the freedom to raise the houses on top of poles and, to a lesser extent, to combine the panels in different architectural distributions. In other words, the customers receive the structural and architectural components that are later assembled by them with little technical assistance. For this reason, such houses were included in the previous section, under urban marginal housing.

Fig. 40: *The interior of an engineered bamboo* bahareque *house, designed by Arch. Jaime Mogollón and financed by ICT, Manizales*

Fig. 41: *Corona-ICT housing project (El Encuentro) in Manizales, designed by Arch. Diaz & Mogollón*

Fig. 42: *Malabar project, Manizales, designed by Arch. Jorge Arcila*

In Colombia, bamboo as an engineered material gained momentum when the Instituto de Crédito Territorial (ICT) – the state organization in charge of the development of housing programs for the most deprived social groups – accepted bamboo as a construction material for their projects. Almost immediately, original and rational designs were conceived and built, some of them still in excellent conditions more than twenty years later (Fig. 40). Later on, a large private company – Corona Corporation – gave an additional boost to bamboo housing by sponsoring open competitions among professionals. One of the winning projects, built with ICT funding, used prefabricated bamboo-timber panels for the interior walls (Mogollón 1993). Most of those houses are still in very good condition (Fig. 41).

Even more ambitious was the Malabar project, developed by Arch. Jorge Arcila for ICT. Built on the typical steep hills that surround Manizales, the project adapted the dwellings to the characteristics of the terrain, resembling the methods and techniques used by the marginal constructors (Fig. 42). The clever architectural design of the project provides each family with a basic area – living room, bedroom, kitchen and bathroom – that can be extended to an extra room by closing the open space created by the inclined topography, providing at the same time the necessary space for communal facilities (Arcila 1985). After more than 15 years of construction, however, the differences in the maintenance practices among individual owners have become apparent (Fig. 43).

Fig. 43: *Houses in the Malabar project after 15 years: (a-above) well-maintained; (b-below) ill-maintained*

Also, the already mentioned dangerous habit of substituting the light *esterilla* walls with heavy and loose masonry walls has become a practice (Fig. 44).

A more recent and bolder low-income housing project is the Divina Providencia developed by Arch. Gilberto Florez in another hilly site in Manizales (Fig. 45). These houses extensively use round bamboo as structural element in walls and roof, and as vertical poles for the balconies (Fig. 46). However, instead of using *esterilla* for the in-fill panels of the walls, a single layer metallic mesh having both sides covered with cement mortar is used (Fig. 47). This departure from tradition has been severely criticized by the more orthodox professionals who wish to have bamboo almost exclusively used as structural components (Florez 1998).

All the housing projects so far mentioned have been developed in the city of Manizales, Colombia, where Guadua as a compromise option for engineered housing construction

Fig. 44: *Addition of heavy masonry to the light structures designed in the Malabar project*

Fig. 45: *The Divina Providencia project developed by Arch. Gilberto Florez*

Fig. 46: *The Divina Providencia project uses bamboo as (a-left) structural element and (b-right) poles for balconies*

is quite strong. In other Colombian cities and in Guayaquil also, there are engineers and architects dedicated to the use of bamboo as a construction material, such as the Ecuadorian architect Jorge Morán (Morán 1986, 1987). Besides regularly offering technical advise to hundreds of users of bamboo houses in the slums, he has introduced bamboo technologies in the university curricula and has built some engineered bamboo structures (Fig. 48).

Fig. 47: *The Divina Providencia houses have in-fill, plastered metallic mesh walls*

Fig. 48: *Colegio Nuevo Mondo in Guayaquil, designed by Arch. Jorge Morán*

As mentioned earlier, some architects have decided to use Guadua for luxury houses in a deliberate attempt to accelerate its social acceptance. Perhaps, the most prominent among them is the Colombian architect Simón Velez, who has achieved worldwide reputation for his imaginative projects where bamboo and other neglected vegetable fibers are blended with modern materials like reinforced concrete or steel. Velez seems to be more a structural artist than an architect, always pushing the material to its structural limits. Some structures, built in Colombia and Ecuador, illustrate these daring possibilities for Guadua (Fig. 49).

Fig. 49: *Bamboo structures for the wealthy designed by Velez: (a & b) Km 41 House, Caldas*

Fig. 49: *Bamboo structures for the wealthy designed by Velez: (c & d) Goldbaum House, Guayaquil*

Unfortunately, with the gradual acceptance of Guadua in upper and middle-income housing, some of the traditional techniques that in the past had guaranteed the adequate structural behavior and durability of the material, are being neglected. Bamboo is a material with its own strengths and weaknesses, and these must be well understood in order to take advantage of the first and avoid the second. Otherwise, the structural soundness of the building will be at peril. Already, with the advent of modernism in the first half of the 20th century, some convenient traditional techniques – like the generous roof eaves that protected the material from the rain – were eliminated or reduced. This becomes particularly evident in some old corner buildings that underwent remodelling on only one of their sides owing to urban changes in the street adjacent to that side (Fig. 50). Another frequent misuse is the combining of bamboo with more durable materials, such as reinforced concrete or masonry, in such a way that it cannot be easily replaced when the need arises (Fig. 51).

Fig. 50: *Inappropriate reduction of roof eaves as a sign of modernization (Manizales)*

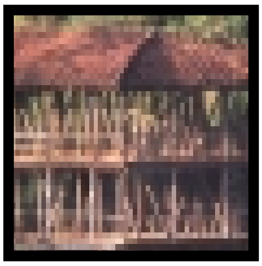
Fig. 51: *Bamboo embedded in longer-lasting masonry (Pereira)*

Some of the worst examples of improper bamboo construction can be observed, unfortunately, in the modern Centro Nacional para el Estudio del Bambú-Guadua (National Center for the Study of Guadua Bamboo), near the city of Armenia in Colombia, created for the promotion of Guadua in its many applications. Here, in a few demonstration bamboo houses, the visitor can see a collection of technical and construction mistakes. Prominent among these are: vertical bamboo poles placed directly on the floor without the necessary pedestal; elements loading other elements at inadequate places; and oversized but poorly jointed elements (Fig. 52). This clearly shows that, together with the promotion of bamboo as a construction material, there is a need to preserve and transmit the traditions that were clearly understood by the craft workers of yesterday but may be lost to the professionals of tomorrow.

Fig. 52a, b, c & d: *Examples of improper construction in bamboo housing (demonstration units at Centro Nacional para el Estudio del Bambú-Guadua in Colombia)*

Chapter Five

Structural Characteristics and Behavior of Bamboo Houses



It is evident from the previous section that the types of houses in the Guadua culture region of Colombia and Ecuador are the result of diverse social, cultural, economic and technological factors, as well as of climate and topography. Nevertheless, from the structural point of view, they are very similar: all of them have a basic structural skeleton made out of timber and bamboo in proportions basically related to the socio-economic conditions of the owners. This skeleton is responsible for the resistance to the vertical loads owing to the weight of materials themselves (dead or permanent loads) and to the weight of the users and their related objects (live or temporary loads). All these loads are transferred from the roof and the floors to the vertical elements which, in turn, carry them through the foundations to the ground.

For the horizontal actions caused by earthquakes and extreme winds, two entirely different conditions are present. In houses where walls are built with bare bamboo (not covered with mortar), the horizontal loads are resisted basically by diagonal elements placed in the vertical walls and supports and, to a much lesser extent, by the moment capacity of the joints. Alternatively, when the walls are plastered with mortar, especially cement mortar, they behave like a composite material with a strength and stiffness far superior to the one provided by the skeleton alone. For earthquake effects, the forces are proportional to the masses of the structure; consequently, they will increase for houses having plastered walls. Wind effects are essentially insensitive to this condition.

In this section, the requirements for a proper engineering analysis and design of structures are discussed first. This is followed by a presentation on the structural behavior of bamboo housing under vertical gravitational loads and the response of these structures to seismic and wind actions. Finally, evidence on their behavior under earthquakes will be analysed, including the effects of the earthquake that struck the Antiguo Caldas in January 1999.

Engineering Analysis and Design of Structures

For thousands of years man has been able to build structures without the tools of modern structural analysis and design based on engineering sciences. Some of these structures were simple dwellings demanding little specialized knowledge, but others were extraordinary structures that have survived until our days and still amaze us. The earliest record of an analytical estimation of forces for structural engineering purposes was done by Poleni in 1748 for the reinforcement of the immense dome of St. Peter's Basilica in Vatican, Rome (Francis 1995). However, most of the major structures of the 19th century were designed and built without the help of engineering science, using trial-and-error procedures typical of the unselfconscious procedures mentioned earlier.

On the other hand, almost all major structures of the 20th century were built with modern materials like steel or reinforced concrete, using rational methods of analysis and design based on engineering science. Timber, a traditional material, became the subject of comprehensive scientific and technological studies and gained a well-deserved place among modern engineering materials. Bamboo, though a traditional construction material for thousands of years, has still to gain an equivalent status.

Two basic requirements are needed for a material to become an engineering material:

a. Reliable knowledge of its physical and mechanical properties; and

b. Proper engineering recommendation for the structural design of its elements, components and joints – what constitutes a Design Code.

Significant efforts have been made in the study of the physical and mechanical properties of bamboo (Janssen 1991), but the tremendous variety of species demands much more work as well as the definition and adoption of International Standards to guarantee objective and meaningful data. The International Network for Bamboo and Rattan (INBAR) has been working along these lines as well as on a Design Code proposal and there are reasons for optimism in the near future (Janssen 1996).

Although the physical and mechanical properties of Guadua have been studied (Sotela 1991a, 1991b; Gnanaharan et al. 1994) and methods have been proposed for the structural design of bamboo elements and some of their joints (Arce 1993), it is not possible to produce reliable models for the structural analysis of traditional constructions like the ones that are the subject of this report. Therefore, the study of these structures under load is not based on quantitative numerical analyses but on qualitative interpretations of their observed behavior, complemented with some available experimental results.

It is convenient to visualize the structural system of a building as consisting of three main subsystems – the horizontal, the vertical and the foundation structural subsystems. The horizontal subsystem is formed by the roof and the floors that directly receive the applied loads and transfer them to the corresponding elements of the vertical subsystem, which in turn will transfer them to the supporting site through the foundations. For methodological reasons, the structural characteristics and behavior of these buildings will be analysed for vertical gravitational loads first and for horizontal earthquake and wind loads later. In both cases, the horizontal, the vertical and the foundation structural subsystems will be considered separately.

Behavior under vertical loads

The main advantage in the study of the behavior of structures under gravitational vertical loads is their permanent nature. The structure must support its own weight, as well as the weights derived of its use, which may experience only minor variations during its lifetime. Therefore, any problem related to lack of capacity of the system to support these loads will become apparent from the very beginning through excessive deflections and deformations, local failures, minor cracks, etc.

As far as the horizontal structural subsystem is concerned, the roof structures of traditional bamboo houses can vary from simple bamboo rafters covered with palm (as in the rural houses of the coastal region of Ecuador) to timber trusses with bamboo rafters and clay tiles (as in the urban houses of the main cities) (Fig. 14). In general, the roof will not present structural problems unless there are unattended leaks that may very quickly deteriorate some of the structural materials.

As already stated, the preferred structural material for the floors of urban traditional houses was timber, with *arboloco* as an alternative (Fig. 21). Although Guadua's high flexural strength make joists easily resist the bending moments produced by the transverse loads, it was rarely used in urban traditional houses because the culms tend to crush or split under these loads on their points of application or support. However, round bamboo joists are widely used in rural housing, and even *esterilla* is sometimes used as flooring instead of timber boards. The tendency to pour concrete over *esterilla* floors needs discouragement as it adds unnecessary masses and increases weights significantly without correspondingly increasing the strength. Additionally, the horizontal seismic forces will also increase, as will be explained later.

Timber was the main material for the vertical structural subsystem of urban traditional bamboo housing: all main posts and beams were of timber, and Guadua was used only for the secondary intermediate elements and sometimes for the diagonals (Fig. 53). Guadua *esterilla* was laid horizontally on both sides of the walls and covered with a mortar originally made out of *cagajón* (a mixture of mud and horse dung), which was later replaced by cement mortar. The vertical loads transmitted by the roof and floors to these vertical systems are in turn transmitted to the foundation by the vertical posts. Cement mortar may play a significant and favorable structural role for vertical loads because it increases the flexural stiffness of the vertical walls and consequently their buckling load capacity. In experiments on *bahareque* panels with timber posts and cement mortar under vertical loads (Fig. 54), carried out by the author and one of his students (González 1998), it was found that the vertical strength and stiffness of the panels almost doubled the values of isolated posts. Nevertheless, this is ignored in the design process because the buckling mode of failure is sudden and explosive, and adequate design safety factors must be included. For horizontal seismic forces, the surface of cement mortar will completely modify the structural response, as will be discussed later.

Two conditions are important for a better transmission of the vertical loads to the ground. One, all structural elements of each vertical subsystem must lie in the same vertical plane. A horizontal shift of the vertical planes for different floors should be avoided as much as possible because they create an unnecessary discontinuous path in the transmission of the vertical forces to the ground. As will be seen later, this condition is even more important for the transmission of seismic horizontal forces. Two, all main vertical and horizontal elements that are common to two or more vertical subsystems must be adequately joined to each other, so as to produce a single three-dimensional structural unit instead of a set of independent two-dimensional vertical subsystems

Fig. 53: *Vertical structural elements in bamboo* bahareque *housing*

Fig. 54: Bahareque *panels being tested under vertical compressive loads at LANAMME, University of Costa Rica*

placed in different vertical planes. This is particularly important for the vertical subsystems that are normal to each other, like the walls in the two main orthogonal directions. There is no doubt that the timber used in the horizontal beams and main vertical posts is more suitable for this purpose than round bamboo, which is always difficult to join, particularly if tension forces are present. With these conditions being satisfied, it has been possible to build four and five-story buildings that have lasted for decades without presenting significant structural problems (Fig. 55).

For economic reasons, rural houses usually use bamboo for all vertical and diagonal posts as well as for the roof rafters, and even for the floor joists and beams (Fig. 56). These houses rarely exceed two stories in height. But in the past, even higher structures

Fig. 55: *A historical, four-story bamboo* bahareque *building in Salamina, Colombia*

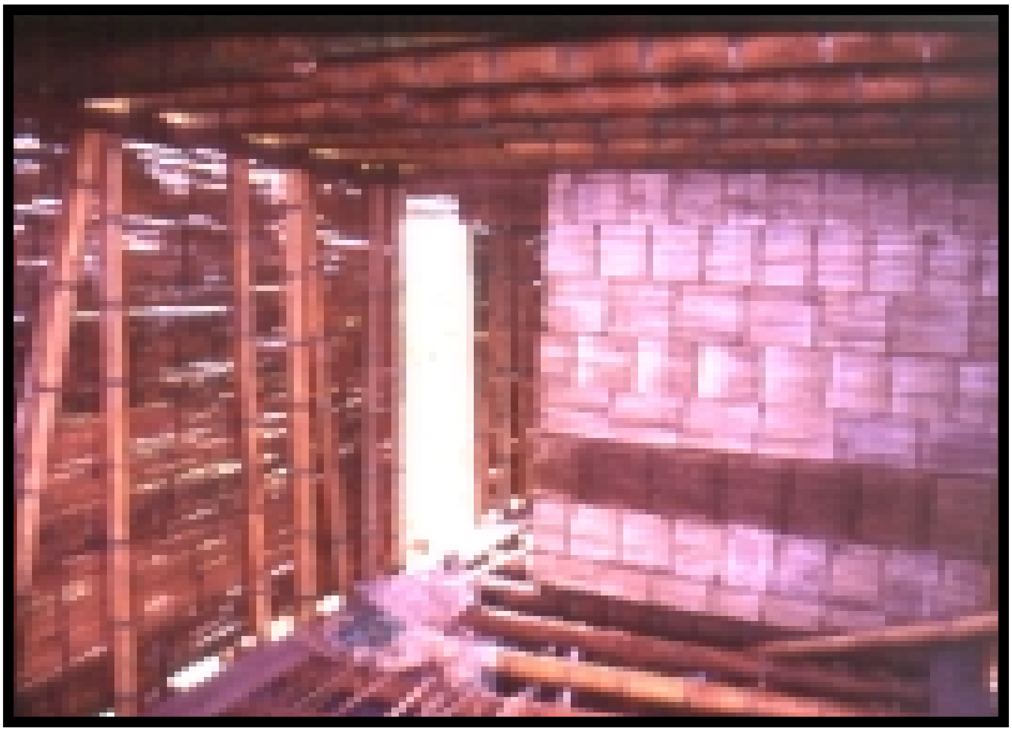


Fig. 56: *A rural bamboo house under construction, using Guadua for wall, roof and structural elements (Pueblo Rico, Colombia)*

(opposite page)

Fig. 57: *An old coffee-airing facility in Caldas, Colombia*

were built that way and many of them associated with the production of coffee, which is the main agriculture crop of the Antiguo Caldas (Fig. 57). These beautiful structures are slowly disappearing from the landscape as modern production techniques turn them obsolete.

What is really amazing is the structural firmness of the urban marginal constructions built with Guadua, such as on the steep hills of the Antiguo Caldas (Fig. 38), using a trial-and-error design process. The main advantage of these units is the extreme lightness

of the structure. For this reason, the situation may become extremely dangerous when masonry walls are introduced for social status, modifying the traditional and proven conditions.

The foundation structural subsystem of any timber or bamboo construction has two functions:

a. It has to transmit the loads to the supporting soil; and

b. It has to raise the structure from the ground to prevent the deterioration of the organic material by fungal attack induced by moisture.

The loads to be transmitted to the ground are low because the buildings are light, resulting in foundations requiring small ground contact areas for most of the supporting soils. Even when cement mortar is used to cover the walls, these buildings weigh only one-third of the weight of an equivalent masonry or reinforced concrete building. The weight reduction is even more dramatic when exposed *esterilla* walls are employed, such as in the rural and urban marginal houses of the lowlands of Ecuador – about one-tenth of a masonry house.

In some places it is customary to support the house on round poles of mangrove, locally available and quite resistant to fungal attack, embedded in the ground and sometimes braced against horizontal forces by diagonal struts. In the absence of mangrove, other timber species, or even bamboo, are used (Figs. 11, 34). This practice should be avoided in all but the flimsiest constructions because sooner or later the material deteriorates and the structure may collapse even under minor disturbances. Protection of the material with water-repellent substances or with concrete poured around the pole will not be of any help to prevent the decay of the organic material placed in the ground. Eventually the water will find a way, through minor cracks or spaces produced by the shrinkage of concrete, to infiltrate and deteriorate the protected material. The only effective way is to prevent the material from coming into contact with the ground, by means of concrete, brick or stone foundations having pedestals or other similar devices to support the structure at an adequate height from the ground.

Behavior under lateral loads

The main difficulty in the study of the behavior of structures under extreme lateral loads is their uncertain nature. The most prominent ones – powerful earthquakes and strong hurricanes – have intensities that can only be estimated by probabilistic methods. Therefore, it becomes necessary to study the history of occurrence of these events and the geophysical characteristics of a particular region in order to make reliable estimates of the probability of a particular event to be exceeded during a particular year. This is called the **Probability of Exceedence** (PE); its arithmetic inverse is called the **Return Period** (RP) and is expressed in years. The lower the PE (or higher the RP) selected for a particular event in a given region, the higher will be its potential destructiveness. Associated with these extreme events are physical quantities that can be used to estimate the actions upon the structure, or the effects that the **context** will place on the **form**. For example, strong winds are usually assumed as a steady flow, neglecting their dynamic gusty effects, thus the representative physical quantity is the maximum wind velocity, which is then related to normal pressures acting on the exposed surfaces of the structure. It is not possible to explain the dynamic nature of severe earthquakes without complex calculations. For the sake of completeness however, a brief introduction is presented here; a more complete treatment may be found elsewhere (Chopra 1981).

The simplest analytical model of a structure subjected to seismic ground excitations is the Single Degree of Freedom (SDOF) system (Fig. 58). In this model, the total mass is assumed as concentrated at the roof level, a linear elastic behavior is assumed for the lateral displacements of the structure and the forces related with damping or dissipation of energy will be assumed as proportional to the velocity. We define **stiffness** as the force required to produce a horizontal unit displacement; hence, its arithmetic inverse – the **flexibility** – would be the displacement associated with a unit force. All these hypotheses lead to a relatively simple differential equation. The response of this model to free vibrations is a harmonic (oscillatory) motion with a **natural period** T, defined as the time required to complete one cycle, which is directly proportional to the square root of the ratio of mass over stiffness.

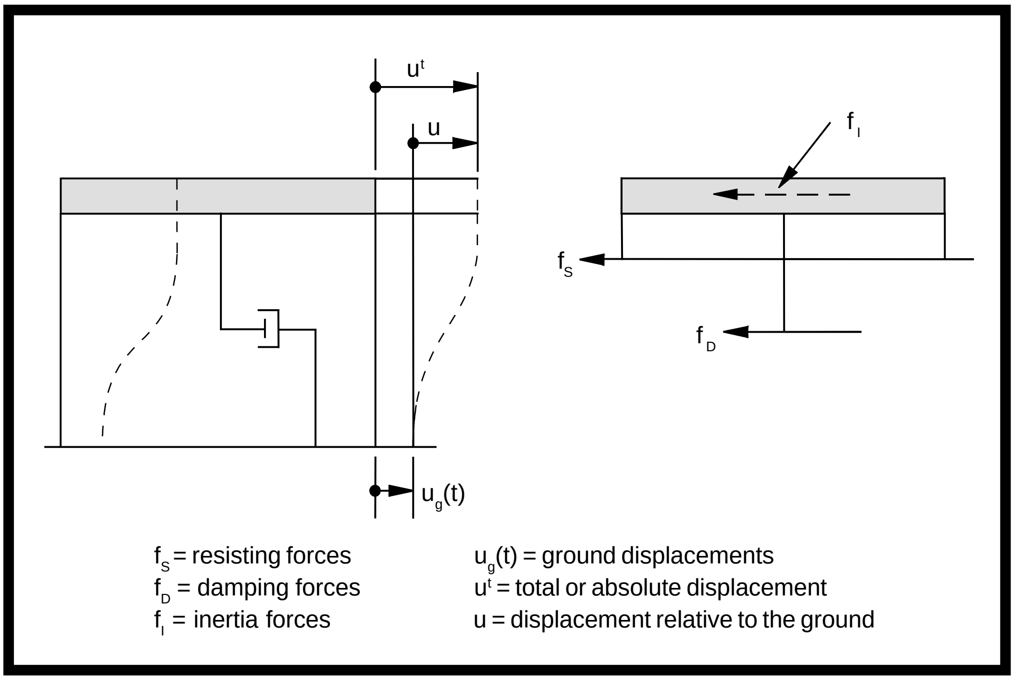


Fig. 58: *The Single Degree of Freedom (SDOF) system*

The equations representing the behavior of the structure under earthquake effects can also be solved, provided that the time history of ground accelerations produced at the site by a particular earthquake is known. The solution would be the history of relative displacements of the concentrated mass during the duration of the ground motion. For a particular history of ground accelerations, the response of the system depends on its natural period and damping. For instance, Fig. 59 represents the actual time history response of three particular structures of different natural periods – 0.5, 1.0 and 2.0 seconds – to the accelerations produced by the well known 1940 El Centro earthquake. For design purposes, the most important datum is the maximum displacement response over time history because it is clear that if the structure can resist that critical displacement without failure, it will be able to resist the complete earthquake. It is, therefore, convenient to represent the collection of maximum displacements for structures with all possible periods over a broad interval. The graph representing the maximum displacements as a function of the structural periods is called a Displacement Response Spectrum (Sd) (Fig. 59).

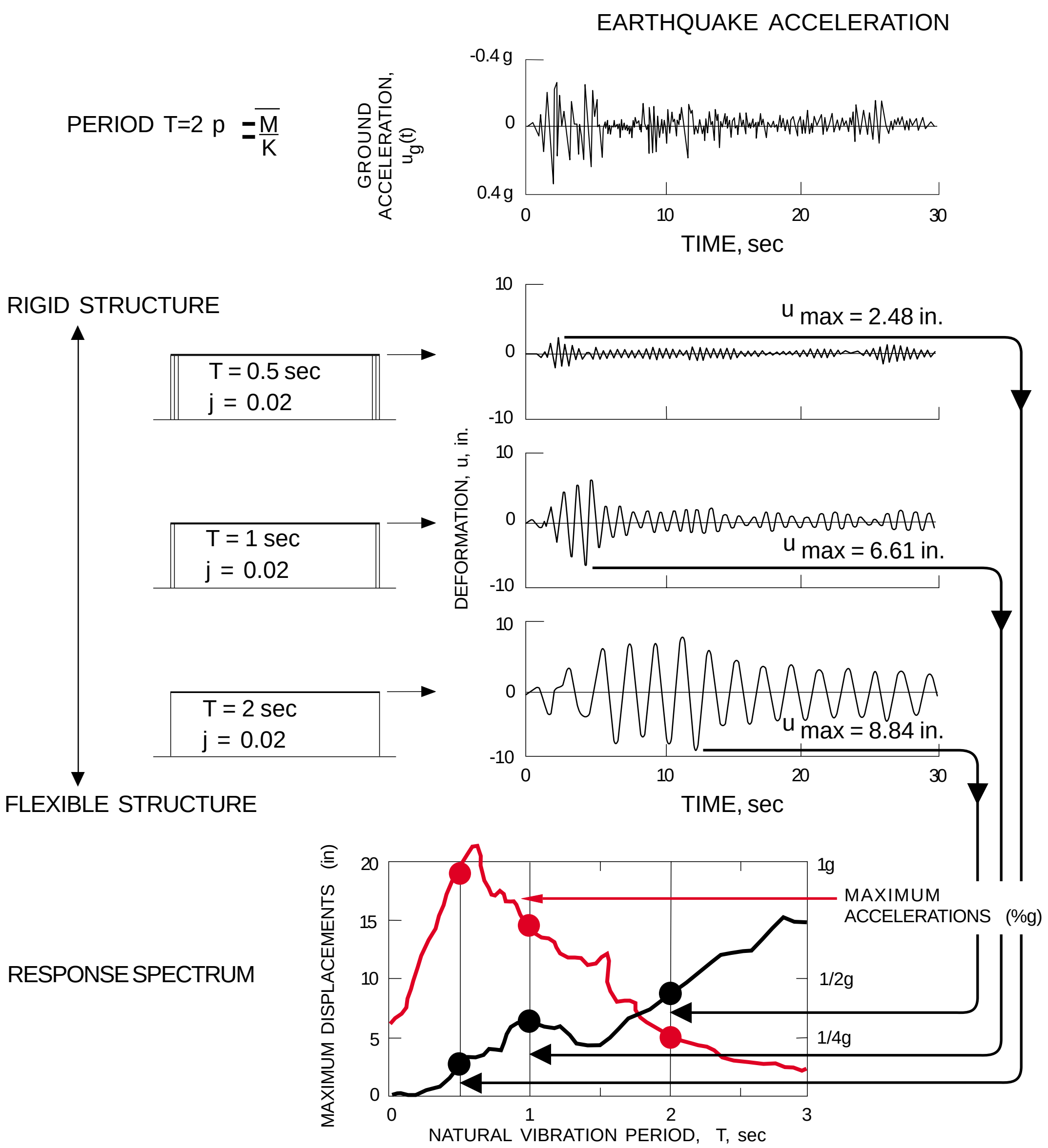


Fig. 59: *Computation of Displacement Response Spectra (After Chopra 1981)*

A related graph – the Acceleration Response Spectrum (Sa) – can now be obtained, multiplying Sd by the ratio of the stiffness over the mass. This quantity has units of acceleration and is commonly represented as a fraction of the acceleration of gravity, Sa/g (Fig. 59). The convenience of this new graph is that all the quantities associated with the structural response at the time of the maximum horizontal displacement, Sd, can now be obtained by finding a much simpler static solution for an equivalent horizontal static force. The numerical value of this static force is equal to the weight of the structure multiplied by Sa/g and it is applied to the mass. In other words, the maximum effect of a particular earthquake upon a structure is equivalent to a static horizontal force equal to Sa/g times its weight. For design purposes, Seismic Codes specify values of Seismic Coefficient (C) as a function of the natural period. These values are derived from the most critical Acceleration Response Spectra for a particular region.

It is evident from the values of Sd and Sa/g in Fig. 59 that for usual natural periods T, the maximum displacements tend to increase with the natural period whereas the corresponding maximum forces tend to decrease. That is, during an earthquake, more flexible structures must resist larger displacements (but smaller forces) than more rigid structures of similar weight. Additionally, for a particular natural period, the seismic forces will increase in proportion to the weight of the structure.

The above information is essential to understand the structural response of bamboo buildings to earthquakes. When the walls are made of *esterilla* without mortar, as in some of the houses in the coastal region of Ecuador, the structure is both very light and very flexible. Its lateral strength and stiffness is basically provided by the diagonal struts placed between the vertical poles or, when the walls lack the diagonal struts as in the panels of Viviendas Hogar de Cristo, by the almost negligible combination of frame action and *esterilla*. Both flexibility and lightness lead to lower horizontal seismic forces and therefore, their combined effect will result in extremely low seismic effects. Given that bamboo is also a very strong material, the seismic safety of these houses should be extremely good provided that the construction details are adequate to prevent material decay and to guarantee their response as an integrated unit. Furthermore, the extreme lightness of the houses will also guarantee that, in case of partial or even complete collapse, physical injury of the occupants is unlikely. This is no trivial matter when we consider the rigid, massive and yet weak adobe or stone houses that are so common in the developing regions of the world; thousands are killed crushed under the heavy roofs and walls even in moderate earthquakes.

The most remarkable earthquake behavior of bamboo housing is the one exhibited by the *bahareque* houses with walls plastered with cement mortar, the *temblorero* style of the Antiguo Caldas. These walls behave as a composite material, because they exhibit a structural behavior that is not present in any of the components when considered separately. It is true that the stiffness and weight of the walls increase significantly – with an increase in the seismic forces – because of the mortar, but the strength of the structure increases even more. The result is a structure that possesses firmness in addition to service, economy and delight, the four components of intention in structural design (see Chapter 2).

The mechanical behavior of timber *bahareque* walls with and without cement mortar has been the subject of many tests conducted by the author. In the first series of tests (Gutiérrez 1993, Mendoza and Villalobos 1990) the panels were subjected to horizontal monotonically increasing loads parallel to their plane (Fig. 60). The results (Fig. 61) clearly indicate the differences in stiffness and strength between the panels without mortar (panels 1-5) and those covered with mortar (panels 6-13). These results also indicate that the diagonal strut placed between vertical poles has a significant effect in the stiffness and strength of the panels without mortar (panels 1, 2 and 5 with diagonals; panels 3 and 4 without). But it does not play any role in panels with mortar (panels 8, 9, 11 and 13 with diagonals; panels 6, 7, 10 and 12 without). The reason for this is that the mortar controls the strength and stiffness of these panels, and the participation of the diagonal strut is very small in the reduced range of lateral displacements.

The main limitation of these tests was the application of monotonic loads; earthquake accelerations are cyclic by nature and they induce cyclic forces. The behavior of structural walls under cyclic loading may be significantly different to monotonic loading, because the material may suffer strength and stiffness degradations during the cycles. To overcome this limitation, it becomes necessary to perform a series of tests of *bahareque* walls under horizontal cyclic loads. The author has already initiated such a test program,

Fig. 60: Bahareque *panels being subjected to in-plane lateral loads (LANAMME)*

using the excellent test facilities of the National Laboratory for Materials and Structural Models (LANAMME) of the University of Costa Rica, which should produce useful data in the near future.

In the tests, full-scale specimens of the *bahareque* wall are fixed to the laboratory's strong concrete floor and lateral cyclic loads that simulate the earthquake effects are applied by a computer-controlled 50-ton hydraulic jack, supported against a massive vertical reaction wall (Fig. 62). The jack can reproduce any predefined set of displacements, usually from smaller to larger values, and electronically indicate the corresponding forces. Data on the complete strength and stiffness degradation process as well as the energy absorption capacity of the structural system are thus obtained (the size of the testing facility allows the extension of these types of tests to full-scale house prototypes as well). They represent the only dependable tool to understand the overall complex behavior of complete structures under earthquake effects.

In the second series of tests (González 1998), the panels were subjected to horizontal monotonically increasing loads normal to their planes, simulating seismic or wind effects normal to the direction of the walls (Fig. 63). The results show again that *bahareque* walls with cement mortar work in composite action, as the strength and stiffness of the timber elements acting alone were almost doubled. The failure always occurred when the vertical timber pole failed in bending.

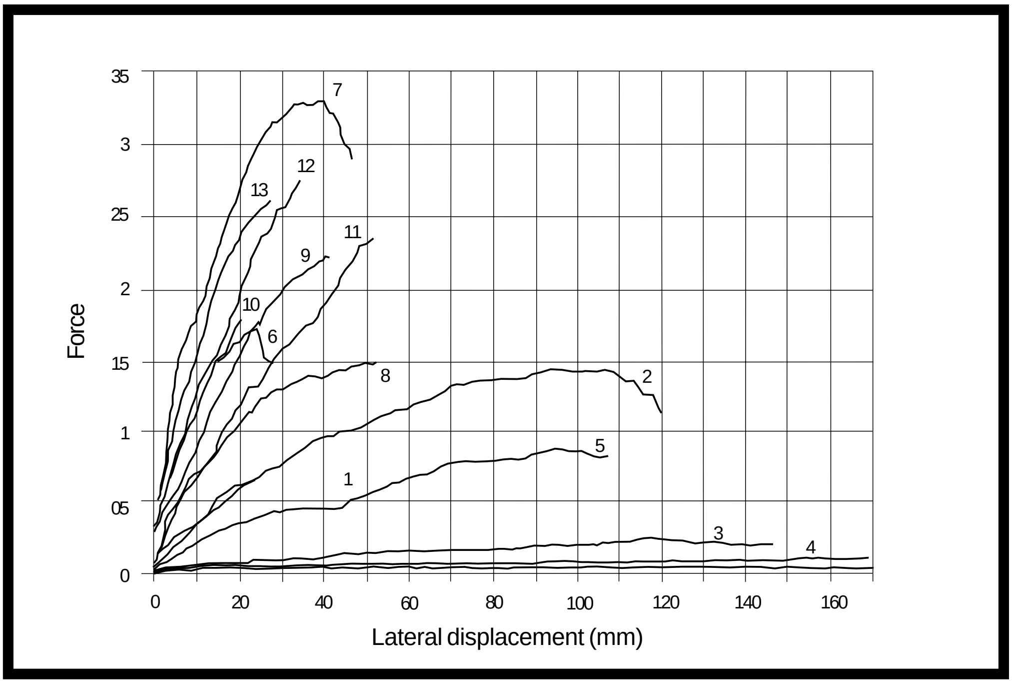


Fig. 61: *Force-displacement relationships for timber* bahareque *panels under in-plane lateral loads (LANAMME)*

Fig. 62: Bahareque *panels being subjected to in-plane cyclic lateral loads (LANAMME)*

A most important result of these two series of tests was the evidence that, for the two types of loading (in-plane and out-of-plane), the cement mortar remained fixed to the *esterilla* even in the extremely large deformations associated with structural failure when significant cracking was present (Figs. 60, 63). If these results remain valid for the more demanding cyclic load tests, they would indicate that the frame and the cement mortar really act together as an effective composite material even under the effects of extreme earthquakes.

Two of the most important characteristics of structures for good earthquake behavior are regularity in plant and along its height. This fact is recognized by most modern Seismic Design Codes that penalize irregular buildings (CFIA 1987, ICBO 1997). A structure is regular in plant if the earthquake forces in each horizontal direction produce only horizontal displacements along the same direction, without significant floor

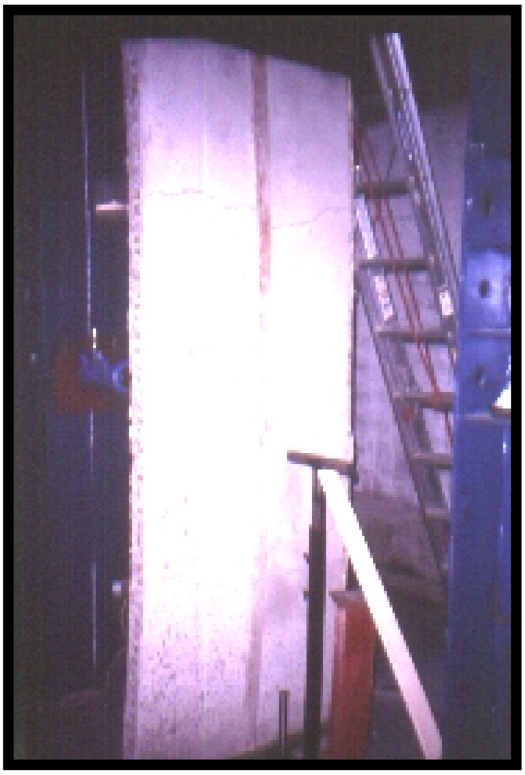


Fig. 63: Bahareque *panels being subjected to out-of-plane lateral loads (LANAMME)*

torsional rotations. This condition is achieved if the masses and the structural walls, which provide strength and stiffness against horizontal forces in each plant of the building, are homogeneously distributed. Regularity along the height is achieved when there are no significant variations on the mass, the strength and the stiffness along the height of the building. In particular, the vertical structural subsystem must contain structural walls lying on the same vertical plane and continuous from top to bottom, without significant interruptions or openings. Most bamboo *bahareque* buildings, especially those more than two stories high, comply with these requirements (Figs. 22, 55) and have plenty of structural walls along the two horizontal directions, producing a convenient box-type structural shape.

The other class of extreme lateral loads that must be considered in design are strong wind effects. As mentioned, the significant physical parameter for this type of action is the maximum wind velocity. The resulting normal pressure is proportional to the square of the velocity. By definition, the hurricanes that every year strike the Caribbean Sea have minimum velocities of 120 km/h, which correspond to basic pressures of 72 kg/m^2. These normal pressures must be corrected by shape factors that for rectangular buildings vary from -0.6 (suction) to +0.9 (compression). The resultant force will then be a function of the basic pressure, the shape factors and the total exposed area of the building. It should be noted that, contrary to the case of earthquakes, the wind loads do not depend on the weight or the stiffness of the structure.

The Guadua culture region is not exposed to hurricanes and hence, there is neither evidence nor experience with the response of bamboo housing to this important phenomenon. Nevertheless, it can be taken that bamboo *bahareque* houses with walls covered with cement mortar, having higher strength and weight, will be able to resist much stronger winds than the bamboo houses with bare *esterilla* walls and light roofs. The latter type of houses is not suitable for zones prone to strong winds. Studies carried out by the author for the one-story *bahareque* houses built by FUNBAMBU in Costa Rica revealed that for a design wind velocity of 120 km/h and a Seismic Coefficient of 0.3, wind was slightly more critical than earthquake for the out-of-plane forces of the exterior walls. But earthquake was the critical effect for all in-plane forces and for the out-of-plane forces of the interior walls.

Bahareque Behavior in Earthquakes

As said earlier, one of the main difficulties for the safe design of buildings against earthquakes lies in the uncertain nature of the event. Even in developed countries, where Seismic Codes that give due consideration for safety have been in practice for many years, quite a number of structures proved unsafe under major earthquakes: for example, Loma Prieta (1989) and Northridge (1994) in California, USA, and Kobe (1995) in Japan. During these events, many high-rise steel buildings and large reinforced concrete viaducts suffered major damages, showing problems of behavior that had been unforeseen by the world's most qualified researchers and practitioners. Praxis is the only valid criterion for truth and it is only under major earthquakes that all theories and recommended design and construction practices are really tested.

For this reason, it is very important to observe the actual behavior of structures when a major earthquake occurs. As far as the bamboo *bahareque* houses of the Guadua culture region are concerned, this was possible on 25 January 1999 when a 5.9 Magnitude earthquake struck the Department of El Quindío in the Antiguo Caldas. The quake caused major damage in the capital city of Armenia (17 km North of the epicenter), where a horizontal peak ground acceleration of 0.55 g was recorded on soil (EERI 1999). It killed more than 1 000 people and left more than 40 000 homeless. Nearby towns like Córdoba, Barcelona, Calarcá and Pijao also suffered extensive damage. Many buildings collapsed or suffered severe damage; some of them were *bahareque* constructions, either very old ones plastered with *cagajón* or newer ones plastered with cement mortar. The most serious collapses, however, were the multistory reinforced concrete and masonry buildings built before 1984, when the Colombian Design Code was issued. These types of structures demand a qualified structural design and carefully supervised construction in order to insure their seismic safety; not an easy requirement in the peripheral cities and villages of developing countries.

Immediately after the quake the prejudice against *bahareque* was expressed and some people proposed that all constructions of this type, which presented certain degree of damage, should be demolished. Fortunately, a group of architects and engineers, conscious of the cultural and technological value of *bahareque*, raised their voices to prevent such a mistake. The truth was that *bahareque* endured the test quite successfully. Many of these buildings, including several historic ones more than a hundred years old, were undamaged or suffered only minor damage, something that all Seismic Codes accept. For those *bahareque* buildings that collapsed or suffered serious damage, there were clear explanations (Robledo et al. 1999):

- Severely deteriorated timber or bamboo structural elements owing to neglected maintenance against rain, humidity and other weathering agents. In some cases only the heavy tile roof structure collapsed.

- Collapse of masonry walls, improperly fastened to the structure, that had replaced the original *bahareque* facades as an expression of socio-economic status. In many cases the collapse of these walls damaged the rest of the house.
- Tipping of the structure owing to failure of improperly braced concrete or masonry piles and other types of foundations.

The repair and structural retrofit of these buildings, using the same proven techniques but substituting the *cagajón* by cement mortar, will be much cheaper and rational than their complete demolition to replace them by more expensive constructions. Modern materials like reinforced masonry or techniques like prefabricated concrete demand careful workmanship and supervision to be earthquake-safe.

Transfer of Bamboo *Bahareque* Technology

The success of bamboo *bahareque* as a sound and safe alternative for the design of structural forms, even in regions prone to strong earthquakes, makes the technology suitable for transfer to countries or regions with similar environmental and socio-economic conditions. There are many regions with large and needy populations, where these basic and proven techniques with their appropriate adaptations could significantly contribute to the production of houses that are safe, functional, economic and beautiful – the four components of intention in structural design.

A very successful technology transfer of the bamboo *bahareque* traditions occurred from the Guadua culture region of Colombia to Costa Rica, where previous bamboo construction traditions were nonexistent. There was, however, a tradition of hollow *bahareque* housing, using timber combined with a strong and resistant cane called *caña brava* (*Gynerium sagittatum*) instead of *esterilla*. With funds from The Netherlands and administrative support from the United Nations (UNDP/Habitat), the Costa Rican National Bamboo Project was initiated in 1988 (Chaves and Gutiérrez 1990). At the outset, the Project planted several hundred hectares of Guadua and started the construction of timber-framed single-layered *bahareque* houses based on the traditions

Fig. 64: Bahareque *houses built by FUNBAMBU under the National Bamboo Project of Costa Rica*

of Costa Rica and Colombia, but with innovative prefabricated construction methods and sound engineered designs (Fig. 64). A research program, carried out in collaboration with the University of Costa Rica, produced the valuable results on mechanical behavior of Guadua culms and *bahareque* panels. The Project also developed effective techniques for the preservation of bamboo (González et al. 1993, González and Gutiérrez 1996, Liese et al. 2000). As bamboo became available it has been gradually replacing the more expensive timber and several prefabricated house alternatives, using bamboo in all structural elements, have already been built (Fig. 65). In 1996, when the external funding ended, the Project was converted into a self-supporting Foundation called FUNBAMBU (Gutiérrez 1998). The houses built by the Project and FUNBAMBU have been extremely successful and their social acceptance very good. The categorical proof of their capacity to withstand earthquakes occurred during the April 1991 earthquake (7.5 Magnitude) that struck the Costa Rican Province of Limón. A group of 30 houses had been built at the site of the epicenter and all of them (Fig. 66) resisted the extreme forces without the slightest damage (Gutiérrez 1993, Handley 1999).

Fig. 65: *A fully bamboo prototype house being built in Costa Rica by FUNBAMBU*

Fig. 66: *Undamaged* bahareque *house after an earthquake of 7.5 Magnitdue on 22 April 1991, Limón, Costa Rica*

Chapter Six

Summary and Conclusions

1. In general, traditional bamboo housing of the Guadua culture region of Colombia and Ecuador represents extraordinary unselfconscious structural designs with a delightful interplay of the four components that constitute the intention in structural design – firmness, utility, economy and delight – and the four components that correspond to the materiality – materials, shapes, constructive technologies and details (Figs. 2-4). In particular, most traditional bamboo hollow *bahareque* houses and buildings possess a level of structural excellence that provides them extended durability in humid environments and adequate resistance to the earthquakes that frequent the region. These construction techniques are worth preserving as well as transferring to other similar regions of the world.

2. One of the most remarkable characteristics of traditional bamboo housing is their lightness. When the walls are left as exposed *esterilla* without mortar, the weight of the house may be less than 10% of the weight of similar masonry houses. The reduction is more dramatic when compared with the traditional adobe houses frequently built in the rural regions of developing countries. Even hollow *bahareque* houses with cement mortar weigh only one-third of a similar masonry house. The significant reduction in the mass of the structure is very convenient because both the gravitational vertical loads and the horizontal seismic loads are directly proportional to this quantity. For this reason, masonry walls or floors with concrete poured over *esterilla* represent a serious threat to the complete structure and should be strictly avoided. Only in the case of strong winds may lightness of the structure pose a problem. In regions prone to extreme winds, bare bamboo walls should be avoided and special structural details must be provided to resist the tensional forces that may be produced by the wind's uplifting effects.

3. Hollow *bahareque* walls plastered with cement mortar form effective structural wall elements with very high strength and stiffness. They behave as true composites, presenting much better mechanical behavior than their individual components. The layers of cement mortar in vertical walls form structural membranes, which are very rigid and strong in their own plane, that effectively transmit to the ground all in-plane shear horizontal forces produced by earthquake or wind. Even for out-of-plane bending forces, the composite action of frame and mortar may duplicate the capacity of the frame elements acting alone.

4. Another desired structural characteristic, present in the traditional bamboo *bahareque* houses and buildings discussed in this study, is their regular distribution of mass, strength and stiffness both in plant and along its height. Most bamboo *bahareque* buildings, especially those that are more than two stories high, comply with these requirements and have enough structural walls along the two horizontal directions to form convenient box-type structural shapes.

5. Proper architectural protection against weathering agents is another remarkable characteristic of many traditional bamboo houses in the region. Generous roof eaves and raised foundations that keep the structure away from the ground both prevent the destructive effect of moisture on bamboo or timber. Cement mortar provides protection for the exterior walls as well and should be preferred to *cagajón* (mud-and-horse dung mixture). Supporting houses on timber or bamboo poles embedded in the ground is a practice that should be strictly avoided in all but the flimsiest constructions.

6. In cases where bamboo is left exposed to weathering effects and prone to early deterioration, the concept of “perpetuity through substitution” becomes a very convenient strategy to extend the life of the complete structure. Construction details should allow the easy replacement of structural elements or components that are likely to deteriorate.

7. In the last few decades, a growing group of architects and engineers have become engaged in the self-conscious design of bamboo housing. Bamboo is receiving the status of an engineering material, and is being incorporated into engineered constructions in combination with other modern materials. Some architects are using bamboo even in luxury buildings in a deliberate attempt to increase its social acceptance. However, special care must be given to the rescue and study of traditions so that the strengths and weaknesses of the material are explicitly understood, avoiding improper uses that could lead to its rejection in the long term.

8. A successful technology transfer and adaptation of the bamboo *bahareque* traditions from the Guadua culture region of Colombia has already occurred in Costa Rica. The country did not have bamboo, but there was a tradition of hollow *bahareque*

construction using timber combined with a strong and resistant cane instead of *esterilla*. The bamboo *bahareque* houses built there have been extremely successful constructions and their social acceptance has been very good. In Limón, a group of 30 houses resisted a 7.5 Magnitude earthquake without the slightest damage.

9. A research program, carried out by the author on behalf of the Costa Rican National Bamboo Project, produced valuable results on the mechanical behavior of Guadua culms and *bahareque* panels. Effective techniques for the preservation of bamboo have been developed as well. It is hoped that, as scientific and technological research receives adequate funds and is successfully executed, proven design and construction techniques using bamboo *bahareque* and inspired in the remarkable bamboo housing traditions of the Guadua culture region of Colombia and Ecuador, will be widely available to satisfy the needs of the people in many regions of the world.

References

Alexander, C. 1964. Notes on the synthesis of form. Harvard University Press, USA. 216 pp.

Arce, O.A. 1993. Fundamentals of the design of bamboo structures. Ph.D. Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands. 261 pp.

Arcila, J.H. 1985. A residential state constructed from bamboo in Manizales, Colombia. *In* IL31 Bamboo. Institute for Lightweight Structures, University of Stuttgart, Germany. pp. 292-293.

Castro, D. 1985. La Guadua, the versatile bamboo. Fundación para la Educación Superior (FES), Bogotá, Colombia. 137 pp. (Also in English).

Chaves, A.C.; Gutiérrez, J.A. 1990. The Costa Rican National Bamboo Project. *In* Ramanuja Rao, I.V.; Gnanaharan, R; Sastry, C.B., ed., Bamboos: current research, Proceedings of the International Bamboo Workshop, Cochin, India, 14-18 November 1988. Kerala Forest Research Institute, Kerala, India; International Development Research Centre, Ottawa, Canada. pp. 344-349.

Chopra, A.K. 1981. Dynamics of structures – a primer. Monograph Series, Earthquake Engineering Research Institute, California, USA. 126 pp.

CEAFAX. 1997. The bamboo city. VHS Video, Viviendas Hogar de Cristo – CEAFAX Production, Quito, Ecuador. (Also in German and Spanish).

CFIA (Colegio Federado de Ingenieros y Arquitectos). 1987. Código sísmico de Costa Rica – 1986. Colegio Federado de Ingenieros y Arquitectos de Costa Rica, Editorial Tecnológica de Costa Rica, 1987.

EERI (Earthquake Engineering Research Institute). 1999. The Quindío, Colombia, earthquake of January 25, 1999. EERI Special Earthquake Report, EERI Newsletter, Vol. 33, No. 3, March 1999, 12 pp.

Florez, G. 1998. Personal communication to author, August 1998.

Francis, A. J. 1995. Introducing structures – a textbook for students of civil and structural engineering, building and architecture. Pergamon Press, USA. 316 pp.

Fuentes, C. 1994. El espejo enterrado. Fondo de Cultura Económica, México. 440 pp. (English translation available).

Gamma, E.; Helm, R.; Johnson, R.; Vlissides, J.; Booch, G. 1995. Design patterns: elements of reusable object-oriented software. Addison-Wesley, 395 pp.

García-Rios, L.E. 1992. Low income housing in squatter settlements in Guayaquil, Ecuador. M. Arch. Thesis, State University of New York at Buffalo, USA. 125 pp.

Gnanaharan, R.; Janssen, J.J.A.; Arce, O.A. 1994. Bending strength of Guadua bamboo – comparison of different testing procedures. INBAR Working Paper No. 3, International Network for Bamboo and Rattan, New Delhi, India. 24 pp.

González, G.; Cambronero, R.; Gutiérrez, J.A. 1993. Preservación de culmos de Guadua. Memorias 1er Congreso Mundial de Bambú/Guadua, Pereira, Colombia, 8-15 August 1992, pp. 77-83.

González, G.; Gutiérrez, J.A. 1996. Bamboo preservation at the Costa Rican National Bamboo Project. *In* Ganapathy, P.M.; Janssen, J.A.; Sastry, C.B., ed., Bamboo, people and the environment, Vol. 3, Engineering and utilization. Proceedings of the Vth International Bamboo Workshop, Ubud, Bali, Indonesia, 19-22 June 1995. International Network for Bamboo and Rattan, New Delhi, India. pp. 121-129.

González, G. Jr. 1998. Comportamiento estructural de paneles de bambú. Thesis, Civil Engineering Department, University of Costa Rica, Costa Rica. 115 pp.

Gutiérrez, J.A. 1993. Comportamiento estructural y resistencia sismica de las viviendas de bambú. Memorias 1er Congreso Mundial de Bambú/Guadua, Pereira, Colombia, 8-15 August 1992. pp.161-171.

Gutiérrez, J.A. 1998. The development of non-traditional bamboo technologies in Costa Rica. *In* Traditional techniques of bamboo in modern life. Proceedings of the International Seminar for the Safeguarding and Promotion of Traditional Techniques of Bamboo in Modern Life, Ho Chi Minh City, Vietnam, 17-20 December 1997, UNESCO, Paris. pp.150-166.

Handley, C. 1999. Building of bamboo. Earthquake Hazard Centre Newsletter, Vol. 2, No. 3, January 1999, p. 6.

Harris, R. 1993. Discovering timber-framed buildings. Shire Publications, 96 pp.

Hidalgo, O. 1974. Bambu, su cultivo y aplicaciones en fabricación de papel, construcción, arquitectura, ingeniería, artesanía. Estudios Técnicos Colombianos, Colombia, 318 pp.

ICBO (International Conference of Building Officials). 1997. Uniform Building Code – 1997. Vol. 2, Structural engineering design provisions, International Conference of Building Officials, California, USA.

Janssen, J. J.A. 1991. Mechanical properties of bamboo. Forestry Sciences, Kluwer Academic Publishers, The Netherlands. 134 pp.

Janssen, J. J.A. 1996. Building codes for bamboo housing. *In* Ganapathy, P.M.; Janssen, J.J.A.; Sastry, C.B., ed., Bamboo, people and the environment, Vol. 3, Engineering and utilization. Proceedings of the Vth International Bamboo Workshop, Ubud, Bali, Indonesia, 19-22 June 1995. International Network for Bamboo and Rattan, New Delhi, India. pp.130-139.

Judziewicz, E.J.; Clark, L.G.; Londoño, X.; Stern, M.J. 1999. American bamboos. Smithsonian Institution Press, Washington, USA. 392 pp.

Liese, W.; Gutiérrez, J.A.; González, G. 2000. Preservation of bamboo for the construction of houses for low income people. *In* Arun Kumar; Ramanuja Rao, I.V.; Cherla Sastry, ed., Bamboo and Sustainable Development, Proceedings of the Vth International Bamboo Congress and the VIth International Bamboo Workshop, San José, Costa Rica, 2-6 November 1998. International Network for Bamboo and Rattan, Beijing, China. (Under preparation).

McClure, F.A. 1993 (1966). The bamboos: a fresh perspective. Smithsonian Institution Press, Washington, D.C., USA. 345 pp.

Mendoza, H.; Villalobos, C.E. 1990. Capacidad estructural de paneles de bambú. Thesis, Civil Engineering Department, University of Costa Rica, Costa Rica. 236 pp.

Mogollón, J. 1993. Vivienda: soporte modular y participación. Memorias 1er Congreso Mundial de Bambú/Guadua, Pereira, Colombia, 8-15 August 1992, pp.111-118.

Morán, J. 1986. La vivienda vernacular de caña – análisis de sus materiales y técnica constructiva. Workshop on appropriate technologies, Vicente Rocafuerte University, Guayaquil, Ecuador. 53 pp.

Morán, J. 1987. Vocabulario de arquitectura campesina en el litoral ecuatoriano. Banco Central del Ecuador and Universidad Laica Vicente Rocafuerte, Guayaquil, Ecuador. 118 pp.

Nino, B. 1998. Traditional techniques for construction on Lake Atitlan, Guatemala. *In* Traditional techniques of bamboo in modern life. Proceedings of the International Seminar for the Safeguarding and Promotion of Traditional Techniques of Bamboo in Modern Life, Ho Chi Minh City, Vietnam, 17-20 December 1997, UNESCO, Paris, France. pp. 140-149.

Parsons, J.J. 1991. Giant American bamboo in the vernacular architecture of Colombia and Ecuador. Geographical Review, Vol. 81, No. 2, April 1991. pp. 131-152.

Rapoport, A. 1969. House form and culture. Foundations of Cultural Geography Series, Prentice-Hall, USA. 146 pp.

Robledo, J.E. 1996. La ciudad en la colonización antioqueña: Manizales. Editorial Universidad Nacional, Bogotá, Colombia, 242 pp.

Robledo, J.E.; Muñoz, J.F.; Duque, G. 1999. A note in an Internet bulletin.

Soderstrom, T.R. 1985. Bamboo systematics – yesterday, today and tomorrow. Journal of the American Bamboo Society, Vol. 6, pp. 4-16.

Soderstrom, T.R.; Ellis, E. 1987. Position of bamboo genera and allies in a system of grass classification. *In* Soderstrom T.R. et al. ed., Grass systematics and evolution. Smithsonian Institution Press, Washington, D.C., USA. pp. 225-238.

Sotela, J. 1991a. Propiedades físico-mecánicas de la especie Guadua en Costa Rica. Informe INII 60-91, Instituto de Investigaciones en Ingeniería, Universidad de Costa Rica, Costa Rica. 62 pp.

Sotela, J. 1991b. Manual ensayos físico-mecánicos para bambú. Informe INII 61-91, Instituto de Investigaciones en Ingeniería, Universidad de Costa Rica, Costa Rica. 36 pp.

Stulz, R.; Mukerji, K. 1988. Appropriate building materials. 2 ed., SKAT-I.T. Publications-GATE, Switzerland, 430 pp.

Villegas, M. ed. 1989. Bambusa Guadua. Villegas Editores, 175 pp. (Published in English as Tropical bamboo, Rizzoli, New York, USA, 1990).

Vitruvius. 1960. Morgan, M.H., tr., The ten books on architecture. Dover, USA. 331 pp.

Further Reading

Bennet, S.S.R.; R.C. Gaur. 1990. Thirty-seven bamboos growing in India. F.R.I. Press, Forest Research Institute, Dehra Dun, India. 100 pp.

Farrelly, D. 1984. The book of bamboo. Sierra Club Books, San Francisco, USA. 332 pp.

Hidalgo, O. 1981. Manual de construcción con bambú. Estudios Técnicos Colombianos Ltda., Colombia. 71 pp.

Hidalgo, O. 1985. Constructing with bamboo in South America. *In* IL31 Bamboo, Institute for Lightweight Structures, University of Stuttgart, Germany. pp. 288-291.

Janssen, J.J.A. 1981. Bamboo in building structures. Ph.D. Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands. 235 pp.

Janssen, J.J.A. 1988. Building with bamboo – a handbook. I.T.Publications, London, UK. 68 pp.

Jayanetti, D.L.; Follet, P.R. 1998. Bamboo in construction – an introduction. INBAR Technical Report No. 16, TRADA Technology Limited, UK. 120 pp.

Robledo, J.E. 1992. Un siglo de bahareque en el antiguo Caldas. Memorias 1er Congreso Mundial de Bambu/Guadua, Pereira, Colombia, 8-15 August 1992. pp. 129-131.

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INBAR

INTERNATIONAL NETWORK FOR BAMBOO AND RATTAN

The International Network for Bamboo and Rattan (INBAR) is an intergovernmental organization established in 1997 by Treaty. As of January 2000, 21 countries (Bangladesh, Benin, Bolivia, Canada, Chile, China, Colombia, Cuba, Ecuador, Ghana, India, Indonesia, Malaysia, Myanmar, Nepal, Peru, The Philippines, Sri Lanka, Tanzania, Togo and Vietnam) have signed the Establishment Agreement. INBAR's mission is to improve the well being of producers and users of bamboo and rattan within the context of a sustainable resource base by consolidating, coordinating and supporting strategic as well as adaptive research and development. INBAR programs link partners from the government, non-government, academic and corporate sectors with knowledge and technologies that directly improve the well being of people in developing and developed countries.

INBAR publishes an ongoing series of Working Papers, Proceedings and Technical Reports, occasional monographs, reference materials and the INBAR Newsmagazine. It also provides an on-line library featuring relational databases on bamboo and rattan products, organizations, projects, experts and scientific information.

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Anyuan Building No. 10, Anhui Beili, Asian Games Village
Chaoyang District, Beijing 100101, People's Republic of China
Tel: +86 (10) 64956961, 64956978, 64956982
Fax: +86 (10) 64956983
E-mail: info@inbar.org.cn
Website: http://www.inbar.org.cn/

MAILING ADDRESS

Branch Box 115, P.O. Box 9799, Beijing 100101, People's Republic of China