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Reciprocal frame structures, a first academic approach to sustainable structures

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Abstract

Herein we introduce an academic approach to teach students spatial structure from a sustainable perspective to give them tools to generate appropriate technology in the building environment. The students explore sustainable and structural properties of construction materials and systems. The base approach for sustainability rely on the biomimetic principles. They use reciprocal frame structures, without any tool and with local materials, to build structural systems for canopies and bridges. These structures give significance to a high performance structural system made of tree branches or other local materials that are built for temporal or permanent use, in small or big scales, with minimum impact to its surroundings. They give special emphasis to generating a reciprocal frame culture in which there is the need to change pragmatical approaches to develop a structure from geometric and material perspective. First, the students break their own schemes when they realized that they do not have control of the final product and cannot reproduce a "simple" concept as fast as they wanted. When they succeed to generate one task, the instructor encourage them to propose another form and teach others, not architects or civil engineer students, to follow their instructions. Finally, they must realize the need to explore different communication ways to transmit the concept of reciprocal frame to a non-builder person.

Keywords: Reciprocal frame, nexorades, timber, sustainable approach

1. Introduction

The reciprocal frames are three-dimensional structures which can work like a design tool in the field of sustainability because incites you to use elements of the environment as wood. Wood has the potential of sustainable material, in contrast to the use of other materials mostly industrialized; also due to the prismatic nature of the frames, friendly figures are consolidated and have simple production processes, so, the system has an easy installation and manufacture. Finally, in social aspects, this kind of structure can be a solution of lack of money, or labor specialized in the design of canopies and shelter in situations of emergency or disaster.

2. Justification

The possibility of learning the beginning of design of the structural systems with the help of computer hardware and by means of analogical approaches it is real. In this research, it is considered that in a critical or in an emergency the computer hardware won't be able to help us, therefore a constructive skill of low demand of resources can be valuable in emergency situations. That's why through the education to students of different academic levels, an experimentation process had taken place to strengthen relations of comprehension of this structural concept in a simple and practical way that can be teach to people in all the academic levels of education.

In this work, a sustainable approach happens to the employment of a local material, with principles that we have found in the nature. Because according to design criteria based on three branches of sustainability: social, environmental and economic aspect; we can use alternative materials of low impact or low energy in its production, which also can be dismantled involving a reduction in expenses and re-used of material for future applications.

The importance of the use of the reciprocal frames takes root in that there are simple, functional structures and structurally safety, which are based on the principle of the relationship human - environment for the solution of habitability that corresponds to a roof structure for four vertical elements (walls), that can be use in a quickly way to any emergency situation.

2.1. State of the art

The research is sustained of certain elements taken place from the following classification:

1. Lattice structures: discreet elements.
2. Continuous spatial structures: membranes, shells.
3. Biform structures: combination of the previous structures.

Referring to the spatial structures because reciprocal frames are in that classification, we can enunciate as "a structural system that involves three dimensions" (Baverel O. 2000 [1]) . The principle of using these structures is old, because they have been used throughout history, so it is difficult to ascertain exactly what was its exact origin or first use. They are referenced structures from the early cultures. In the Neolithic period and medieval manuscripts of writers and works and precursor investigations by Leonardo da Vinci as drawings of geometric forms in wood for the design of bridges; such work even though they are not reciprocal frames. Its design applies arched beams, which are important in the context of spatial structures and take the same principle of binding elements.

In addition, there is information about Chinese and Japanese culture that dates from the XIIth century, related to the construction with wood and bamboo and its application in the design of roofs better known as mandala roofs. Popovic stated, “Which are based on geometric figures that include circles and frames, positioned in a certain way to give a symbolic meaning” (Popovic O. 2008 [6]). Nowadays, these ceilings are still used primarily with more complex and sophisticated frames and with local materials.

A model of this structure, is applied in residential Japanese architecture known as Sukiya; which is an architectonic style developed in the XVth century, that today use reciprocal frames with contemporary designs. Thus, this kind of architecture keeps on being recognized by the use and improvement of wood in construction, especially in details of connections between elements as posts and beams; because of the importance in safety against earthquakes due to their geographical location.

As an example, we can certainly enunciate some work of the architect Kazuhiro Ishii, who designed the Spinning house in 1985, reciprocal frame structure in Japan, made of steel. This residence uses reciprocal frames in its structure "inspired by the method of holding hands where there is no support for loading at points of crossing arms and hands, inspired by Islamic drawings as well as the rotation of the cosmos" (Popovic O [7]). These models are an interesting pattern in the field of design, as well as having structural purposes, respond to the use of local materials and are visually harmonious and aesthetically pleasing.

However, for all that we have mentioned it is important to know: What is a reciprocal frame? According to the meaning, a reciprocal frame is a grid structure used primarily as roofing structure, which are formed by mutually supported beams (Popovic O. S.f [8]). The end of each element is supported on the next one and so on until close the circuit, thus the structure can be supported by load-bearing walls, columns or rings. It is important to explain that Graham Brown patented the exact name of reciprocal frame in 1989, who developed this kind of structure in the UK, called reciprocal by the way that the beams are mutually supportive.

According to the geometry, the morphological structure principle of reciprocal frames is defined as a three-dimensional system of inclined beams and arranged around a central symmetrical point, that's how with the end of the beams, a polygon or circle is formed in the inside. "The concept of this structure is that each element acts as a unit that works to distribute loads uniformly" (Chilton J. and I. Cartes , Sf [5]). So, one of the principles of this structural system must contain at least three beams or logs because the triangle is the first minimum manifestation of this technique.

Popovic (2008 [6]) said that the parameters defining a reciprocal regular polygons frame with circular geometry are:

Number of beams (n), Radios through the outer supports (ro) and through the points of intersection of the beams (ri), Vertical increased external supports to the points of intersection of the beams (H), vertical spacing of the center lines at the points of their intersection (h2), Length of the beams on the slope (L).

The parameters that define the geometry of the frames can provide different variations, such as the size of the notch, which depends on the width of the beams and angle, etc. Thus, the geometric characteristics of reciprocal frames offer a number of possibilities for decks whether in regular or irregular floors.

A key feature of these frames is that they are capable of reforming crosses with different geometries, which can be dismantled and reformed, taking different points of support that are not necessarily coplanar. In addition, in practice and application of these structures, they can be quickly built with local materials, so that in an emergency and in certain disaster situations are an optimal response to the necessary solution.

In the reciprocal frame the terminal point of a bar corresponds to the terminal point of another bar; so due to the geometrical characteristics of the structure, most suitable form for use in buildings using reciprocal frames are circular, elliptical and regular polygons, being circular first and vernacular buildings used in the plane. "These structures allow the realization of any shape, so the final configurations obtained are surprisingly stable [...] as they are able to withstand considerable loads." (Biagio C. 2008 [4]). An example of this structure can be a fan, as this is a structure of four identical nexores creating a polygon to the center of the element.

An innovative way the spatial structure is nexorado, which is composed of woven elements, basic principle of the reciprocal frame. "A nexorado is an arrangement of mutually supported nexores" (Baverel O. 2000 [1]). The nexorados or "grill" are a family of spatial structures that are generally constructed of wood or scaffolding tubes; each element constituting what is known as "Nexor". According Baverel (2000 [1]), each Nexor has four points, two of which are the ends of the element, the two are intermediate points along the Nexor.

To generate the geometry of nexorado, it is first part of a simple version of the structure, this plan; then a genetic approach is used to transform the desired model, this process is known as "fan" and Formian programming language has a feature that allows the process. "An efficient way to generate the geometry of a nexorado, you begin by having reference to the simple basic model configuration, then through a genetic approach the initial configuration becomes the required nexorado". (Baverel O., Nooshin H, S. F. [2]). This as in all design processes, states that from the initial idea, is continuously working and changing, until you respond and comply with the required characteristics and the expected optimal design.

According to some research genetic algorithms (GA Genetic algorithm) are also applied as a method of generating structured nexoradas. This concept of genetic algorithm according to Pró L. et al (2004 [10]), refers to the studies found in the area of artificial intelligence and evolutionary computing, are so called "because it is inspired by biological evolution and genetic-based molecular". They are systematic methods for solving optimization problems that search and apply the same methods of biological evolution: population-based selection, reproduction and mutation and parameterizing the optimization

problem in a number of variables. Genetic algorithms are studies that let you work with a large number of parameters, do not require derivative information and if necessary, can be optimized existing parameters with extremely complex requirements.

Moreover, another concept within the spatial structures is "Elements mutually Supported" (EMS), which could be considered reciprocal frames and having the same principle assembly and both are structural solutions focused on the geometric configuration.

According to this configuration, an important feature for the slope of the reciprocal frames and geometry of the EMS is that the location of the central axes, these elements generally do not match. As the eccentricity, in the connection between two nexorados circular section, the distance between the centroids of the sections is known as nexores thus the axes have to be accommodated and incorporated into the connection system.

According to the references cited in the teaching of architecture have adopted reciprocal or nexorados frameworks; these workshops specifically for design, exploration and construction of such elements. An example was developed for a workshop (workshop) developed by Udo Thönnissen in 2015, where he sought to orient projects towards the field of construction, in which the approach "learning by doing" is, it is offered a strategy based on processes arises design and construction for solving problems by using reciprocal frames.

This workshop was conducted by the department of architecture at the University of Thessaly in Greece, where in addition to the two experts reciprocal frames (Thönnissen and Vrontissi [14]) , the participation of 14 students from different grade was included. "The research unit was to discuss the potential of design through a specific perspective, exploring morphological results generated by a design methodology; the emphasis is given on the subject of expansion patterns of elementary reciprocal frameworks in relation to the proposed limitations on research "(Thönnissen U., 2015 [14]).

At the workshop, the concepts are understood first, then documented and analyzed similar cases for small-scale structures, mainly in outdoor use. linear, flat or space, to make way for the process of designing prototypes made of wood and connected by willing wires over notches or cuts the material: After the principle of "reciprocity" focusing on one of the three patterns of structural expansion was explored.

Also according to studies by Tongzhou Chen and Dr. Rodolfo Lorenzo of the University of London [13], the feasibility of using bamboo cane for armed arises because of its extensive structural characteristics as well as strength and potential notched building frameworks, based on 3D design and experimental testing.

It may be noted that "The position of the notches or cuts cause different types of failures in the bamboo [...], cut below the connection of the bamboo secured with bolts, has a better design for building reciprocal structures frames. The carbon fiber wraps as basecoats influence behavior against crack development. "(2010 [9]). As the use of carbon fiber increases resistance; In addition, the irregular features of bamboo can present challenges in the design process of the structure; so were opening points for research and application of the material in the system.

Similarly, at the Swiss Federal Institute of Technology, for the class of "Architecture and Construction" a number of small buildings applying reciprocal systems frameworks were developed. The first phase of the project focused on the examination of the construction methods with short wooden elements for long distances efficiently. "It focuses on the principle of reciprocal frames because it allows reduction in a constructive way to a small number of parameters; also because it has great potential in combination with new technologies "(Thönnissen and Werenfels U. N., 2011 [12]). The project attempts to apply the use of simple wooden elements more attractive buildings with structural forms of low cost. It aims to introduce students into the building through large-scale works so that they can understand the constraints

involved, states that it is "a progression that becomes important specifically in working with computer models and designs".

In somewhat more work that is contemporary, one of the first architects to use these structures was Emilio Perez Piñero, on which his work highlights mobile and folding structures in Spain. Currently, some researchers as John Chilton, Olga Popovic and Wanda Lewis have developed studies on reciprocal frameworks.

After analyzing the information and in accordance with the cited literature, for better understanding of structures implementing workshops or working groups where they can make small-scale building exercises, interpolating a larger scale with certain digital tools is recommended as these tools increase the design and scope of the potential application of reciprocal frames systems.

For example, nexorades have the advantage of requiring low technology to be built. Generally are designed for a single material and a single type of connector, so a cost reduction implied by not using more elements in the design mean some sort of special connection between different materials, their structure is sometimes used temporarily, so in practice some students have an interesting exercise in easy construction. Also in the field of study of automated design processes genetic algorithms to develop nexorados used is counted with the opening of improving studies and develop better structures exercises with nexorados. It is noted that in the process of generating the "fan" instead of having a given value for the radius of each Nexor can provide a variety of values for each. Similarly, as these are used to nexorados temporary applications or they could even be designed as emergency structures; it is necessary to study from the behavior of its structure to profitability and life critical situations.

2.2 HYPOTHESIS

The application of reciprocal frames is a structural system that can function as a refuge by covering a clear fact of items available on the site with optimal functionality with preset geometry. This research hopes to give a formal reciprocal use of frames, which can meet minimum requirements as shelter approach.

2.3 OBJECTIVES

- To introduce students to the knowledge of the structure of reciprocal frames.
- Relate the student with the material, with the system and with external possibilities.
- Encourage the use of natural elements that the context offers.
- Strengthen understanding processes of certain structural elements.
- Encourage students to expand their creativity in designing structures.
- Designing freeform reciprocal frameworks that meet minimum criteria for structural safety.
- Perform exercises experimentation and construction of medium-scale elements through workshops that encourage teamwork.
- Develop guidelines, manuals or other ways to share information and lessons learned.
- Transfer the final knowledge to others so that they can adopt the system.

3. METHODOLOGY

For the methodological approach in the implementation of reciprocal frames it held a mixed method, ie qualitative and quantitative, which sought the student generate a structural system with elements available in the environment, in this case wood design frames reciprocal which may have a basic functionality ie serve as cover for an element of four walls.

The scope of the research is correlational in nature, because first it is intended that the student relates to the material on the site, then with the system and then with the external user to share the knowledge acquired during the design process to construction and possibilities of use of the element.

According to the planning proposal, the research design was experimental, where two different academic sessions for both undergraduate and master's level to level were held between 8 to 12 participating students. Knowledge procedures to construction element are described as follows:

3.1. Theoretical Concept

As first, it was necessary to understand the concept of reciprocal framework and its origin and early uses. First we start from the classification of the structures to give a preamble and specify which field that classification as civil engineering, frames are reciprocal; then he gave an introduction to their applications throughout history, first approaches and recognition of work and research that led to this type of structure.

It is important to note that the approach to new knowledge, the theoretical part is fundamental to the understanding of the issue, because without these criteria or the lack of them the proper construction and application of the element is delayed when testing "blind ". Once landed the part, it proceeds to the first approaches to the physical element.

3.1.2. Basic Combinations

We proceeded to the basic and initial development in the design of the structure, made with sticks of pinewood rectangular top 120 cm. Long with a section of 3.5 2.0 cm. According to Chilton and J. Cartes, I., [5] as a principle of the structural system, you must have at least three elements such as beams or in this case sticks, as "the triangle is the first slightest manifestation of this technique". Thus, proceeds to build the concept theoretically acquired after performing cores for three elements, one element was added, with straps or moorings joints.

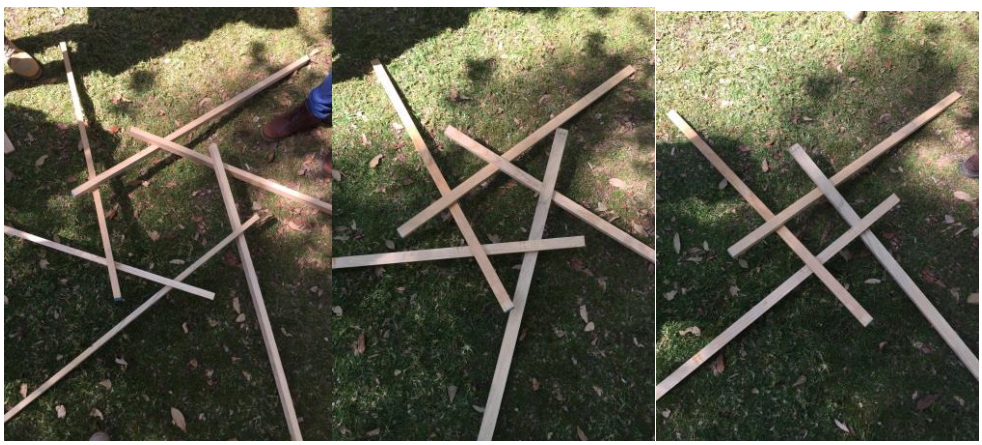

Figure 1 Development of reciprocal frameworks in their basic concepts. Source: Own

3.1.3. Composite Combinations

In the second phase of design and construction, composite structures were made, uniting more than 4 wooden sticks, from three to six items with selection of free unions.

Figure 2 Reciprocal frames, composed combination. Source: Own

3.1.4. Free Combinations

For this phase, students were encouraged to design their model freely, based on the concepts studied and exercises previously performed. This exercise allows through student creativity, expanding possible solutions to the problem of original and innovative way, as each participant expresses his ideas and lands on a tangible element.

Figure 3 Structures of reciprocal frames. Source: Own

3.1.5. Transfer of Knowledge

This transfer is necessary to create ways to explain to others, how to build mutual frameworks, so that in this way the possibility that the system can be used to give shelter need.

For this section, students gave as possible transfers:

- Verbally. That is, explaining the origin of the concept and how to work it, exposing the subject.
- Through a manual. Explaining step by step how to make reciprocal frames with instructions for anyone who is not familiar with the subject can understand and build.
- Through employers or unions with colored ribbons as a "puzzle" with certain instructions that indicate the proper disposition of the tapes.

It is important knowledge transfer and arises that in an emergency or to some need, reciprocal frames can be a solution to the lack of a space that serves as a refuge. Thus, having the knowledge, you can connect the user with the material, with the system and the design possibilities to fulfill certain functions.

Since 2008, Olga Popovic [8] specialist in the field of mutual frameworks, has conducted courses in spatial structures in architecture school in Copenhagen with weeklong workshops where the student is

introduced first time the issue of reciprocal frames theoretically (theoretical conception mentioned), features and possibilities that these structures offer then begin exploring such possibilities physically exposed.

Under the proposed schedule, you have a day to the exploration of literature and knowledge of morphology through modeling a small scale. Then passed directly to develop some models studied to implement a large scale. As in the proposed methodological approach, rectangular wooden elements for building structures are used.

According to researcher students find attractive and innovative design of structures through workshops that allow be in direct contact with the model, then this model knowledge through virtual modeling tools.

Figure 4 Bridge frame reciprocal structure. Source: Own

Figure 5 Portal structure of reciprocal frames. Source: Own

4. Results

In each class managed to build basic and complex nexorados; however it was not even the ability to transfer knowledge and some students (between 10 and 20%) did not identify the parameters that determine the geometry of the system.

In most cases it was achieved:

- Propose alternative to those recommended by the instructor forms.
- The parameters that define the geometry and the influence of the material in the final form were complicated to see.
- Students visualized what materials can be applied to the system.
- It manages to insert a constructive paradigm in two sessions or less.
- The student displays the possibility of constructive independence in people who may be familiar with the building system.

5. Conclusion: submission of contributions

In the literature can be noticed digital approaches for generating complex concepts based on reciprocal frameworks and applications for residential or conceptual; so it is important to continue these studies and practices that can be worked on different scales and with different components to provide criteria or experiences in the field and immediate response structures.

From this research we can conclude the following:

1. Explore the possibility of generating field relatively complex structural systems with simple elements.
2. Identify the parameters defining the geometry of the nexorados and influence of material system demands.
3. Demonstrate the diversity of forms that can be generated without formal analysis tool.
4. Being a sustainable approach to building systems.

5. Moving from the theoretical aspects to practical in a short time.
6. Adopt alternative systems as a constructive philosophy of independence.

Thus, this research could continue the following work proposals:

- To train students for teaching about a constructive system of reciprocal frames in particular.
- Use the principles of biomimicry for generating a constructive system.
- Linking directly with biomimetic principles.
- Change a constructive paradigm in a community by students.

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