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NOTES ON THE SEISMIC ADEQUACY OF VERNACULAR BUILDINGS

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SUMMARY

Vernacular constructions represent a very large share of the built environment. Being, by definition, non-engineered constructions, they are the result of ancient traditions, improved with time as a response to the requirements of their social and physical environment. Consequently, they are well-fitted solutions to the demands of their social and natural environment and possess a certain built-in fixity, only modified as a result of persistent and extraordinary circumstances. Strong earthquakes are indeed extraordinarily disruptive events, but they also have large return periods, making it difficult to learn from them in short time spans without the tools offered by modern engineering research and design, absent, by definition, from the vernacular. Consequently, in many cases these constructions have proven inadequate to resist strong earthquakes and they can be held responsible for most of the resulting human fatalities caused by major quakes, demanding an effective participation of the earthquake engineering community.

To address this subject the paper presents a conceptual framework with a methodology for the assessment of the design of buildings and other structures and the basic principles required to achieve a proper seismic behavior. This framework is used to review the seismic adequacy of vernacular buildings, discussing the reasons for the success or failure of some notorious examples, and discusses what should be the role of earthquake engineering in the improvement of those solutions that have proven to be seismically inadequate, presenting some notorious national and international examples. In particular, the case of the vernacular technology of bamboo 'hollow *bahareque*' developed in Colombia and Ecuador is described. This technology has been transferred to other countries, like Costa Rica, where it has been improved through research and development and it has demonstrated its capability to resist strong earthquakes. The possibilities of bamboo, an ancient traditional material, to follow the path of structural timber and turn into a modern structural material through engineering methods, including systematic research and development of standards, are also commented.

INTRODUCTION

Historically, the major cause of death of most destructive earthquakes has been the collapse of dwellings. In the near past, the 1976 M_s 7.6 Tangshan earthquake in China, by far the most deadly event of the 20th century, almost razed the city of 1 million people killing over 250000 and injuring another 500000 (Bolt [13]). This catastrophe actually exceeded by a factor of ten the deadly experiences of other major quakes on that century, but the destruction of entire cities, the consequent death of thousands of people and the

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resulting social and economic upheaval has been a constant in our planet since the dawn of civilizations to the present times. Indeed, on 26 December 2003, as this paper was been drafted, a M_w 6.6 shallow earthquake struck Southeastern Iran, killing at least 30000 people, seriously injuring another 50000 and leaving more than 100000 homeless in the historical city of Bam, where a MMI of IX was reported and maximum accelerations of 0.98g were recorded. Over 90% of the buildings collapsed and, because the event occurred before dawn, most of the victims died in their own homes, crushed by the heavy walls and roofs characteristic of the vernacular adobe houses of that part of the world (Fig. 1).

Figure 1. Iran earthquake, 26 December 2003. Collapse of vernacular houses in the city of Bam. (www.ngdir.ir)

Vernacular dwellings are nonengineered constructions. This broad category represents a very large share, sometimes the vast majority, of the built environment and by definition it includes all type of constructions built without professional assistance. There is very little chance that they will comply with building codes or official construction permits and quite often they are built in dangerous or inappropriate sites. In consequence, non engineered constructions represent a very serious threat for most of their occupants in the event of a major earthquake.

However, vernacular buildings possess certain specific qualities that radically differentiate them from other types of nonengineered constructions. They are the result of ancient traditions, gradually improved along time in response to the needs of their occupants or to the changing requirements of their physical environment. In a permanent trial and error process, they are able to reach an asymptotic and dynamic adjustment to become well-fitted with their surroundings, gradually changing in response to the new circumstances. In consequence, vernacular constructions have been praised by architects, engineers and cultural anthropologists as being extremely effective solutions to the needs of their dwellers and to the physical requirements posed by their environment (Alexander [3], Rapoport [60], Rudofsky [62], Oliver [57]).

In the seismic regions of the world, where small and moderate earthquakes are quite frequent, these events are considered as another specific action of the physical environment and the required structural capacity to resist them is usually well incorporated within this Darwinian strategy (Shiping, [64]). However, with strong earthquakes the situation changes dramatically as these are events of extremely low probability of occurrence and high disruptive effects over the built environment. Therefore, it becomes practically impossible to incorporate any effective resistant strategy by these gradual and asymptotic procedures and only certain types of vernacular buildings, notably those with low mass and properly used tensile resistant materials, may prove adequate for such events. For the rest, the task is considered by most cultures as been beyond their reach because strong earthquakes, like many other natural disasters, are considered *acts of gods* of unpredictable and unrestrained behavior[2, 3].

To complicate the situation even more, as a result of human migrations, there are many instances of vernacular solutions that had proven adequate for non-seismic or low-seismic environments, but when uncritically reproduced in regions of medium to high seismicity, result in very vulnerable constructions. Paradoxically, in not few cases, the advent of engineered constructions has worsen the situation, as they may induce the adoption of structural configurations and construction details, appropriate for modern engineering materials, to vernacular materials and construction methods unsuitable to them. For example in the Peruvian Andes adobe construction is quite popular, even in middle class housing, but it has adopted many architectonic and constructive features proper of reinforced masonry, as larger openings for doors and windows, increasing their seismic vulnerability (Fig 2).

Figure 2. Adobe middle class house in the Peruvian Andes with architectonic and constructive influences from reinforced masonry.

The truth of the matter is that only the powerful tools of modern science and engineering research and development have proven effective to overcome this Gordian knot. However, these tools have been traditionally absent from vernacular constructions. In fact, in spite of the tremendous incidence in terms of loss of lives, the society at large and the engineering community in particular pay little attention to the problem of the poor seismic performance of some types of vernacular construction, in many cases leaving the communities unattended on their efforts to rebuild their houses. This consolidates the fixity of inadequate construction practices and, quite frequently, after the widespread destruction caused by a strong earthquake, the survivors rebuild their homes using materials from the rubble and reproducing the same structural configurations and constructive details, without adequate technical guidance or supervision, perpetuating a vicious circle of death and destruction.

However necessary, any engineering involvement would be doomed to failure unless it is rooted in a genuine appreciation to the wisdom of vernacular constructions and pays careful considerations to the process. In it, the owners and tradesmen must be effectively incorporated, as they should become believers and disseminators of any proposed upgrading; additionally, these technical improvements

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[2] Like Ruaumoko, the Maori god of earthquakes and volcanoes, hostile to man, sending now and then an earthquake or volcanic disturbance to destroy him. Adopted as the symbol of NZSEE and IAEE, his image is prominently displayed in all WCEE. These supernatural beliefs are not only restricted to the most primitive cultures but widely imprinted in the collective imagination of the vast majority.

[3] Teiji Itoh masterfully summarizes the Japanese attitude towards earthquakes: *They are unpredictable catastrophes that must be coped with by the human spirit, not by the structure of buildings.* (Itoh as cited by Tobringer [71]).

should sprout from a deep understanding of the local traditions, overcoming their weaknesses and consolidating their strengths, paying careful consideration to the community cultural idiosyncrasies. This is not an easy task for engineers, knowledgeable in materials and structural mechanics but not in sociology, psychology or cultural anthropology.

This paper addresses the topic of the seismic adequacy (or inadequacy) of vernacular buildings. To undertake this elusive subject, some basic definitions will be presented first, followed by a conceptual framework of the process of creation of building forms to be used as a referential system of analysis. The necessary requirements for an adequate seismic behavior will be discussed next, summarized in a few common sense rules, applicable to all earthquake resistant buildings. Then, vernacular constructions will be examined through the lenses of the conceptual framework and some successful and unsuccessful examples, both historic and contemporary, will be presented.

Finally, the paper will comment on the role of the earthquake engineering community in the urgent task of improving the seismic safety of vernacular buildings, not only to protect the lives and possessions of millions of people that still live and will continue to live in unsafe constructions, but to rescue, improve and disseminate the successful solutions. To illustrate this point, a particular experience related to bamboo, an ancient traditional material widely used for vernacular constructions in most of the tropical and subtropical regions of the world, will be discussed. This material may follow the path of structural timber and turn into a modern structural material, adequate for many types of earthquake resistant construction. The attention will be focused in the vernacular technology of bamboo hollow *bahareque*, which developed in the 19th century in seismic regions of Colombia and Ecuador. The technology has been transferred to other countries, like Costa Rica, where it was improved through research and development and used in the construction of thousands of houses all over the country with an excellent record of earthquake performance.

WHAT IS VERNACULAR?

Vernacular architecture *comprises the dwellings and all other buildings of the people. Related to their environmental context and available resources, they are customarily owner –or community- built, utilizing traditional technologies. All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies and ways of life of the cultures that produce them* (Oliver [56]). A simpler definition could be *The architecture of the people, and by the people, but not for the people* (Oliver [57]); this *architecture without architects* received special attention from the professional community of the industrialized nations since the 1965 namesake exhibition at the Museum of Modern Art of New York (Rudofsky [62]).

In his pioneer work on the vernacular house and its cultural determinants, Rapoport [60] distinguishes between *folk*, *primitive* and *vernacular* construction. In his own words *the folk tradition is the direct and unselfconscious translation into physical form of a culture, its needs and values -as well as the desires, dreams, and passions of a people. It is the world view writ small, the 'ideal' environment of a people expressed in buildings and settlements, with no designer, artist, or architect with an axe to grind*.

Unselfconsciousness is a key characteristic of the vernacular. In his seminal work on the nature of design, Alexander [3] dedicates a complete chapter to *the unselfconscious process* of creation of building forms. He identifies *tradition* as the first key element of this process. Tradition implies rigidity, strong resistance to change, and he mentions examples like the *trulli* of Apulia in Southern Italy, with their stone corbelled domes, or the *black tents* of the nomadic Arabs, which have remained virtually changeless during thousand of years with their *wealth of myth and legend attached to building habits*. At the same time, tradition simplifies the learning process because *there is a way to do things, a way not to do them* and these ways are accepted beyond question by all builders.

However, as the owner is usually an active participant of the building process, he performs a permanent maintenance program, fixing any malfunctioning or replacing any deteriorated component without further delay. He also adapts the building to the expanding needs of his family. Building and repair are an everyday affair where *impermanent materials and unsettled ways of life demand constant reconstruction and repair*; thus, the inadequacy of the building form leads directly to the action. This *directness* is the second key element of the unselfconscious process of vernacular building. However, given the built-in fixity set by tradition, major changes in the process will only be introduced, under strong compulsion, when there are powerful irritations which demand corrections; these irritations are usually the result of variations in the surrounding context. For those reasons, there is a permanent process of adjustment which will eventually converge to well-fitting forms. However, this fit requires time to happen and in consequence *the adjustment of form must proceed more quickly than the drift of the cultural context*. This is an essential condition that differentiates vernacular constructions from other nonengineered dwellings, like most of the slums that sprout almost overnight in many large cities of the developing world.

In summary, *tradition* and *directness* represent two antagonist features that dialectically drive the unselfconscious process, with directness pushing the process and tradition supplying the necessary viscous damping to provide the necessary stability and permanence.

As a complement, Rapoport [60] differentiates between *primitive* and *vernacular* and simply defines primitive buildings as *those produced by societies defined as primitive by anthropologists*; the term therefore does not refer to the builders' intentions or abilities, but to the society in which they build. As for vernacular, his definition is more complex, as it is done in terms of the *process*, on *how it is designed and built*. The vernacular design process is one of *models and adjustments or variations* even though *it is the individual specimens that are modified, not the type*. During the process, the owner is an active participant both in the definition of the individual characteristics and the adjustments to the model as well as in the construction process, even though specialized craftsmen do play an important role as they possess a better knowledge of certain rules and procedures. Finally, he adds other characteristics to vernacular buildings: i) lack of theoretical pretensions; ii) tuned with the site and micro-climate; iii) respectful with other people and their dwelling and with the total environment; iv) circumscribed within an idiom, with variations within a given order; v) having an open-ended nature, accepting changes and additions defined by their occupants according to use and necessity. It is evident that in the above definitions, both primitive and vernacular constructions present the same characteristics of tradition and directness; consequently, for the purposes of this paper *primitive* and *vernacular* will not be separated, as both are manifestations of unselfconscious design.

The terms *housing* and *dwelling* do need of some clarification. Although the dictionary defines '*housing* as *shelter, lodging, dwelling provided for peopl*e' the fact is that *all houses are dwellings but all dwellings are not houses. To dwell is to make one's abode: to live in, or at, or on, or about a place. For many people this implies a permanent structure, for some it means temporary accommodation, while for others it is simply where they live, even if it is little evidence of a building. Dwelling is both process and artifact: it is the experience of living at a specific location and it is the physical expression of doing so* (Oliver [57]). For a world population of over 6 billion people it is reasonable to estimate over 1 billion dwellings; of such a huge figure, only a very small percentage is the result of professional intervention; the rest is nonengineered although, as already commented, not all of them can be classified as vernacular because they lack the specific features commented above. With such huge figures, the variety of vernacular housing types built around the world is enormous as illustrated in some selected examples (fig. 3) or in beautifully illustrated books (Oliver [13], Steen [68]).

Many of these houses contain the seeds of most of the structural shapes of modern construction, like tensile structures, space frames, arches, vaults and domes, represented in multiple forms in what may be regarded as analogous to the rich biodiversity of the tropical forests. Even if grouped by use, construction materials of walls and roofs, climate, etc. the diversity remains, because similar sites and climatic conditions, as well as the same construction materials, usually produce quite different solutions, as it becomes evident with the housing types of the tropical regions of Latin America and South East Asia. Rapoport [60] presented the different theories that have been proposed to explain a particular house form and classified them according to *physical* and *social* determinants. Within the *physical* he mentions three: i) Climate and need for shelter. ii) Materials, construction and technology. iii) Site. In the *social* he includes another three: iv) Defense. v) Economics. vi) Religion. He concludes that no single determinant suffices to explain this immense variety, as house form is indeed the result of very complex interactions of all of them. This is important for the topic of this paper as it implies that the strategies developed for the earthquake resistance of vernacular buildings would not respond to single determinants like site, available construction materials or construction technology.

Figure 3. Vernacular diversity (clockwise from upper left): wattle and daub in Kenya; bamboo in Ecuador; adobe in Peru; timber in Costa Rica; timber-framed in France; masonry in Greece.

Although housing represents the largest share of vernacular constructions, it is by no means the only one. There are other types of buildings and structures which can also be classified as vernacular, as they satisfy its previously defined basic characteristics. Among them: i) Community buildings; large scale buildings mostly used for trade and community meetings. ii) Palaces and chiefs' houses; usually their architecture is an expanded version of the traditional house. iii) Sacred places; as in the previous case, the dwelling of the gods usually evolve as enlarged versions of traditional houses; for instance, the stone Mayan Pyramids of Tikal are in essence huts on top of stepped tall foundations, the pyramid proper, where the hut resembles in stone the traditional cane and palm house type built in the area. Some others sacred structures like campaniles, minarets or pagodas, are spiritual symbols craving for height, as the vertical is considered a sacred dimension. iv) Storages; crucial for the survival of the community, in many cultures are considered as quasi-sacral; a beautiful example are the *horreos* in the Spanish Galicia and the similar *espigueiros* in adjacent Northern Portugal, a Celtic legacy, which are granaries constructed of wood or stone, mounted on *pilotis* for protection from ground moisture and rodents and slated for ventilation. v) Bridges; an important item for communications and trade, some of them, as the ancient Chinese or Inca rope hanging bridges, are the seed of our amazing modern structures. vi) Ships; essential for long distance communication, trade, conquest and expansion since very ancient times; in their fabrication, superb constructive techniques were developed that in many cases were used in other type of buildings, as the timber vaults of some churches in the French Normandy.

As the variety of existing vernacular constructions distributed all over our planet is immense, the temptation of a detailed description of materials, constructive methods, architectonic styles and the like, although instructive and interesting (Taylor [70], Steen [68]), must be set aside as it will only result in a partial vision and would not allow us to understand the integrated whole. This complex task demands the development of a conceptual framework to be used as a referential system of analysis.

STRUCTURAL ADEQUACY: A CONCEPTUAL FRAMEWORK

To answer the crucial question of what makes a particular construction adequate, a conceptual framework proposed by the author [31] to evaluate a particular class of vernacular buildings is presented. Although developed for vernacular constructions, it is general enough to evaluate all types of engineered or nonengineered constructions.

Following Alexander [3], we define the process of design as *the process of inventing physical things which display new physical order, organization, form, in response to function*. This definition equally applies to the selfconscious process characteristic of engineered constructions or to the unselfconscious process proper of vernacular and other nonengineered constructions. In both cases the creation of buildings is the consequence of an interplay between the two concepts of *form* and *context*, where the form is the new created physical reality whereas the context is the surrounding environment, comprising everything that does not belong to the form and, in consequence, completing the universe of our interest. In Alexander's words: *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 of 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. As the context is not precisely known, the question of achieving fitness, or *adequacy* as we prefer to call it, seems as 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.*

Now, *form* is composed of *intention* and *materiality*. The first represents the ideal conditions that are sought after for the creation of forms, while the second 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 ideal desire of perfection, and *materiality* holding down the process to the imperfect reality of the material world. 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 touch, deeply implanted in the philosophy and theology of western civilization.

Searching for the components of intention, we may borrow from the Roman architect Vitruvius [80] which in 1st century BC defined what for almost two thousand years has been a desiderata for the creation of building forms. He established three requisites for any successful architectural work: *venustas, firmitas and utilitas,* which has been translated to English as beauty, durability and convenience but we prefer to call *delight, firmness and service*.

From the structural point of view the essential component of the building form is *firmness*, which can be defined as the capacity of the form to resist its gravitational loads as well as all the other loads and actions produced by the context, like ground settlements, temperature changes and eventual extreme effects such as 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: i) *Strength,* to withstand the specific loads and other actions defined by the context while keeping the mechanical integrity of its structural components under prescribed limits. ii) *Stiffness,* to keep the displacements and internal deformations under tolerable limits while resisting the specific loads and actions. iii) *Stability,* to be able to hold its original equilibrium position after the application of minor perturbations.

The next in importance is *service***.** It is obvious that the building form has been created to perform a series of functions and that a failure to satisfy any of them constitutes a failure, even if its firmness is not impaired. Additionally, a functional structure should not affect the environment (its context) beyond clearly defined limits of tolerance.

Last but not least is the *delight* or beauty, a source of frequent controversy erroneously left to architects and aestheticians, which should be of main concern to all engineers and professionals and to the general public. Every design should explicitly consider aesthetics as a fundamental component. Similarly to service, delight involves both the form and its context, because the beauty of a particular form can not be judged in isolation, but as related to its surroundings. The concern for delightful structures has been explicitly stated in some recent large engineering projects, where some over-costs were accepted for more pleasant solutions.

For illustrative purposes, the three Vitruvian components of the intention can be represented by the three nodes of an equilateral triangle (Fig.4). In it, each node is connected to the remaining two and each component is equally important, although delight is located in the upper node as it relates to the higher spiritual aspiration of beauty.

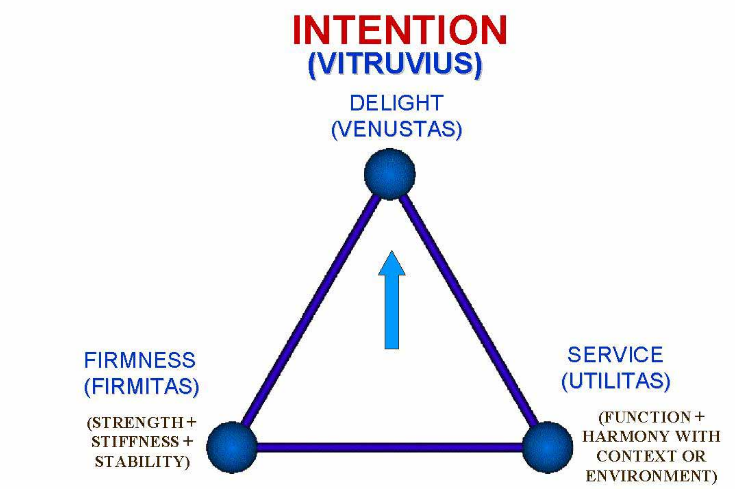

Figure 4. Triangular representation of the Vitruvian components of intention.

In the above representation an important fourth component is missing: *economy* or *cost*. Incidentally, Vitruvius included it in his famous book, but under a different heading. Within the economic considerations, the costs of at least three different stages should be evaluated: *construction* (materials, labor and equipment), *operation* and *maintenance*. When the fourth node of economy is added, to keep the idea of an equilateral figure with interactions between all the nodes, a three-dimensional tetrahedral with *delight* in the upper node is the appropriate representation (Fig.5).

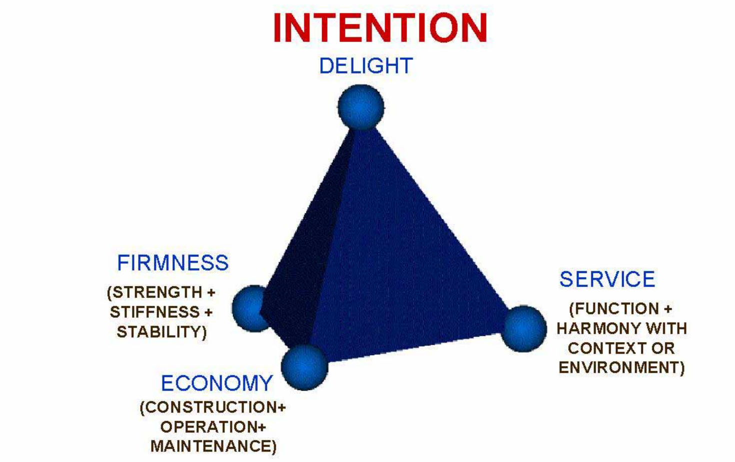

Figure 5. Tetrahedral representation of intention.

Coming down to *materiality*, the imperfect reality that limits our ideal *intention* in the process of creation of forms, the *materials* themselves define the first component. Many materials have been used to build structures since the dawn of civilization: vegetable fibers, adobe, timber, stone, brick and natural concrete in historic times and artificial concrete, iron and steel in the last two centuries. A deep understanding of the behavior of materials, their strengths and weaknesses, their opportunities and threats, is essential for the creation of adequate built forms. Each material would be more or less suitable to fulfill some of the specific purposes of the intention and what is important is to understand their behavior to take advantage of their strengths while avoiding their weaknesses. When evaluating materials, different parameters will rate them differently. Unit cost, local accessibility, simple manufacture, simple tools requirement, durability, or energy required for its production, could be in some cases more important than strength or stiffness. This is a key concept for the evaluation of the vernacular constructions.

Closely related to the *materials* is the *shape* or *configuration*. The shape of a well conceived structure must take full advantage of the material characteristics and its definition demands extreme care, as it is the most creative stage of the design process. Sometimes the shape is defined by the structure itself, as when a flexible rope adopts the parabola to resist uniformly distributed loads. The same shape of the rope, but inverted upward, forms the parabolic arch, which consequently will resist by compressive internal forces what the flexible rope resists in tension. Roman engineers intuited this basic concept and expanded the spans of their arches to built superb masonry bridges out of stone, a material with enough strength in compression, but extremely weak in tension at its interface. An explicit statement of this basic concept had to wait until 1675[4].

Two other components complete the *materiality* of the structural form: *dimensioning and detailing* of the structural elements, to provide the individual components and their joints with the strength, stiffness and stability required for the structural integrity, and the *constructive technology*, which includes the tools and the logistics necessary to build the conceived form. Again, as these four components of the *materiality* are equally important, they can be represented by another tetrahedral, with each component representing a node and *materials* occupying the lower position (Fig.6).

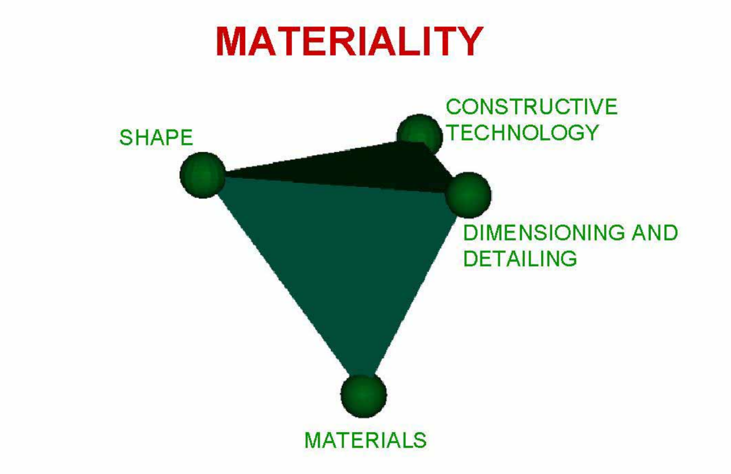

Figure 6. Tetrahedral representation of materiality.

As mentioned, *intention* and *materiality* constitute the dialectic components of any built *form*. The first corresponds to the thesis and the second to the antithesis. The synthesis is precisely the *design*, the creative process demanding a satisfactory solution for this dynamic interplay between the ideal aspirations of the *intention* and the hard reality of the *materiality*. This optimal synthesis may be represented by the eight node three-dimensional star, s*tella octangula*, formed by the two original tetrahedral symmetrically interpenetrating each other (Fig.7). This beautiful shape conveniently represents the process involved in the creation of adequate forms that we call design[5].

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[4] When it was enunciated by Robert Hook in his remarkable anagram *Ut pendet continuum flexile, sic stabit contiguum rigidum inversum* (as hangs the flexible line, so but inverted will stand the rigid arch).

[5] Incidentally, Eduardo Torroja [73], the great structural artist, conceived the design process as the simultaneous solution of four *equations* with four *unknowns*. With slightly different names, his four *equations* correspond to the four components of the *intention* and his four *unknowns* to the four components of the *materiality*..

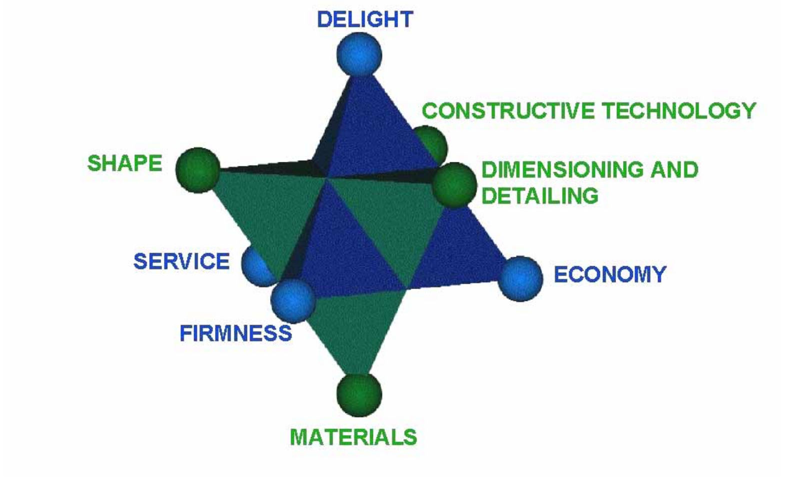

Figure 7. Design as synthesis: Stella Octangula.

As explained before, form and context represent another dialectic unit, with each one interplaying with the other. In structural theory the effects of the context upon the form are called *loads* or, more generically, *actions*. These actions must be defined with a certain degree of precision and reliability, which is not easy for eventual extreme actions like large earthquakes or strong hurricanes, which can only be defined in probabilistic terms. Associated with the response of the form to its specific context, represented by the actions, is the concept of *fitness* or *adequacy*. This concept can not be defined in positive terms as any list of requirements will remain indefinitely open and unbounded, but can be defined in negative terms, specifying whatever constitutes a *misfit* or unacceptable behavior and defining their corresponding limits of tolerance. Under this *limit design* criterion, the form will be considered unfit or inadequate if any of these predefined limits is violated. There may be as many *performance objectives* as necessary, each one defined by a pair consisting of a selected combination of concurrent actions and its corresponding expected performance, defined in terms of prescribed limits of tolerance, in this *performance-based engineering* approach. It must be emphasized that the design of a form is defined by the context, hence it is historically, culturally and geographically dependent or, in brief, time and space dependent. Hence, when evaluating the fitness or adequacy of a particular creation, it is essential to consider the particular historic, cultural, socio-economic and physical conditions of the context, graphically illustrated in Fig. 8.

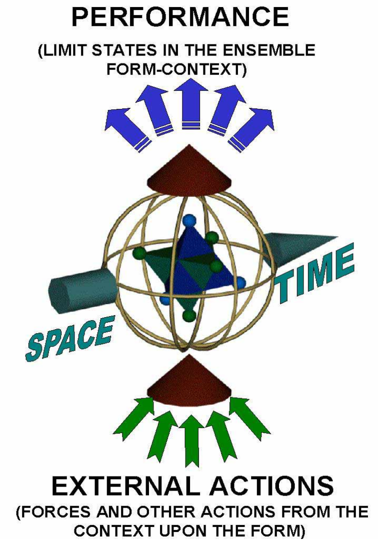

Figure 8. Actions from context, and adequate form-context performance.

As already commented, for evaluating the adequacy of built forms, this conceptual framework is equally applicable to the *selfconscious* process of design, performed by architects or engineers, or to the *unselfconscious* process, characteristic of vernacular constructions. In the next sections, the framework will be applied to our subject matter: the seismic adequacy of vernacular buildings.

BASIC PRINCIPLES FOR EARTHQUAKE RESISTANCE

As described in the conceptual framework, an adequate earthquake resistant construction should be able to withstand the extreme events of ground shaking and other earthquake related effects likely to occur during its lifetime, fulfilling previously defined performance objectives defined in terms of prescribed limits of tolerance. Broadly defined, these objectives are life protection for the building occupants and minimization of property damage. For vernacular and engineered constructions alike there are some basic principles that, since old times (Kirikov [45]), have proven desirable for earthquake resistance. Obviously, not all of them must always be present, but the more the better.

Proper site selection

The first requirement to achieve building safety is a proper selection of the site. Buildings must be placed on soils able to bear the stresses caused by their weight and all other actions, while avoiding excessive or differential settlements. Additionally, there are other potentially destructive earthquake effects on buildings which are associated to improper site selection, some of them are directly related to failure or severe disturbance of the ground at or near the building site, whereas other may be considered as indirect effects. Among them: i) Landslides and other forms of slope instability. ii) Liquefaction. iii) Ground subsidence. iv) Fault rupture at surface level. v) Tsunamis. vi) Seiches. vii) Flooding caused by earthquake induced failure of water reservoirs (Lew [47]). Nonetheless, as potentially destructive as these effects are, all of them can be prevented by a judicious site selection. Even ground shaking, the unavoidable source of potential building damage, can be significantly reduced in an appropriate site, as some soil profiles are likely to amplify the seismic waves by several orders of magnitude.

Lightness

The late Buckminster Fuller insistent question: *Gentlemen, how much do your buildings weigh?* acquires special relevance in the presence of earthquakes, as the acceleration induced inertia forces are in direct proportion to the masses of the buildings and its contents. Weight reduction, by judicious selection of building materials and avoidance of unnecessary masses is always desirable. Furthermore, in the event of partial or complete collapse, the consequence of a heavy construction falling upon its occupants dramatically increases the chances of serious injury or death. The motto *fail easily but not lethally* (Oliver [57]) well applies to some flimsy vernacular constructions that, due to their lightness, are not life threatening to their dwellers even in the event of complete collapse, as illustrated by the house in the upper-right picture of Figure 3.

High quality and well protected materials

Superior material quality is essential for any structure. Properties such as strength, toughness, ductility, elasticity, lightness, viscous energy dissipation and resistance to weather effects are necessary and convenient under normal conditions and crucial in the event of severe earthquakes or other extreme events. Certainly, not all of them must be present in a material to qualify for earthquake resistance. Of particular importance in vernacular constructions are those materials with the capacity to resist tensile forces, as the horizontal ground shaking is very likely to induce net tensile stresses. This, of course, is the *Achilles' heel* of unreinforced masonry constructions, either of adobe, brick or stone. Being inherently weak in tension, these houses are designed to resist all gravitational and permanent loads by compressive stresses, with excellent behavior during periods of earthquake silence but very bad performance when these events occur.

Quality of construction and adequate protection against their decay are essential to guarantee that the materials will be able to attain and maintain their expected behavior. All materials decay with time, but this effect is severely enhanced by the presence of moisture. Timber and similar organic materials, which are very valuable for seismic resistance as their cellulose fibers makes them highly effective to undertake tensile stresses, are especially vulnerable to fungi and xylophagous insects. Vernacular constructions are particularly notorious by their highly effective constructive details, like raising the building from the ground or overextending its roof eaves, to protect these vulnerable materials against moisture from soil humidity, floods and rain[6]. Furthermore, when particular materials are likely to decay faster than the rest of the building, the constructive procedures should allow for their easy replacement. This strategy of *durability trough substitution*, demanding the immediate replacement of any decayed element, is well established in vernacular construction.

Proper structural layout and proportions

Structural symmetry and regularity are generally recognized as essential requirements for proper earthquake behavior, as buildings possessing this conditions respond with fairly regular displacements along height and almost negligible floor rotations due to insignificant torsional effects; in consequence their deformation pattern is well distributed among the structural elements, and their paths of force transmission to the foundation are simple and effective. Most seismic codes recognize the benefits of symmetry and regularity and encourage these conditions in buildings, penalizing height or plan irregularities. When not spoiled by the imitation of trends from modern architecture, vernacular constructions have a tendency towards symmetry and regularity. Equally important is a good plan layout with all walls supported by cross walls or buttresses at regular intervals in both directions. Finally, overall building dimensions must be well-proportioned, with adequate height to width, length to width ratios, as well as height to width ratio of walls and pillars and maximum dimensions of well centered doors, windows and other wall openings. Again, this is usually the case with vernacular constructions.

Structural integrity

For all type of actions, but particularly important for earthquake ground shaking effects, the complete structure must be able to respond as a single integrated system, *providing a stable matrix inherently stronger than the individual components* (Blondet [12]). According to the fundamental theorem of structural mechanics, the *Safe* or *Lower Bound Theorem* of Plastic Theory, *if a structure can stand the forces it will stand them* (Heyman [35]). The integrity of the structure will be insured if there is at least one force configuration, for example a particular strut and tie arrangement, satisfying equilibrium without exceeding the strength of the structural elements. Obviously, Plastic Theory assumes plastic behavior, allowing force redistributions whenever the material strength is reached at a particular zone. However, this force redistribution does not necessarily implies the orthodox plastic yielding, as what is really necessary for the materials is to be able to sustain their strength with increased deformations, allowing the redistribution of forces in the structure. Under particular conditions, even unreinforced masonry exhibits this behavior, which was essential for the *firmness* of one of the greatest structural achievements of all ages: the cathedrals of the High Gothic (Heyman [34]). Last but not least, the joints among elements and components must have enough strength and ductility to either resist the forces holding the elements together or deforming to limit the transmitted forces.

Shaking isolation

The strategy of reducing the structural deformations and internal forces caused by earthquakes by means of base isolation, energy dissipation or mass damper devices is a promising trend in earthquake engineering. Nevertheless, it should be pointed out that in a rudimentary way, some vernacular constructions introduced these concepts long time ago. For example, sand or palm leaves, placed between

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[6] This is nicely expressed in the Chinese motto referred by Arya [7]: *Clay houses need hat and boot for safety against rain and flood waters*.

the supporting soil and the construction foundation, have been used for base isolation and the suspended central pillar of some Japanese pagodas is an effective mass damper pendulum (Tobriner [71]).

VERNACULAR SEISMIC DESIGN

In this section, the unselfconscious design process of vernacular constructions in seismic environments is commented through the lenses of the previously described conceptual framework.

Regarding the components of *intention*, obviously *firmness* is essential as buildings are expected to resist the ground shaking produced by the probable extreme quakes while fulfilling its performance objectives. *Economy* is also important as any increment in seismic resistance should represent affordable cost increments and result in reasonable cost/benefit ratios. As for the two remaining components, *service* and *delight*, seismic considerations have little implications in the building functional requirements or in its esthetic qualities. In contrast, the four components of *materiality* have important implications when procuring earthquake resistance in vernacular design, and they will be examined next.

Materials

Logically, the prevailing structural materials of vernacular constructions are the traditional materials adopted by mankind since the dawn of civilization which, for the purposes of this work, will be grouped in three major categories:

Small-diameter organic

Conformed by small trees, branches, shrubs, reeds, lianas, bamboo culms, canes and other grasses. Their cellulose content makes them strong in tension and, when woody, they are able to resist small amounts of bending and compression. Of small length and low weight, they are generally used as round poles and can be easily cut, transported and manipulated. Their main weakness is their natural proclivity to decay.

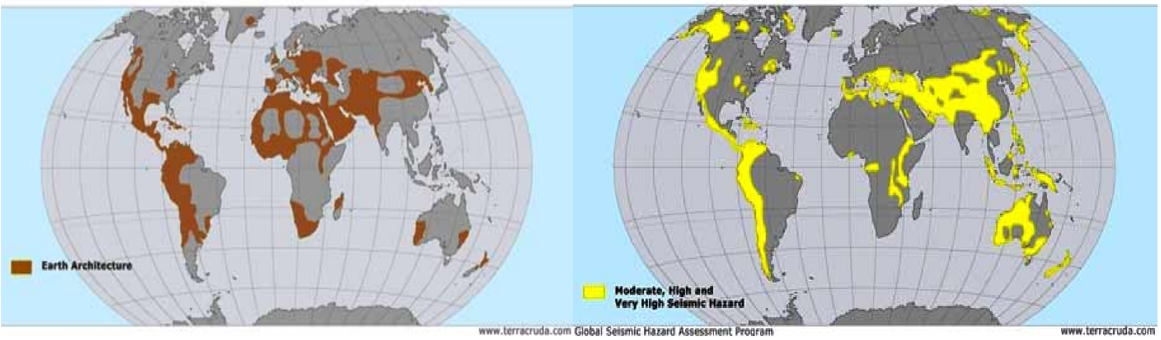
Timber

The product of trunks and major branches of large trees; it is also resistant to tension, compression and bending. In primitive constructions, round wood poles were directly obtained and used; much more difficult was the transformation to rectangular sections, until the emergence of mechanical sawmills in mid eighteen century. However, ingenuity prevailed and large posts, beams, planks and studs of superb quality are not uncommon in ancient construction, resulting in an excellent alternative for a large variety of construction types built in seismic regions. Similar to the small-diameter organic materials, when improperly seasoned and protected, they are vulnerable to natural decay caused by fungi and xylophagous' insects. In many places of the world the once abundant material has totally disappeared or become very scarce as a result of the reckless deforestation caused by population pressure or plain human greed, resulting in a serious limitation, particularly for vernacular constructions.

Conglomerated

This broad category groups a large variety of structural materials with the common characteristic of being inherently weak in tension. When their structural *shape* resists the loads by compressive stresses, extraordinary and long lasting constructions can result. This is relatively easy for the vertical and ever present gravitational loads but not for the effects caused by occasional horizontal earthquake shaking, which very likely will produce net tensile stresses. This fact, combined with the large masses usually required for stability, result in high vulnerability in earthquake prone regions. This category can be further divided into three sub-categories:

i) Earth. Found underfoot, earth is the dominant vernacular material as it is utilized in an amazing array of methods and techniques for everything from walls to roofs to floors. As sun dried mud, with or without straw, it becomes masonry adobe, but it can also be cast and rammed into a continuous structure or hand-packed into structures or frames of other materials. Its abundance, high plasticity and very low thermal conductivity offers many constructive and architectonic advantages and very old and extremely beautiful vernacular constructions can still be found in the dry non seismic regions of the world (Oliver [57], Steen [68]). Unfortunately, being massive, not very strong in compression and extremely weak in tension, it is the worst material for earthquake resistance, representing a permanent threat for innumerable people in many places around the world (Fig. 9).



(a) Distribution of Earth Architecture **(b) Distribution of Seismic Risk**

Figure 9. The perils of earth construction in earthquake prone areas (De Sensi [18])

ii) Masonry. Consisting of small pieces of adobe, stone, fired brick or any material cohesive enough to be easily handled and arranged in much larger volumes. Even if the individual blocks were strong enough in tension, they are assembled into forms either without mortar or with mortar which has little tensile strength, resulting in a material highly vulnerable to tensile forces. As the required shear strength in the interface is provided by friction, a minimum compressive force is necessary. Extremely sophisticated constructions have been built with this material by different world civilizations[7].

iii) Mass concrete. Non-reinforced continuously cast mass concrete hardens chemically, resulting into an ‘artificial stone’. The use of concrete is not new as the Romans used natural concrete, mixing lime and locally available volcanic pozzolana for the mortar with rubble stone, but the technology was lost until the 19th century, when artificial Portland cement was introduced. Being weak in tension, mass concrete was eventually reinforced with steel bars, resulting in one of the predominant modern structural materials of the 20th century, but it is also empirically used in non engineered constructions.

Shape

In vernacular constructions *shape* is the direct result of the physical and mechanical properties of their construction materials, as the unselfconscious design process should assemble them to be able to resist the predominant actions by trying to obtain full advantage of their major strengths, minimizing their weaknesses. Consequently, each one of the previously defined categories or materials should produce different structural shapes: small-diameter organic materials are usually associated with a large variety of light wattle shapes; timber, with post and beam frames and conglomerated materials with massive walls.

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[7] The most remarkable use of masonry as a structural material is that of the sacred and ceremonial buildings of the Inka civilization of Peru. Perfectly matched stones interpenetrate one another without any mortar. In the Coricancha Temple in Cusco, the walls are inclined towards the interior of the rooms, thus reducing the possibility of falling towards the exterior, and the upper rows are held together by pieces that perfectly fit into boxes carved in the stone. In other buildings a similar effect was achieved by pouring molten bronze into holes in the stone. Logically, this extremely sophisticated technology was absent from their vernacular houses, although in those of Machu Picchu the roof joists and rafters were supported by, and tied to, stones protruding from the walls (Gallegos [25]).

Small-diameter organic shapes

This category comprises a wide variety of constructive *shapes*, which are usually associated with the dwelling of most primitive cultures, whose structure is fabricated with poles either isolated or interwoven with slender branches, canes or reeds (upper pictures of Figs. 3). They may be covered with animal skin, leaves or grass or sometimes daubed with mud for better protection, privacy and thermal insulation. Being extremely light, they are excellent for earthquakes as their inertia forces are very small and their structure is highly redundant. However, for cultural reasons and due to their fast natural decay, lack of privacy and modest appearance, they are held in very low esteem by their occupants which will take advantage of any opportunity to replace them by a different alternative, which in many cases will result in higher seismic vulnerability. For instance, in Flores, Indonesia, a low interest loan program allowed the people to build unreinforced brick masonry housing to substitute their humble but very light bamboo dwellings; the new buildings suffered major damage in a 1992 earthquake (Edwards [22]). Sadly, under the sweeping forces of globalization, these light vernacular constructions seem doomed to extinction, together with the primitive cultures that created them.

Timber shapes

Timber is available in predominantly one-dimensional, large and straight elements able to resist tension, compression and bending. Therefore, the corresponding shapes are posts and beams ingeniously assembled into all sorts of structural frames (lower pictures in Fig. 3). As the many variations of joints between elements possess some degree of flexibility and have less bending strength than the connecting elements, unbraced frames may not be adequate to resist lateral loads, and either diagonal bracings or effective structural shear walls, and not simple architectural dividers, are necessary to provide the required resistance to horizontal wind or earthquake loads. Protection of timber against natural decay can be effectively accomplished through architectonic details, like generous roof eaves to protect the walls from the rain or well ventilated stone or brick foundations to raise the timber from the ground moisture or eventual floods.

Vernacular Japanese wooden construction, with a post and beam structure and light architectonic walls, have received worldwide praise for their beauty and functionality and had a great deal of influence in the modernist movement prevalent in the architecture of the 20th century [Engel, 1985; Ueda, 1990]. However, the January 17, 1995, Hyogoken-Nambu (Kobe) earthquake evidenced the poor seismic performance of these otherwise adequate buildings (report N° 86 EERI/IAEE [21], Tobriner [71]). Although structural decay due to biological degradation was pointed out as one of the main causes of collapse (Doi [19]), the real culprit was the lack of proper diagonal bracings or effective shear walls in the structural frames, which were unable to support the inertia forces induced by their heavy roofs. On the contrary, when properly protected and maintained, there are evidences in many places of the world of the adequate seismic behavior of vernacular timber-framed housing with lateral resistance provided either by diagonal bracings or other shear resisting elements as indicated in several house construction types presented in the EERI/IAEE Encyclopedia [21] or in the 'hollow *bahareque*' constructions discussed latter.

Shapes from conglomerated materials

When conglomerated materials are used, the resultant building *shapes* (middle pictures in Fig. 3) have heavy walls and pillars for the vertical height and arches, vaults or domes for the horizontal span, although timber beams are a usual alternative for floors and roofs. The walls play a crucial role not only as architectonic dividers but as structural elements able to support both the permanent gravitational vertical loads as well as the in-plane horizontal loads induced by wind or seismic ground shaking. To provide them with out-of-plane stability, orthogonal walls or buttresses are necessary. For gravitational loads, the compressive stresses in the material are very low as compared with their strength; however, as friction is crucial for shear resistance, minimum values are necessary for structural stability.

As already mentioned, the seismic adequacy of these constructions is very poor as they are very massive, inducing very large inertia forces, and very weak in tension, resulting in the loss of the structural integrity among the orthogonal structural walls, which will induce an out of plane collapse and the consequent fall of the usually heavy roofs. As mentioned, for masonry construction, the introduction of judiciously placed reinforced concrete elements have resulted in an effective seismic upgrading of this type of vernacular constructions This is the case of the vernacular confined masonry, with their unreinforced masonry walls strengthened with vertical and horizontal reinforced concrete elements, bond beams and tie-columns around the perimeter, which originated in Italy after the Messina earthquake of 1908 (Meli [52, 53]) and has evolved into different manifestations in many parts of the world. Another example is the use of reinforced concrete instead of unreinforced stone masonry for the long barren vaults of the beautiful vernacular constructions in the Greek Cyclades (Fig. 3); this effective upgrading was introduced after the 1956 earthquake, allowing the preservation of their beautiful shapes (Oliver [57]).

Dimensioning and detailing

Mignot's dictum *Ars sine scientia nihil est,* stated in 1400 when evaluating the construction of Milan's Duomo, summarizes two millennia of a methodology used for the dimensioning of structures, that extended to the 19th century for all kind of buildings and to our present time for vernacular constructions. In that sentence, *scientia* has nothing to do with the meaning of the word in our day, but referred to the existing knowledge, resulting from tradition and synthesized in comprehensive set of rules for the design of new constructions. Similarly, *ar*s did not have aesthetics implications but referred to the practical knowledge of skilled craftsmen. Hence, the aphorism should not be understood as *art without science is nothing* but rather as *practice is nothing without the application of proven rules* (Heyman [35]). Indeed, proven rules of building dimensioning and detailing have been established and transmitted by different cultures from all parts of the world since the distant past. Some of them were expressed and transmitted as mathematical relations, like the famous *Golden Rule*; others reached us in written form, like the influential compendium of Greco-Roman cannons written by the Roman architect Vitruvius [80] in 1st century BC, the Chinese '*Yingzao Fashi*' (Building Standards), a manual of architecture issued in the 12th century at the court of the Song emperor Huizong (Steinhardt [69]), or the compilation of Gothic rules in the 13th century sketchbook of Villard de Honnecourt (Gimpel [26]). Nevertheless, the vast majority belong to the oral traditions transmitted from master to disciple, generation after generation. Most of these rules define the correct proportions of the elements and components of the building, defining their dimensioning and detailing. Of course, to be effective, well-proven rules of dimensioning based in the overall proportions of the buildings do require a similar scale among them, as illustrated by Galileo [24] with the different proportions of the bones of mice and elephants. They also need similar loading environments, a condition that is not fulfilled when as a result of human migrations vernacular solutions, adequate for non-seismic or low-seismic environments, are uncritically reproduced in regions of high seismicity. Similar problems may also arise when standard rules, developed for materials of a particular quality and strictly enforced constructive practices, are blindly applied to informal constructions using other materials or materials of lesser quality or built without the *ars* of skilled craftsmen.

Constructive technology

Rapoport [60] considers the appearance of building tradesmen, possessing the *ars* of skilled practical knowledge, as one of the key steps in the transition from primitive to preindustrial vernacular construction. Anyway, in the construction of vernacular dwellings it is usual than the owner and the complete family, and at some decisive stages of the process even their neighbors, participate in what becomes a collective constructive process. Because all the participants possess some practical skills, the expertise of tradesman is a matter of degree and their contribution is essential to achieve the desired quality. Usually the construction involves two different phases: preparation, when the site is selected and materials gathered and brought to the site; and building, when the house is actually completed. Standardization and prefabrication of building components is not unusual in the vernacular; like in the remarkable timber-framed constructions (Fig. 10) built in Europe since the middle ages (Harris [33]).

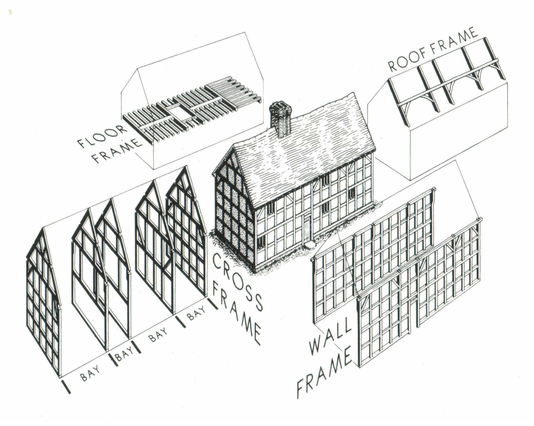

Figure 10. Prefabricated medieval timber-framed building (after Harris [33])

THE ROLE OF ENGINEERING

It is the responsibility of society at large to reduce the risk of death and the associated loss of property resulting from seismically vulnerable constructions located in regions of moderate to high seismicity all over the world. This task is particularly difficult for vernacular and other types of informal nonengineered constructions, which represent a majority of the built environment, as they lack the most basic forms of technical control, but it is a pending assignment for the engineering profession as, in many cases, effective seismic upgrading can be achieved with low cost but very effective minor interventions. For instance, Klingner [46] estimated that the seismic upgrading of self-built masonry constructions in the city of Medellín, Colombia, represented a cost/benefit of well over 40. Nevertheless, near-sighted policies and poor organization and methodologies in key institutions usually prevent the important from taking precedence over the urgent and this imperative requirement is postponed until a new earthquake stirs, for a short time, the debate and the attention of the society.

From the standpoint of this paper, the role of structural engineers and related earthquake engineering specialists as key protagonists on this important task should receive special attention. The formal educational process will be examined first, including possible ways for research and technology transfer. Then, some notable national and international efforts to systematically classify, study, improve and disseminate the existing knowledge as well as the successful experiences will be presented.

The curricula of most civil engineering schools hardly consider any teaching in the subject of vernacular constructions, and few research programs are concerned with the improvement of their seismic vulnerability. The theme does not capture the interest of professors, neither of students. From the scientific and academic perspective it is not a challenging problem; it does not require sophisticated theories to master it and it is impractical to apply traditional computer programs, as the standard analytical models are usually unsuitable for the structural systems involved. The understanding of the response of these systems to earthquake shaking and the development of effective solutions to improve their behavior belongs to the art of conceptual structural design, usually neglected in most university programs (Billington [9], Schlaich [63]) which place an excessive emphasis in the physics and mathematics necessary for the analysis of structures, while neglecting their attention to genuine problems of design (Simon [65]). Also neglected are the courses in the history of building construction and the evolution of structural materials and shapes, leaving the students without the historic background essential to understand the development of structural forms and the contribution of the unselfconscious design to the process (Billington [10]). Regarding research, it is not usual to award grants for a subject limited to traditional materials and simple structural systems. As a result, to a large extent, teaching and research on this important subject has been left to the universities and research institutions of some of the developing countries, that most face this acute problem with very limited resources. An additional limitation is the fact that most of the scientific and technical interchange of information among engineers and researchers of the developing countries is done through the publications and meetings of developed countries. There is very little South-South scientific and technical interchange among developing countries, even if they have many important problems in common.

To further complicate the situation, engineers in general are not even aware, less could they understand, the complex cultural factors involved in vernacular constructions; hence, it is quite unlikely that the problems that need technical solution are going to be well focused within their holistic context. To apprehend the vernacular, a multidisciplinary approach is required, involving architects, sociologists, cultural anthropologists, economists, public health specialists, in addition to engineers. One particular feature in the building may be the product of many years, even centuries, of ingenious tinkering[8] and, if modified without a proper understanding of its interrelations, may result in serious and unexpected consequences. Furthermore, to effectively intervene in vernacular housing, it is essential in the first place to modify the cultural attitude towards seismic adequacy of their dwellers. As already commented, in no few cases seismic safety is considered as beyond their human possibilities and other more immediate hazards, like fire or floods, are given priority[9]. In the second place, it is necessary to have reliable information about the predominant building types, with reliable data on the number of houses, the quality of their materials and constructive details, their decay patterns and maintenance practices, their main seismic vulnerabilities, etc. Only with this type of information (Alcocer [2], Blondet [11]), would be possible to identify the most urgent and important technical problems and the possible nature of their solutions.

Because of the practical nature of the technical problems involved, their understanding and the consequent development of effective solutions requires the support of reliable data generated by experimental testing on the proposed prototypes; therefore, structural laboratories with large-scale testing capabilities are necessary, either at universities or official research institutions, to test the materials, structural elements, components, joints and representative models of the complete structure. The proposed technical solutions should always be practical, of affordable cost and in agreement with the culture and the traditional practices of the region. Their implementation should be complemented with pertinent transference programs and technical assistance, supported by appropriate didactic material and training workshops, which should provide an excellent opportunity for discussion and feedback with the community.

Even if the task seems colossal, some developing countries are carrying out serious and sustained efforts to reduce the seismic vulnerability of their vernacular constructions and other types of nonengineered buildings. In general terms these efforts emphasize pre-disaster mitigation and preparedness as a necessary ingredient in addition to the traditional emergency response capacity, issuing guidelines for the construction of predominant and particularly vulnerable nonengineered buildings. These guidelines are based in the prevailing constructive practices, emphasizing the major causes of their vulnerability and focusing in the critical structural components, proposing economical and technically feasible methods for their improvement, if possible supported by experimental research. Concurrently, there have been some important international efforts aimed at recollecting and sharing these experiences and all the existing knowledge regarding house construction in the earthquake prone regions of the world. Some noteworthy experiences will be briefly commented:

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[8] The verb is used here with the meaning given by McClellan and Dorn [49] in their illuminating book about the development of science and technology in the world.

[9] Resulting in houses protected with heavy tiles in the roof in the first case or in houses built over *pilotis* in the second, two detrimental features against earthquake resistance.

i) In India, the second most populated country in the world, 50% of the total (195 million) housing units consist of clay, adobe or stone walls and another 35% of brick walls, both highly vulnerable constructions (Arya [7]). After the M_L= 6.4, Maharashtra earthquake of 1993 that killed 8000 people and left one million homeless (in some places up to 70% of the buildings were destroyed), an innovative and successful recovery program was implemented (Arya [5], Nikolic-Brzev [55]). In that region, 84% of the buildings were a particular vernacular construction type with uncoursed random rubble stone walls and heavy earthen roofs supported by timber planks and joists. The heavy roof may be adequate for thermal insulation but not for earthquakes and suffered extensive damage or collapse. To upgrade these constructions, an effective and economical procedure was developed (Arya [6], Momin [54]). The method was then implemented, in a pilot program for demonstrative purposes, to 5000 private buildings scattered through 13 districts in the area. This and other similar experiences should be carefully analyzed and adapted to other parts of the world.

ii) In the Spanish speaking countries of Latin America highly vulnerable adobe is the prevailing material for vernacular constructions, accounting for a large share of the total earthquake death toll[10]. For instance, official statistics in Mexico indicate that more than 70% of the total dwellings are nonengineered constructions, basically adobe and to a minor extent unreinforced masonry (Alcocer [2]); hence, it should not be a surprise that, for some earthquakes, one-third of the total losses correspond to the housing sector. Responding to this reality, the '*Universidad Nacional Autónoma de México*' (UNAM) initiated a research program on adobe construction several decades ago (Bazán [8], Meli [51]). The situation is similar in Peru, where adobe or rammed earth account for 60% of the total houses (Blondet [11]); there, the '*Universidad Nacional de Ingeniería*' (UNI) and the '*Pontificia Universidad Católica del Perú*' (PUCP) have developed similar programs (Torres [72], Vargas [75, 76], Otazzi [58]). During all these years, both programs have grown strong, have been extended to other vulnerable building types like unreinforced masonry and have involved other universities (Alarcón [1]) and national centers like CENAPRED in Mexico or CISMID in Peru, generating and disseminating a wealth of valuable information, including technical publications aimed at the builders and dwellers, benefiting many people from these and other countries with similar housing conditions. A recent Tutorial, available in the web (Blondet [12]), presents a good synthesis of these and other experiences.

iii) Recognizing the experiences of India, Mexico, Peru and other countries facing similar problems, the International Association for Earthquake Engineering (IAEE) established the Committee on Non-Engineered Construction. Among other valuable products, the Committee made a 1980 publication which was later revised, expanded and published in 1986 as '*Guidelines for Earthquake Resistant Non-Engineered Construction*' [37], a rich compendium of technical knowledge and accumulated experience on the subject, presented in easy to read chapters dedicated to the general principles of earthquake engineering design and to the predominant vernacular materials and building shapes and their more common problems and possible solutions.

iv) Another important effort was the five year research and dissemination project denominated '*Building for Safety*', conceived as a contribution to the International Decade for Natural Disaster Reduction (IDNDR). The project involved an international multidisciplinary group of researchers which formulated a set of guidelines aimed at the builders of vernacular constructions in hazard prone regions, trying to satisfy several technical and cultural parameters to facilitate their acceptance (Davis [17]). Four volumes were prepared as guidelines and published by the Intermediate Technology

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[10] A remarkable exception is Costa Rica, where highly vulnerable adobe and '*tapial*' (rammed earth) were forbidden in 1910, after an earthquake destroyed the colonial capital of Cartago. Widely available wood became the predominant construction material and a beautiful timber vernacular architecture emerged all over the country. This visionary decision explains the very few casualties due to earthquakes in the 20th century in the country.

Development Group (ITDG), among them the '*Technical Principles of Building for Safety*' [16], a valuable compendium with key recommendations for earthquake resistant construction.

v) Last but not least it is fundamental to mention the '*Web-based Encyclopedia of Housing Construction Types in Seismically Prone Areas of the World*' [21, 14], an ingenious and innovative joint project of the Earthquake Engineering Research Institute (EERI) and the International Association for Earthquake Engineering (IAEE) launched in January 2000. In four years, the project has collected and placed in the web an enormous wealth of information regarding a variety of housing construction types ranging from single family adobe to structural concrete and steel multistory buildings. For each entry, there is valuable written and graphic information presented in a standard form and related to ten categories: general information; architectural features; socio-economic issues; structural features; evaluation of seismic performance and seismic vulnerability; earthquake damage patterns; building materials and construction process; construction economics; insurance and seismic strengthening technologies. The web database allows the user to create a specific data search with 13 options related to these categories. At the time this paper was being drafted, there were 28 construction types from 16 different countries listed under the category of nonengineered constructions; however, the figures increase to 36 from 23 countries when all construction types with a period of practice of 100 years or more are considered. The already mentioned Tutorial on adobe [12] was prepared as a contribution to this singular effort.

Evidently, the responsibilities of the engineering profession in the never-ending task of mitigating the destructive effects of earthquakes for the billions of people living in vernacular or other forms of nonengineered constructions are enormous and can not be exhausted with these notes. As a practical case, the particular experience of the author with bamboo as an appropriated construction material for earthquake resistant housing will be presented.

THE STORY OF BAMBOO BAHAREQUE

As a vernacular construction material, bamboo is widely used in all parts of the world where it grows. In many places it is restricted almost exclusively to very humble dwellings, usually built by the owners. 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 (Parsons [59], Villegas [78]) with a strong tradition of vernacular bamboo housing (Fig. 11).

The bamboo houses of South America are built almost exclusively with one particular species of bamboo: the elegant, large, woody and straight *Guadua Angustifolia Kunth,* belonging to the genus *Guadua*. According to McClure [50], *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* for simplicity, is the most extensively used and economically important bamboo native to the New World (Judziewicz [44]). It was used as a construction material for housing and other applications much before the arrival of the Spaniards (Parsons [59], Robledo [61]). Nowadays, Guadua is widely available in the market as structural poles and beams 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 used as boards in walls and ceilings.

Figure 11. Left: The Bamboo Culture Region of Colombia and Ecuador (after Parsons [59]). Right: Typical rural bamboo *bahareque* houses with Guadua in the background.

Corresponding to their particular socio-economic conditions, the bamboo houses of the region can be classified in four different types: i) Rural; vernacular houses 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 vernacular traditions. ii) Urban-vernacular; corresponding to vernacular buildings and dwellings located in the downtown areas of the main cities and larger towns. They were usually built in the first half of the 20th century, before cultural changes led to their rejection and substitution by masonry, reinforced concrete and other modern materials. Many of these houses are still in use and very well preserved. iii) 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. Obviously, all of them are nonengineered constructions but only a minority may be considered vernacular. iv) Engineered; the result of the efforts of architects and engineers who are aware of the extraordinary potential of Guadua as a construction material, and are using it in housing projects for low and middle-income groups or even in luxury houses for the very rich. In this paper the emphasis is placed in the first two types, with a minor comment on the last, but a complete description can be found elsewhere (Gutiérrez [31]).

Rural

There are two main climatic and environmental conditions in the region of our attention: i) The lowland coastal regions of Ecuador and ii) The high-altitude, hilly Colombian region of the Antiguo Caldas. Rural construction of bamboo vernacular houses presents drastic differences depending on their location. In the coastal lowlands of Ecuador, these houses are made almost exclusively of vegetable material, using 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 to raise the floor from the ground. Owing to the hot climate, the esterilla of the walls is left uncovered, producing an extremely light structure (upper right picture, Fig. 3). These houses may easily last over two decades, with the esterilla of the walls and the cover material of the roof replaced every 4-5 years.

The house typology is different in the rural houses of the Antiguo Caldas, Colombia. Because of the cool mountain climate, the *esterilla* of the walls is placed in double layers at both sides of the internal timber or bamboo poles, and daubed; originally, the daub was '*cagajón*', a mixture of mud and horse dung but later on, when it became commercially available, Portland cement replaced *cagajón*. The roof structure is usually made out of bamboo and it is covered with clay tiles, resulting in houses with a different appearance (Fig. 11). This construction technique is known as *bahareque*[11], and has been extensively used in many countries of Latin America since colonial times. Traditionally, it uses timber for the poles, braces and beams of the structural frames and two entirely different procedures for the walls. The first, known as '*bahareque macizo*' (solid *bahareque*), uses spaced horizontal canes or bamboo laths to hold mud, sometimes combined with broken tiles, that fills the interior. The second, known as '*bahareque hueco*' (hollow *bahareque*), places nothing in the interior of the walls and uses a double layer of horizontal bamboo *esterilla* or small diameter horizontal canes as a supporting surface for the daub, which is applied on both faces. Obviously, hollow *bahareque* is much lighter and drier than the solid, and consequently, it generates lower inertia forces and is better protected against decay; furthermore, if plastered with cement mortar, the walls turn into effective structural shear walls. In this section the word *bahareque* refers to the hollow *bahareque*.

Urban-vernacular

According to Robledo [61], the use of Guadua to substitute the ever more scarce timber in the poles and diagonal bracing of the frame was initiated in the city of Manizales, but eventually found its way to the rural houses and *haciendas* of the region. For this reason there is a similarity between the rural and the older urban-vernacular houses (Fig. 12a); many of them are more than a century old and in excellent conditions, giving a clear indication of the capacity of the bamboo *bahareque* to resist weathering as well as the moderate and strong earthquakes that frequently shake the region. In early 20th century, frequent and devastating fires destroyed large portions of these cities. When rebuilt, bamboo *bahareque* adopted the prevailing architectonic trends of the times. In consequence, many buildings in the downtown areas are bamboo *bahareque* buildings but plastered with cement mortar, with facades confusing for all but the very knowledgeable (Fig. 12b); the trend extended to the new urban developments built at the time.


(a) **(b)**

Figure 12. Urban-traditional housing in Antiguo Caldas.

From the structural point of view, these buildings satisfy the basic principles of earthquake resistance: i) They are regular in height and plan, with exterior mortar walls continuous from the base to the top. ii) They are very light because of their hollow *bahareque* walls and timber floors. iii) They have a timber-and-bamboo structural frame, which is built to provide the necessary structural integrity to resist the vertical gravitational forces and horizontal seismic forces. iv) They have effective architectural features for protection against weather decay, like generous roof eaves for rain protection and brick or stone foundations to protect the timber and bamboo from the ground moisture.

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[11] The Spanish word '*bahareque*' or '*bajareque*' comes from '*Taíno*', the vernacular language of the pre-Columbian Caribbean people.

Engineered

In the last decades, as a result of the work of early pioneers like Oscar Hidalgo [36], a growing number of architects and engineers working in the region assumed the challenge of using bamboo as a construction material for low-income housing, a promising trend that could eventually incorporate Guadua as an engineering construction material, overcoming its negative social connotations. Some architects are even using the material for luxury houses, built for the very rich, in a deliberate attempt to accelerate its social acceptance. In particular, Simón Vélez [79] has achieved worldwide reputation for his imaginative projects where bamboo and other vegetable fibers are blended with modern materials like reinforced concrete or steel. Vélez is more a structural artist than an architect, always pushing the material to its structural limits, like in his daring ZERI pavilion at Expo 2000 in Hanover [77].

Bahareque behavior in The Quindío earthquake

On 25 January 1999, a M_L 6.2 earthquake struck the Department of El Quindío in the bamboo region of 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, and in several near by towns, killing more than 1000 people and leaving more than 40000 homeless. Many buildings collapsed or suffered severe damage; some of them were *bahareque* constructions, either very old ones daubed with *cagajón* or newer ones plastered with cement mortar. However, the most serious collapses were some multistory reinforced concrete and masonry buildings built before 1984, when the Code was issued. In fact, bamboo *bahareque* endured the test quite well as did all the bamboo engineered buildings (EERI [20]); many of these buildings, including several historic ones more than a hundred years old, were undamaged or suffered only minor damage. For those that collapsed or suffered serious damage, there were precise reasons: i) Highly deteriorated timber or bamboo structural elements owing to neglected maintenance against rain, ground moisture and other weathering agents. In some cases only the heavy tile roof structure collapsed. ii) Collapse of heavy masonry walls and veneer improperly fastened to the structure that had replaced the original *bahareque* facades as a cultural expression of improved socio-economic status. In many cases the collapse of these walls damaged the rest of the house or adjacent buildings. iii) Tipping of the structure, owing to failure of improperly braced concrete or masonry piles and other types of foundations. For those damaged buildings, their repair and structural upgrade, using the same proven techniques but substituting the *cagajón* by cement mortar, will be much easier, cheaper and rational than their complete demolition to replace them by more expensive construction types.

ENGINEERED BAMBOO BAHAREQUE IN COSTA RICA

The potential of bamboo *bahareque* as a building form that is firm, functional, economic and aesthetic, the four components of *intention*, even in earthquake prone regions, makes this technology suitable for transference to other places with similar environmental and socio-economic conditions, where it could be adapted and become an alternative for low income housing. In a not so distant past, Costa Rica had extensive areas of tropical forests full of precious woods and developed a tradition in timber construction, including hollow *bahareque*. However, the country destroyed its resources with such intensity and recklessness that one per cent of the total territory was being deforested every year. Today, almost all the remaining forests are under some type of protection and timber is expensive, scarce and of low quality; consequently, inexistent but fast growing bamboo could be an interesting alternative for timber *bahareque* in vernacular housing.

To transfer the Colombian experience, the '*Costa Rican National Bamboo Project*' was initiated in 1988 with funds from The Netherlands and administrative support from the United Nations [15]. At the beginning 200 ha (hectares; 1 ha = 2.47 acres) of Guadua were strategically planted in different sites of the country to eventually supply the required building material to the construction sites keeping low transportation costs; later on, the total cultivated area was incremented to 350 ha. In the meantime, as mature bamboo was not available, a timber-framed type of *bahareque* house was developed, with large (2.7 m x 2.4 m) but light prefabricated panels, consisting of small section (2.5cm x 5cm or 5cm x 5cm) timber frames with a single layer of canes, that were easily transported, manipulated, assembled on top of a continuous foundation and plastered afterwards with 5 cm of cement mortar, resulting in a very light but strong house type (Fig. 13a,b). The social acceptance was very good and in a ten year period, more than three thousand houses were built with this technology (Fig. 13c).

(a) Prefabricated panels **(b) Plastered with cement mortar** **(c) A *bahareque* community**

Figure 13. Prefabricated light *bahareque* housing in Costa Rica

To provide technical support to the project, a research and development program was carried out with collaboration from the University of Costa Rica and assistance from Technical University of Eindhoven and Hamburg University. Effective techniques for the preservation of bamboo against the attack of xylophagous insects, essential to prevent its early decay, were developed (González [28], Liese [48]). Additionally, valuable data on the mechanical properties of Guadua culms was obtained (Sotela [66, 67]), and large scale mechanical tests (Fig. 14) to determine the strength and modes of failure of the *bahareque* panel walls under monotonic loading were performed (Gutiérrez [30]). Even if the tested results clearly indicated that the houses were seismically adequate, the categorical proof came during the M_L 7.5, April 22, 1991, Limon, Costa Rica earthquake. A group of 30 *bahareque* houses had been built at the site of the epicenter, where a MMI of IX was reported; all of them resisted the strong shaking without the slightest damage (Gutiérrez [30], Handley [32]), even in sites with widespread liquefaction (Fig. 15).

Figure 14. Monotonic load test to structural *bahareque*.

Figure 15. Undamaged *bahareque* house after the M_L 7.5, 1991, Costa Rica earthquake.

The excellent earthquake performance of all the houses indicated that their demand had been well below their strength and deformation capacities. Hence, it was important to determine the strength and the mode of failure of the *bahareque* walls under cyclic horizontal loading. A series of tests were carried out at the Materials and Structural Models National Laboratory (LANAMME) of the University of Costa Rica (Fig. 16). The results reaffirmed the excellent behavior observed both in the monotonic load tests and in the real earthquake as the walls developed considerable strength and kept their structural integrity under large deformations (Gonzalez [29]).

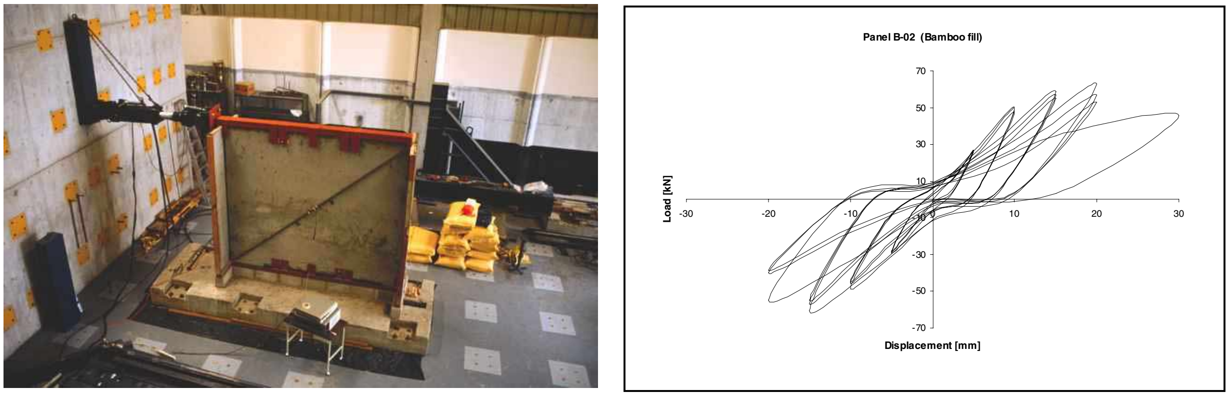

Figure 16. Cyclic load test to structural *bahareque*, LANAMME.

The *bahareque* housing types made out of prefabricated panels, with a timber frame and bamboo laths, had proven to be *firm* in an earthquake prone region as well as *functional*, *economic* and *aesthetic*. In consequence, they were in high demand and several thousands were built all over the country. However, it was clear that timber frames were a temporary solution that should be substituted by bamboo, once the material became available. Prefabricated panels with bamboo poles instead of timber were not feasible as the variable diameters of the bamboo poles are not suitable for standardization and modulation; additionally, transportation is less effective and handling more difficult. Therefore, a radically different solution was necessary for a type of prefabricated housing with bamboo poles replacing all the timber in the frame and the roof, but allowing for standardization and modulation in spite of their inherent variations in diameter.

The resulting design effectively eliminated the panels and substituted them by individual bamboo posts placed on top of similar diameter prefabricated concrete cylinders that served as the foundation and raised the bamboo from the ground for the required humidity protection. The cylinders were then integrated at the ground level by a continuous 6mm steel bar embedded in U shaped concrete masonry blocks and the bamboo poles were connected at the top by horizontal bamboo beams, providing the required structural integrity. After building the roof that provides further stability to the system, prefabricated bamboo *curtains*, made out of laths and flexible wire, were hanged down from the beams to the concrete base and joined to the poles; finally, the walls were plastered with cement mortar. A prototype has been built to test this technical feasibility and promising solution (Fig. 17).

(a) Bamboo structure. **(b) Bamboo *curtains*** **(c) Finished house**

Figure 17. Bamboo *bahareque* house with prefabricated poles and *curtains*.

FINAL REMARKS

Vernacular constructions are well-fitted solutions, able to solve the usual requirements posed by environment and society. However, when exposed to events of low probability of occurrence and high consequences such as strong earthquakes, many of them exhibit inadequate responses, usually with fatal consequences for their dwellers. Only the effective methods of science and engineering may prove able to deal with the complex nature of these catastrophes; nevertheless, to have any chance of success, the problem must be tackled within a holistic perspective, addressing not only the technical problems but the cultural vision of the dwellers, in particular their attitude towards earthquakes. It is along these criteria that the technology of vernacular bamboo *bahareque* developed in South America, and the way in which it was adopted and adapted to Costa Rica, represents an interesting study case.

However, it is important to note that the shift of bamboo from vernacular building material to engineered structural material is not restricted to a single case. Bamboo is attracting the attention of researchers interested in the mechanical properties of its many species (Janssen [41, 42]) or in their design (Arce [4], Janssen [43]) and constructive possibilities (González [27]).

To further enhance the possibilities of bamboo, in November 1997, the governments of 9 countries agreed to turn a successful research and development bamboo program into the International Network for Bamboo and Rattan (INBAR) which as today has expanded to 28 countries representing four continents. Among its many activities, the organization sponsors programs in scientific research and technology generation, including the important process of approval of the ISO Standards [38,39,40] necessary for the eventual transformation of this vernacular material into structural bamboo.

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