REVISTA DESIGN & TECNOLOGIA
ISSN: 2178-1974
2021, Vol. 11, No. 23
DOI 10.23972/det2021iss23pp01-12

PGDESIGN
www.pgdesign.ufrgs.br

Structural system based on tensioned wood panels: experimental and numerical validation

Scarlet B. Montilla[1,2]; Mauricio Vargas-Mosqueda [3]; Maylett Uzcátegui [4]; Ricardo Picón [5].

1 *Assistant Professor Federal University of Latin American Integration, Latin American Institute of Technology, Infrastructure and Territory ILATIT. Foz do Iguaçu, Paraná, Brazil..*

2 *PhD student Chongqing University, school of Civil Engineering, Chongqing China.*

3 *Department of Construction Sciences, University of Bio Bio, Av. Collao 1202, Concepción, Chile.*

4 *University of the Andes, School of Architecture and Design, Center for Housing Research and Habitat, Venezuela.*

5 *Catholic University of Temuco. Department of Civil Engineering and Geology, Chile.*

ABSTRACT

Housing in modern societies is a priority need. In underdeveloped countries there are very marked contrasts with respect to the housing deficit, affecting families with fewer economic resources, which solve their problem through inhuman constructions, made with construction waste and dismantling of old buildings.

The need to create new building systems based on wood for homes arises when considering the few existing alternatives in developing countries that guarantee an economic, massive and fundamentally sustainable construction. In this sense, this research aims to make a contribution to the implementation of new structural elements for the sustainable construction of wooden houses, which can be manufactured by low technology processes, allowing easy use and appropriation by the general population. The system is called Tenso-Wood, which is conceived as a system of solid wood plates of Caribbean pine, developed by means of low technology processes that allow an easy appropriation by the population in general. This paper presents a frame structural system using tensioned wood panels as structural elements. It is a lightweight prefabrication system for the construction of two-storey wooden houses. The system consists of bolted wood elements, creating different structural panels such as beam and column. An experimental program was carried out, which allowed knowing the mechanical behavior of each panel of the frame structure. In addition, it permits to know their maximum stress and deformations. The numerical models were compared with the experimental tests to validate and calibrate some parameters in the simulations. Therefore, the numerical models can be able to compute the load capacity and deformation of the wooden elements, obtaining behavior curves.

KEYWORDS

Timber building systems;
Timber housing;
Laboratory tests;
Computer models

Sistema estrutural baseado em paineis de madeira tencionados: validação experimental e numérica

SUMARY

A habitação nas sociedades modernas é uma necessidade prioritária. Nos países subdesenvolvidos onde existem contrastes muito marcantes respeitos ao défice habitacional, atingindo famílias com menos recursos económicos, que resolvem o seu problema através de construções desumanas, feitas com resíduos de construção e desmantelamento de edifícios antigos.

A necessidade de criar novos sistemas de construção à base de madeira para residências surge quando consideramos as poucas alternativas existentes nos países em desenvolvimento que garantem uma construção econômica, maciça e fundamentalmente sustentável. Nesse sentido, esta pesquisa tem como objetivo contribuir para a implementação de novos elementos estruturais para a construção sustentável de casas de madeira, que podem ser fabricadas por processos de baixa tecnologia, permitindo fácil uso e apropriação pela população em geral. O sistema é denominado Tenso-Madeira que é concebido como um sistema de chapas de madeira maciça de pinus do Caribe, desenvolvido por meio de processos de baixa tecnologia que permitem uma fácil apropriação pela população em geral. Este artigo apresenta um sistema estrutural de pórticos usando painéis de madeira tensionados como elementos estruturais. É um sistema de pré-fabricação leve para a construção de casas de madeira de dois andares. O sistema consiste em elementos de madeira parafusados, criando diferentes painéis estruturais, como vigas e colunas. Foi realizado um programa experimental, que permitiu conhecer o comportamento mecânico de cada painel da estrutura do chassi. Além disso, permite conhecer sua tensão e deformações máximas. Os modelos numéricos foram comparados com os testes experimentais para validar e calibrar alguns parâmetros nas simulações. Portanto, os modelos numéricos podem calcular a capacidade de carga e deformação dos elementos de madeira, obtendo curvas de comportamento.

PALAVRAS-CHAVE

Sistemas de construção de madeira;
Casas de madeira;
Testes de laboratório;
Modelos de computador.

CONTATO: Scarlet B. Montilla – *Scarlet.kmb03@gmail.com*

© 2021 – Revista Design & Tecnologia

1. INTRODUCTION

Wood is used in the construction of buildings under a wide variety of formats that include products of greater or lesser degree of transformation, which coexist and are in force at present. In recent years, the industry of wood-based products with structural use is clearly aimed at the design of prefabricated components with high mechanical properties and typified, thus achieving to overcome the limitations of natural wood (anisotropy, dimensional variation, hygroscopicity, defects and anomalies). In addition, wood is a material derived from a renewable resource, requires low energy consumption for its transformation, can be recyclable, reusable, has great capacity to adapt to functional requirements in the building (structural, enclosures and furniture). These characteristics in general give it competitive advantages that make it a paradigmatic material in the global construction industry (Grzegorz Pajchrowski et al. 2014).

At present, wood construction has reached a great development worldwide with an important trend towards prefabrication and industrialization (Koppelhuber et al, 2017). Among the different prefabricated timber building systems for housing are the so-called mass timber systems, made up of large elements manufactured by joining sawn timber together by different means, whether they are adhesives, nails or dowels (Harte, 2017).

This paper proposes a new sustainable timber building system of, potentially, massive production for affordable housing in Latin America countries named Tenso-Wood System. The system can be manufactured with wood of fast growth and low cost.

Tenso-Wood System constitutes a structural system that is based on the principles used in dowels and nails laminated timber, as well as the tensioned wood panels (Ugalde, 2004) used in bridge structures and post posttensioned wooden system (Chen, Venkatesh, Gangarao, Stephens 1990). The deflection of wooden elements is often a weakness and an issue for designers (Augeard E., Michel L., Ferrier, E., 2018).

The objectives of the project consists on achieving a structural system that allows the construction of affordable housing in an economic, massive and sustainable way, achieving an easy and appropriable manufacturing process. Therefore, when proposing a novel system, questions arise about its structural behaviour under service loads and seismic forces, as well as the construction techniques used for the conformation of the components, and in this way comply with an affordable housing design requirement.

In this sense, were necessary to carry out a proof of concept through experimental tests and additionally it is necessary to carry out numerical simulations of the system components, to calibrate parameters and to validate the behaviour of the structures composed by elements of Tenso-Wood System. From the economic aspect, it is necessary to use the resistant capacities of the wood efficiently in order to achieve an optimized and safe design.

According to this, an experimental program was initially carried out, in order to reproduce the real behavior of the proposed structural components through laboratory tests. Initially, each of the components was tested separately (carrier panel and beam panel) under monotonous loads. Then, their interaction as a system is evaluated by testing a frame subject to lateral loads.

2. PROBLEM APPROACH.

Considering the housing deficit in Latin America, the project seeks the validation of a proposed prefabricated timber building system for affordable housing. These system consist of laminated wood panel manufactured based on slats of Caribbean Pine joined through bolts. In this sense, the approach to new proposals must take into account the use of the limited technological resources that most of these countries have in this matter.

For instance Caribbean Pine, this species exist in many countries of Central America, as well as in Mexico and Venezuela. The Caribbean Pine corresponds to the structural wood type "C" according to the classification established by the “Junta del Acuerdo de Cartagena” (JUNAC, 1985). This pine has physical-mechanical properties very similar to other wood species of the same genus used in other regions of the Americas such as Radiata Pine in Chile and Eliotis Pine in Argentina, Uruguay (PADT-REFORT, 1984).

3. METHODOLOGY

The wood tension system is a light prefabrication system based on Caribbean Pine wood that allows the construction of houses under flexible configuration schemes.

Once the configuration has been made, it is preceded to carry out experimental tests, in order to estimate the load capacity and deformation of the column panel, beam panel and the gantry formed by said components.

In order to verify the rest of the system and to validate it numerically, a series of numerical simulations carried out in order to obtain the stress and strain state that the analyzed elements can withstand are presented. The models were elastically analyzed to simulate their behavior under service loads. Likewise, finite element models allow comparing the results obtained in experimental tests.

Finally, a practical application of the system is presented. In the elaboration of the models, not only the main structural elements (columns panel, beam panel) are considered, but also the weight exerted by the slab and non-structural elements such as walls, through the imposed vertical loads and the additional mass in the elements.

4. CHARACTERISTICS FOR CONSTRUCTIVE WORK WITH CARIBBEAN PINE.

Wood is produced and used for structural purposes, it is a very resistant material, thanks to this characteristic and its natural abundance it is widely used by man, from very remote times.
From the point of view of its physical and mechanical properties, its response depends on the direction of the effort applied in relation to the orientation of the fibres that constitute it (Arriaga, 2003). It is an inhomogeneous, anisotropic and orthotropic material.

The woods can be divided into two large groups (separated according to how the seeds are born). Gymnosperms (bare seeds) that include all trees that produce softwood, and angiosperms (covered seeds) that include all hardwood trees (Hoadley, R. 2000).

Hardwoods are those that come from slow-growing trees, so they are denser and better withstand the inclement weather. These woods come from deciduous trees, which take decades, and even centuries, to reach sufficient maturity to be cut and to be used in the elaboration of furniture or structural elements for the construction of structures such as homes, buildings, bridges

The Soft Woods are wood of the trees belonging to the order of conifers. This type of wood does not have a life as long as the hard ones, but it can be used for specific jobs. For example, red cedar wood has natural repellents against insect and fungus pests, so it is widely used outdoors. The handling of softwoods is much simpler, although it has the disadvantage of producing more chips.

4.1 Caribbean Pine.

Pine wood is a soft wood that has resistance characteristics suitable for construction and, due to its characteristics, enables any transformation and application, likewise is suitable for autoclaving preservation method. Among the multiple species of pine, some adapt better than others, those that are better processed and that are usually and abundantly found in Venezuela are: Wild Pine, Oregon pine, Laricio pine, Pinaster pine and Caribbean pine (Under study for the present work). However, Caribbean pine is the only species cultivated in large areas of sustainable forests in Venezuela.

There are many properties known as its color, brightness, smell, taste. The basic properties to be used in the characterization of the elements to define the Tenso-Wood system will be defined. The specifications of the characteristics defined below are taken from American National Standard (2005):

- Machining, gluing, nailing and screwing, without problems.
- Finish: Difficulties with resin bags. Impregnable wood, heartwood not impregnable.
- Applications: Veneers for decorative coatings and plywood boards. Interior and exterior carpentry. Joinery and shipbuilding: deck, mast. Hydraulic works, posts, sleepers, structures in general.
- Drying: It dries easily and slowly outdoors and artificially, presenting slight deformations. For carpentry it must be dried in the oven up to 8-12%.
- Natural Durability: Moderate if not dried properly. To increase its durability in outdoor use must be immunized.
- Preservation: The wood is very easy to treat by vacuum or immersion vacuum systems, presenting great retention of immunizer
- Workability: It is easy to work with hand tools and in the different machining operations. It gives excellent finishes and is easily glued.

4.2 Classification for Caribbean Pine

A classification for Caribbean Pine wood is presented according to its use:

Dry Dimensioned Wood (MDS): Corresponds to rustic sawed wood of artificially dried Caribbean Pine, for use in roof structures, wraps, partitions and various construction applications.

Green Dimensioned Wood (MDV): Corresponds to unprocessed rustic pinewood from Caribbean Pine, with anti-stain bath application, for various uses where an economical and homogeneous material is required.

Dry Brushed Wood (MCS): Corresponds to dry brushed wood of Pino Caribe (S1S, S2S and S4S) for uses in partition walls, wraps, structures and various applications in construction, where accuracy of dimensions is required, used in sight applications in constructions, decoration and furniture.

Physical-mechanical characteristics of the Caribbean Pine.
Mechanical properties. The Caribbean Pine is located in the structural group "C", which meets the wood with basic density between 0.43 and 0.55 g/cm^3, following the classification criteria of the structural groups proposed by the JUNAC (1985).
Mechanical properties:
Modulus of rupture = 800.179 kf/cm^2

Statistical flexion (beams)
Modulus of rupture = 132.283 kf /cm^2
Modulus of elasticity = 7216.03 kf/cm^2

Parallel compression
Elasticity at the limit of proportionality = 142.934 kf/cm^2
Modulus of elasticity = 21124.46 kf/cm^2
Perpendicular compression
Elasticity at the limit of proportionality = 50.567 kf/cm^2
Cut= 108.83 kf
Hardness of sides = 376.906 kf
Extreme hardness = 492.975 kf
Tenacity = 1.266 kf-m

5. TENSO-WOOD SYSTEM

Tenso-Wood System is a prefabricated mass timber building system for minor span structure (housing) of up to two storey of height through easy and quick assembly. Its concept allows the design of multiple spatial configurations from frames made up of bearing panels and beams (Vargas, 2015).

Timber building systems for minor span can be classified into lightweight framework systems and solid wood systems, according to the classification established by Hempel and Poblete (1994). Among the most commonly used solid wood systems, plate systems are made from pieces of solid wood formed by wooden boards or strips, nailed, dowel or glued. From the consecutive arrangement of these elements, walls or load-bearing walls are constructed, being able to form structures of several levels. For this research, given its functional and constructive simplicity, the following are taken as starting points, both the dowel laminated timber developed today for the construction of houses in Europe (Brettstapel, 2012), as well as the stretched wooden panels used in bridge structures (Ugalde, 2004).

Although there are many constructive systems developed worldwide for the construction of wooden houses, the design of new systems is justified insofar as they adapt effectively to local social and technological conditions, as well as to the extent that achieve greater functional and / or aesthetic efficiency. Given the innovation that should characterize them, these new systems should be considered with a non-limiting vision, built from the management and knowledge of the different existing construction typologies. Thus, the design proposed in this research is based on a comprehensive and comprehensive knowledge of the existing typologies for smaller and larger structures in wood according to the provisions of Hempel and Poblete (1994).

In the case of timber, it is possible to make a first differentiation of the construction systems, taking into account the squares and types of structural elements used. This first classification (Queipo, et al, 2010) considers the following different construction systems:

Small squares, systems formed by structural elements of small thickness (36-70mm) placed at reduced distances (less than one meter) and braced together.

Large squares, systems formed by structural elements of great thickness (greater than 80 mm), normally placed with distances greater than one meter between them.

Tensed wooden boards are elements used in bridge construction. They consist of planks tensioned in the transverse direction by means of high-strength steel bars. The board acts like a solid wooden plate, whose structural function is to distribute the loads in a uniform way. Likewise, the union of the boards through steel bolts allows the conformation of an element of great strength and structural stability. The concept of tensioned laminations was originally developed in Canada in 1976. Later in the 80s this technology was also implemented in the USA. (Giuliano, et all, 2011). These boards, even though they do not work supporting loads longitudinally and parallel to the fibre, are taken as references to devise the union between

the slats that constitutes the constructive components of the Tenso-Wood System.

For joining the slats, galvanized threaded or rods of diameter 1/2 " are used as transverse tensioners. These galvanized threaded or rods are widely available. They present high durability over time due to its galvanization. Its fixation arises through the use of nuts and double washer (flat and pressure). With regard to the dimensions of the structural panels of the system, it is taken into account that they can be handled and transported easily by two people, also taking into account a previously established modular coordination for the configuration of spaces in the house. (Vargas, et al, 2015)

A brief description of each structural panel will be presented below. The dimensions and the way to assemble the slats to build the structural panels of beams and columns will be showed.

5.1 Column Panel.

This panel aims to support vertical, lateral and longitudinal loads to the fibres of the wood (Figure 1). The following configurations are proposed (Vargas 2015):

- **Panel 1 (P1):** Consisting of 7 slats (0.10 x 0.05 x 2.40) m. The dimensions for the panel are 2.40m high, 0.35m wide and 0.10 m thick. The assembly of the panel is made through 4 bolts spaced 10 cm from the ends and 73 cm between them.
- **Panel 2 (P2):** Consisting of 5 slats (0.10 x 0.05 x 2.40) m. The dimensions for the panel are 2.40m high, 0.25m wide and 0.10 m thick. The assembly of the panel is made through 4 bolts spaced 10cm from the ends and 73cm between them.

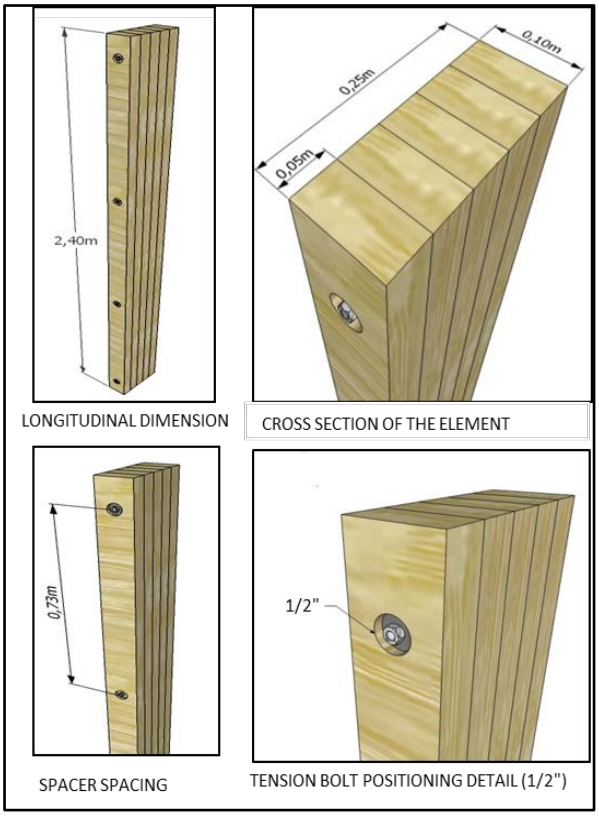


Figure 1 Structural configuration Panel P1.

- **Panel L:** To obtain this configuration, a panel P1 and a panel P2 must be connected using pins. (Figure 2).
- **Panel T:** To obtain this configuration, one panel P1 and two panels P2 must be joined using bolts. (Figure 2).

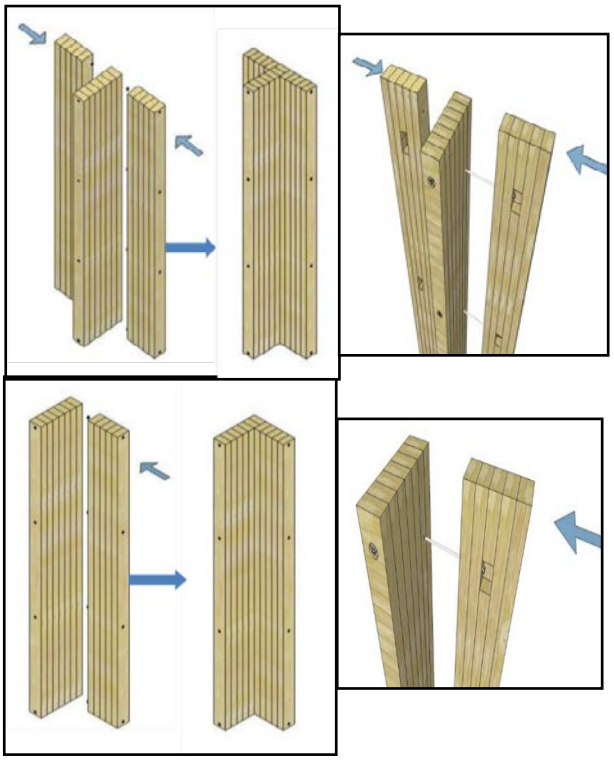


Figure 2 Structural configuration type L and T.

5.2 Beam Panel.

It was built with the aim of supporting loads along the length of the element (Figure 3). The following configuration is proposed in the Table 1.

Panel B1 is made up of 5, 6 and 7 slats of (0.10 x 0.05 x 2.40) m, used as main beam. The dimensions for the panel are 0.10m wide, 0.25, 0.30 and 0.35m high and. 2.40m long. The conformation of the beam through 4 bolts is proposed.

Table 1 Types of beam

Name	Type (cm)	Length (cm)
B1	10x25	2.4
B2	10x30	2.4
B3	10x35	2.4

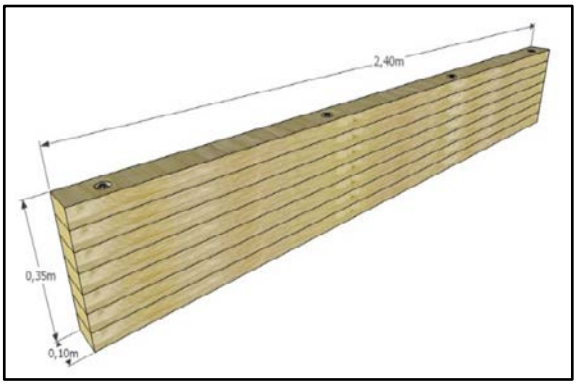


Figure 3 Structural configuration of the beam.

5.3 Frame.

Consisting of two column panels and a beam panel, the resulting frame has a height of 2.40m, an outside width of 4.00m and a free span of 3.30m. The joints between the elements are made with 2 steel plates per side, 4mm thick and with 8 screws of 5mm diameter and 50mm in length (Figure 4).

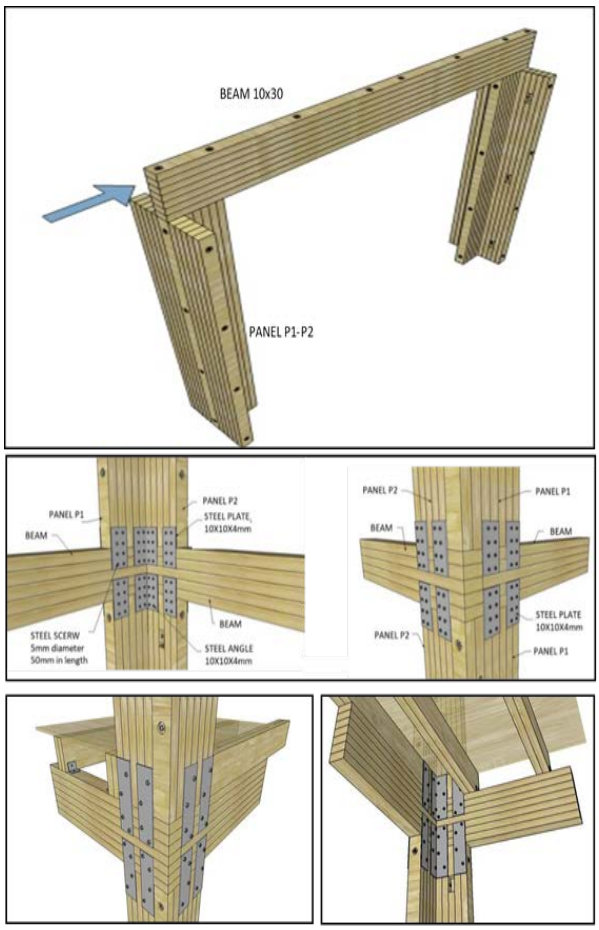


Figure 4 Structural configuration for a frame

6. ASSEMBLY SEQUENCE

The system establishes a structure constituted by the porches constituted by tensioned wood panels, with a timber slab supported on belts. All loads are transmitted to the ground through the foundation. The types of structures are single-family homes. In the figure 5 it shows sequence of assembly.

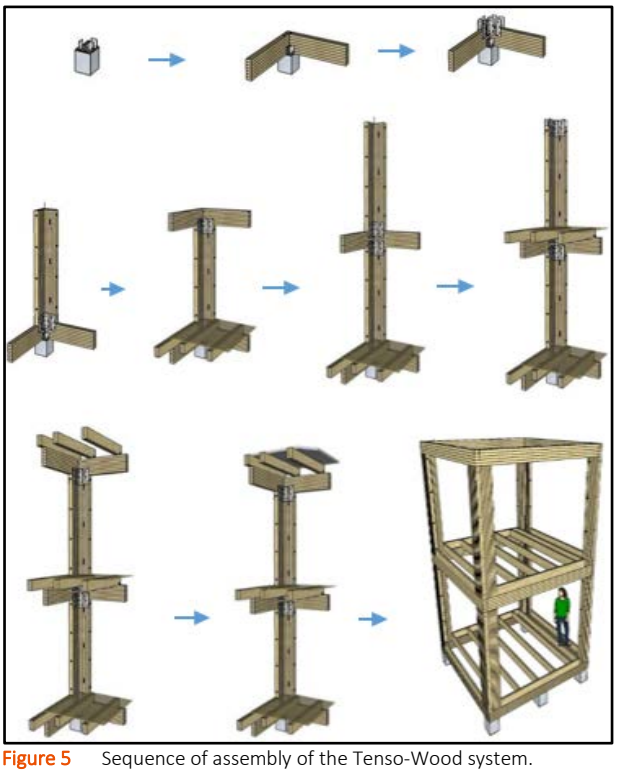


Figure 5 Sequence of assembly of the Tenso-Wood system.

7. EXPERIMENTAL PROGRAM

7.1 Column Panel.

Two experimental test of panel P2 were tested. The load in each test was a compression load applied monotonically with intervals of 9.806KN up to a maximum load of 194.171KN. The failure mechanism of the element was global buckling, obtaining a longitudinal shortening of 5.36mm. The figure 6 shows the component at the beginning and at the end of the test.

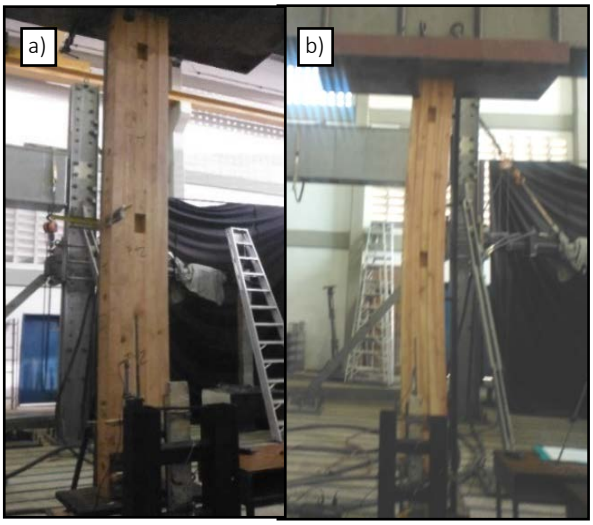


Figure 6 Panel subjected to compression: a) before and b) during of the test.

The column had a lineal behavior. This behavior does not show permanent displacements and the force of 147.099 KN was reached. An initial permanent longitudinal deformation was reported to 0.12mm. Finally, the figure 7 shows that the panel 1 supported a force of 193 KN for a longitudinal displacement of 5.363mm. After unloading, a permanent longitudinal displacement is equal to 0.4mm. The panel 2 supported a force of 169 KN for a longitudinal displacement of 8.263mm. After unloading, a permanent longitudinal displacement is equal to 0.38mm. The column fracture was not reached; the column fails due to global buckling.

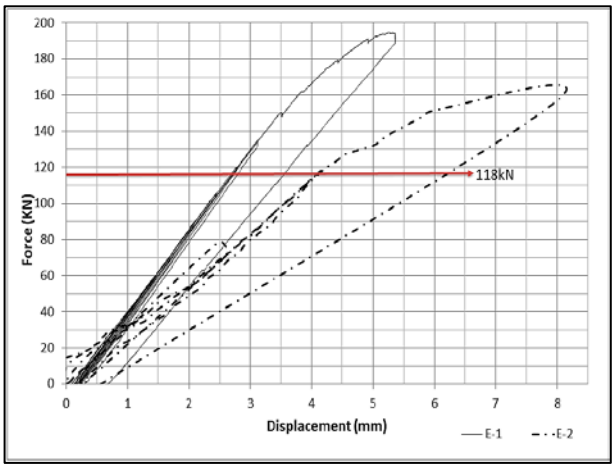


Figure 7 Force vs. Displacement of three tests subjected to monotonic compression loads of the columns panels.

The specimens were labelled P2. The table 2 shows the results obtained for each of the tests. These include the maximum compressive strength reached by the panels, the maximum displacement and the permanent shortening at the end of the test:

Table 2 Test results of compression panels.

Test	Maximum Load (KN)	Longitudinal displacement (mm)	Permanent shortening (mm)
E1	194.171	5.36	0.66
E2	156.904	8.30	0.56

In this sense, it is possible to conclude that the proposed column panel can be used as a structural element in the design of two-level wooden houses since. Under service loads, it is estimated that a column / wall can be subjected to compression loads of less than 118KN including all load combinations and security factors (see figure 7), when a maximum separation of 2.4m between the structural elements is considered.

7.2 Beam Panel

Three (3) beams were tested (see table 1 and figure 3). For each of them, Caribbean pine wood strips were used, joined through 4 bolts spaced 10 cm from the ends and 73cm between them. Each beam was subjected on three-point bending test. Figure 8 shows the beam panel at the start (Figure 8a) and end of the test (Figure 8b), and Figure 9 shows the respective force vs displacement behaviour curve of the different beam panels test.



Figure 8 Beam 10x30 subjected to a point load at the beginning and at the end of the test. a) start test, b) end test

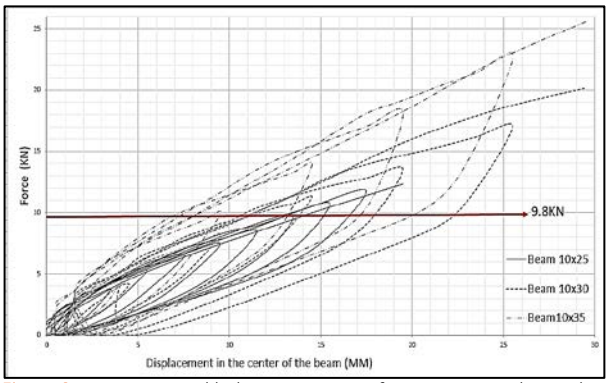


Figure 9 Experimental behaviour curves of Beam 10x30 subjected to 3 point load.

In the figure 9 shows that the B1 beam reached a maximum load of 11.738 KN, with a vertical displacement in the center of the beam equal to 1.80cm. While the B2 and B3 beams reached maximum load to 16.906 KN and 22.545 KN respectively, for a displacement of 2.60 cm. Also during the test, the beams showed a ductile behaviour.

Based on the results obtained, the beam panel proposed with the following characteristics: 2.40m in length, 0.10m in thickness, and 0.35m in height. A point force of 9.806KN is needed to produce the maximum admissible deflection L/300 = 0.80cm (ABNT, 1996) for this kind of element.

7.3 Frame

The experimental test is shown in figure 10. The frame anchoring system to foundation plate consists of steel plates, with openings for the placement of horizontal and vertical bars, guaranteeing the movement in the direction of displacement applied by the actuator (figure 10a). The test was stopped when the frame presented global lateral instability (figure 10b). The damage to the tension wood panels is due to the distortion of the section given the evolution of the global buckling. When applying histories of displacements in the top of the frame subject to mono-sign load type (cyclical), it fails by buckling after few cycles with large displacements.

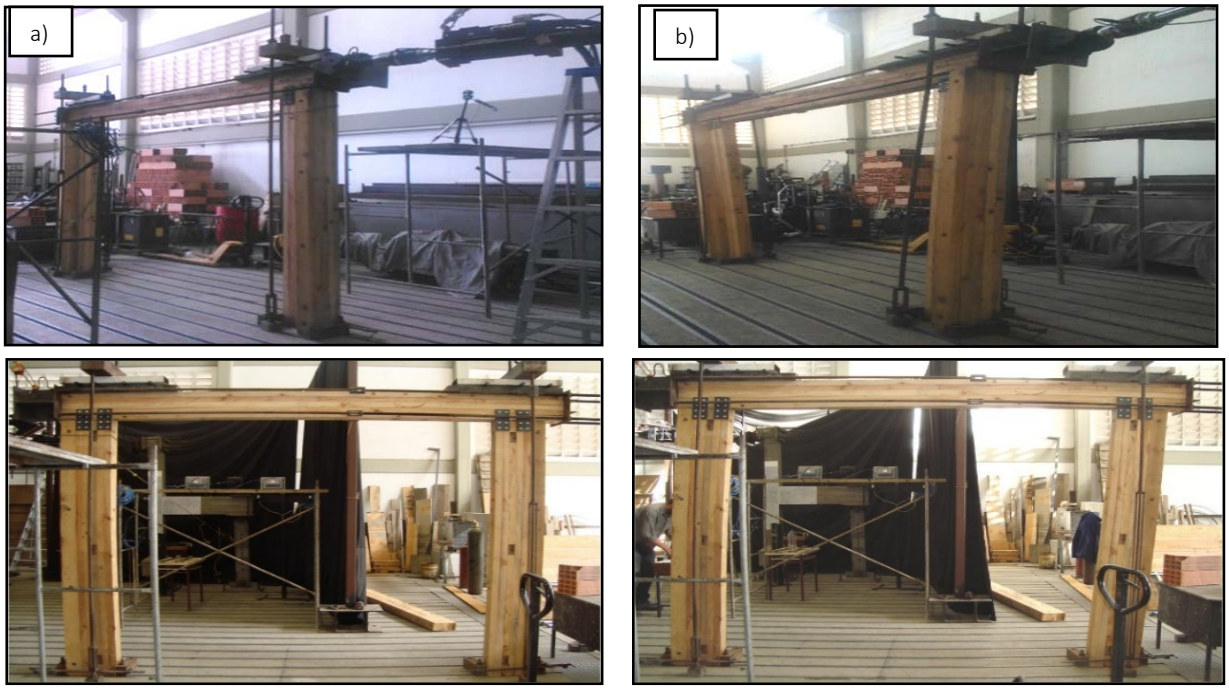


Figure 10 Experimental Frame subjected to lateral displacements at the a) beginning and at the b) end of the test.

The figure 11 shows the behaviour curve F vs D of frame subject to lateral displacement. During the test, eight loading and unloading cycles were applied.

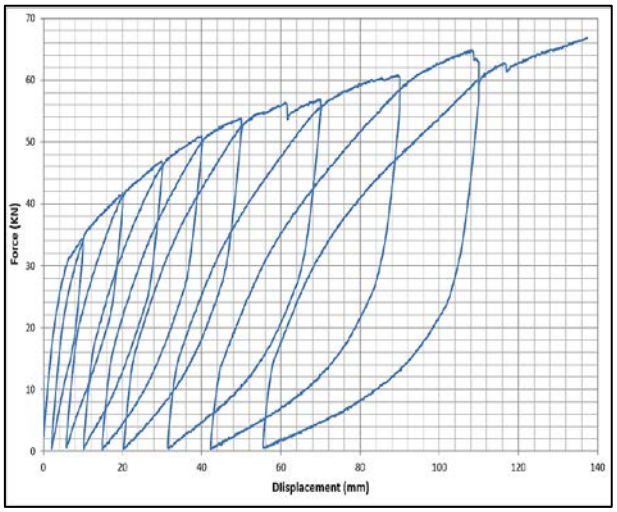


Figure 11 Behaviour curve Force vs. displacement of the frame subjected to lateral displacement.

From the curve, several main characteristic points can be defined, as maximum elastic force of 32.5 KN with displacement 10 mm, maximum force achieved in the last cycle of 63.7 KN, with a lateral displacement of 108 mm. At the end of the test, the frame had a lateral permanent displacement of 55.71 mm. During the test, the frame presented an inelastic behaviour, since permanent displacements at the end of each cycle with lateral force equal zero. So, the energy dissipation can be notice during the unloading-reloading processes due to damping effects of system. The frame presented a high ductile behaviour being the ductile factor equal to 10.8. The beam-column connection showed a good behaviour.

8. NUMERICAL SIMULATIONS

8.1 Column Panel

The numerical simulation was done with the finite element programs: ABAQUS and SAP2000. The basic properties to be used in the characterization of the elements to define the Tenso-wood system are taken from American National Standard 2005.

Geometry: Geometric modelling was based on the dimensions of the supporting panel used in the experimental test, which corresponds to panel P2.

Properties: The properties used in the elastic model are elasticity modulus = 867.348 KN/cm^2, Poisson's ratio = 0.4.

Loads and conditions of support: the component was fixed at the bottom and a distributed pressure was applied at the top. This pressure represents the maximum load applied in the test (137KN).

Mesh: For the model in ABAQUS the finite element C3D8R was used: Solid type element, in 3 dimensions, with 8 nodes and reduced integration. While in the SAP2000 program the element is homogeneous solid type. The meshes used are of hexahedral type.

The Figure 12 and 13 show the results of maximum compressive stresses and the strains distributions at the end of element obtained with Abaqus and SAP2000.

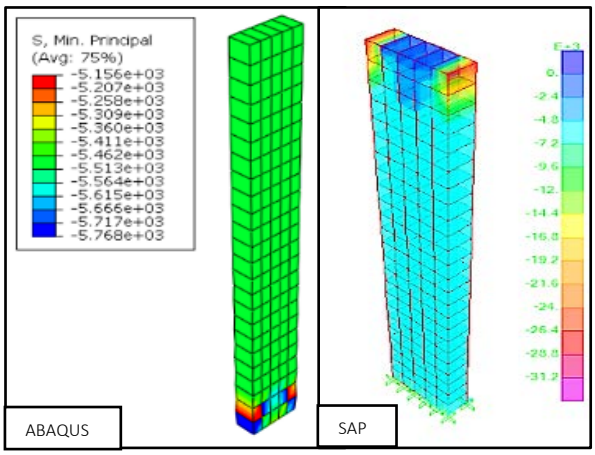


Figure 12 Stress of columns panels ABAQUS and SAP2000. (KN – m^2)

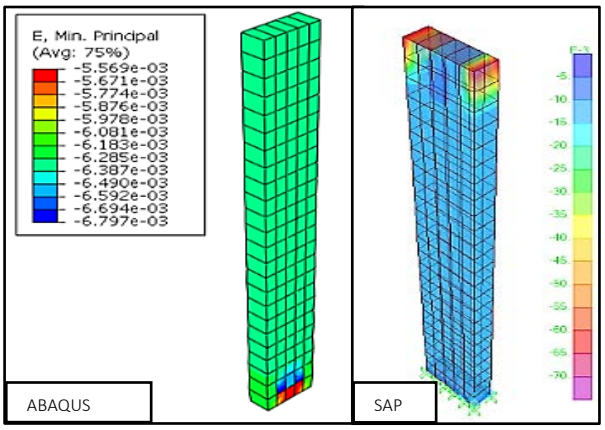


Figure 13 Maximum compressive strains of columns panels ABAQUS and SAP2000. (KN – m^2)

The table 3 shows the results of stresses and strains of the experimental test and the simulations. As can be observed the results in the simulations for the two programs used are very similar to those obtained in the experimental test.

Table 3 Results of efforts and deformations of the load-bearing panel in the experimental test, ABAQUS and Sap2000.

Specimen	E-1, E-2
Maximum Load (KN)	137
Maximum compression stress (KN/m^2) test	5490
Maximum compression stress (KN/m^2) ABAQUS simulation	5156
Maximum compression stress (KN/m^2) SAP2000 simulation	5355
Deformation ABAQUS simulation	5,569x10^{-3}
Deformation SAP2000 simulation	5,558x10^{-3}

8.2 Beam Panel

Abaqus finite element programs was used for the modelling of the beams.

Geometry: geometric modelling was based on the dimensions of the beam used in the experimental test (B1, B2, B3).

Properties: the properties used in the elastic model are modulus elasticity = 70,765 KN/cm^2, Poisson's ratio = 0.4

Loads and conditions of support: a beam simply supported on the ends was used to represent the boundary conditions.

The loading was represented as an imposed displacement up to the maximum value obtained in the last cycle applied for each test. The load was applied in the center of the beam for B1 is, 1.8cm, B2 and B3 are 2.6cm.

Mesh: for the model in ABAQUS, the finite element B33 was used: beam type element, in 3 dimensions, with reduced integration, which allow transverse shear strains.
The figure 14 shows the maximum force at the end of the simulation in Abaqus. The results are expressed in KN

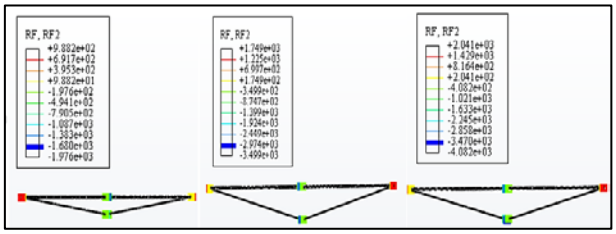


Figure 14 Strength of beam 1, 2 and 3 in ABAQUS.

The table 4 shows the strength values obtained in the experimental tests and the numerical simulation in ABAQUS. It can be observed that the results vary with a 10% approximately.

Table 4 Loads of the beams tests and ABAQUS.

Test	Maximus Force (KN) Test	Maximus Force (KN) ABAQUS
B1	11.738	10.100
B2	16.906	14.837
B3	22.545	23.428

8.3 Frame

ABAQUS finite element program was also used for the numerical simulation of the frame.

Geometry: the geometric modelling was based on the dimensions of the L-type panel and the beam B3.

Elastic properties: the properties used in the model are, modulus of elasticity = 1848.014KN/cm^2, Poisson's ratio= 0.4.

Plastic properties: Yield Stress= 12944,78 KN/m^2 with Plastic Strain=0m; Yield Stress= 14.906,11 KN/m^2 with Plastic Strain= 0.01042m;

Loads and conditions of support: the frame is fixed at the base, with restrictions on the upper part to prevent vertical movement. The solicitation on the frame consists in lateral displacement history applied monotonically.

Mesh: corresponds to the finite element C3D4: Element of tetrahedral type in 3 dimensions of linear order.

The figure 15 show the deformed and the displacement at the end of the simulation in ABAQUS.

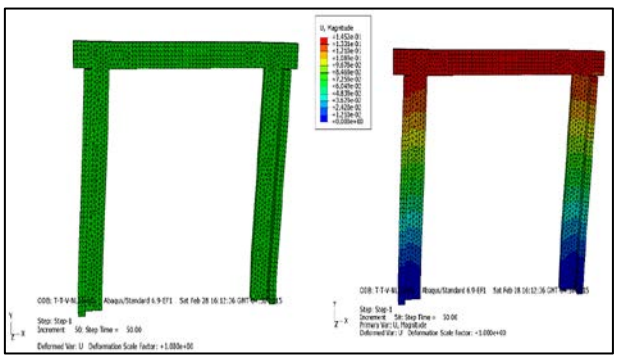


Figure 15 Deformed frame subjected to lateral displacement using ABAQUS. (KN – m)

The behaviour curve of the frame using ABAQUS and the experimental test are shown in the figure 16. One can observe the great similarity that exists between the experimental test and the model. The simulation was applied a monotonic behaviour, the force push the frame on top of numerical frame.

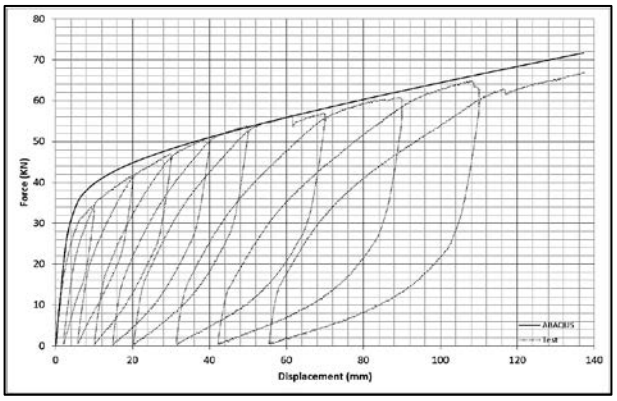


Figure 16 Monotonic behaviour curve of wood frame subjected to lateral displacement on top

Finally, after the simulations carried out on the supporting panels to compression, beam to bending and wood frame subject to monotonic loads can said that through the ABAQUS program to represent the experimental models, since values are very similar to those of the tests obtained.

9. STRUCTURAL EVALUATION OF A TIPICAL HOUSING UNIT USING THE WOOD-TENSION SYSTEM

9.1 Design requirements

Based not a general objective, defining the following project requirements. To define a set of five fundamental aspects:

Material requirements:

Industrialized materials or products must be used based on wood that is easily produced and acquired nationwide.

Housing requirements:

It must allow proper thermal and acoustic conditioning of the home;
It must allow proper lighting, sunning, and healthiness of the air inside the home;
It must ensure good safety levels within the building.

Requirements you work:

It must allow the flexible configuration of houses of different areas of construction and progressive growth;
It must meet the minimum resistance required for load solicitations of up to two floors;
System components must allow efficient storage, both at the factory and on site;
The system components must be adapted to a maximum extent to cargo vehicles with a width not exceeding 2.40m and a maximum load length of 7mts;
It must allow efficient, safe assembly with a minimum of 2 people without requiring additional loading systems;
The intelligibility of the system should be clear and easy allowing its efficient use with little training;
The system should minimize measurement operations for the location and assembly of its components;
It must minimize the processes of cutting and machining on site for assembly components.

Technical-productive requirements:

Apply rationalization systems for design, manufacturing and construction management.

Use light prefabrication criteria.

Aesthetic Requirements:
It should contribute with a good architectural quality.
It must allow the adaptation of the dwelling to its physical environmental context.

Acoustic Requirements:
It should contribute a good acoustic quality.
It should be able to allow sound insulation against internal air noises.

9.2 TIPICAL HOUSE.

The structural design of any building consists of combining the prescribed performance requirements with the anticipated loading. One major performance requirement is that there is an adequate margin of safety between the structure's ultimate capacity and the maximum anticipated loading. The probability that the building will ever collapse is minimized using material property information recommended by the material manufacturers along with code-recommended design loads (Wood Handbook 2010)

For the slab, low-weight timber-based solutions can be alternative to the use of concrete topping (Gubana A., Melotto M., 2018).

The experimental evaluation of the components of the Tenso-Wood system, obtaining the maximum load values that can be supported the column panel, as well as the validity of the constructive technique for tensioning. Therefore, the next step is to validate numerically those elements under the basic dimensioning equations, used in the theory of beams and columns.

Below is an example of the evaluation of a house. It consists of two levels, with a construction area of 33 m^2 per floor. The ground floor is distributed as follows, kitchen, dining room, living room, bathroom, while the upper part corresponds to the private area of the house where 2 bedrooms and a bathroom are planned (Figure 17).

Based on the Venezuelan code COVENIN 2002-88, which is similar to the American ASCE7-16, the following loads were considered:

- Dead load is 0.76 KN/m^2 and Live Load 0.5 KN/m^2, for the roof.
- Dead load is 1.27 KN/m^2 and Live load 1.72 KN/m^2 for the mezzanine.

For the seismic analysis, a design spectrum was considered with a seismic zone of 5 corresponding to the Mérida State in Venezuela. The same will be carried out according to the Venezuelan code for Buildings COVENIN 1756: 2001, which is similar to the FEMA 356. The following aspects of the building were defined:

- Location: Mérida, Municipality, (Seismic Zone 5)
- Value of Ao = 0.30
- For a soft / loose soil with a spectral shape S2
- Correction factor Ø = 0.90
- For Buildings of public or private use, of low occupation, that do not exceed the limits indicated in Group B1, such as: Buildings for public or private use, densely occupied permanently or temporarily
- Importance factor. 1.15
- Required Design Level: N3
- Type of Structure: the building can be classified among structures capable of resisting the totality of the seismic actions through its beams and columns, such as the structural systems constituted by frames. The column axes must be kept continuous until their foundation.
- Response Reduction Factor: R = 4.5

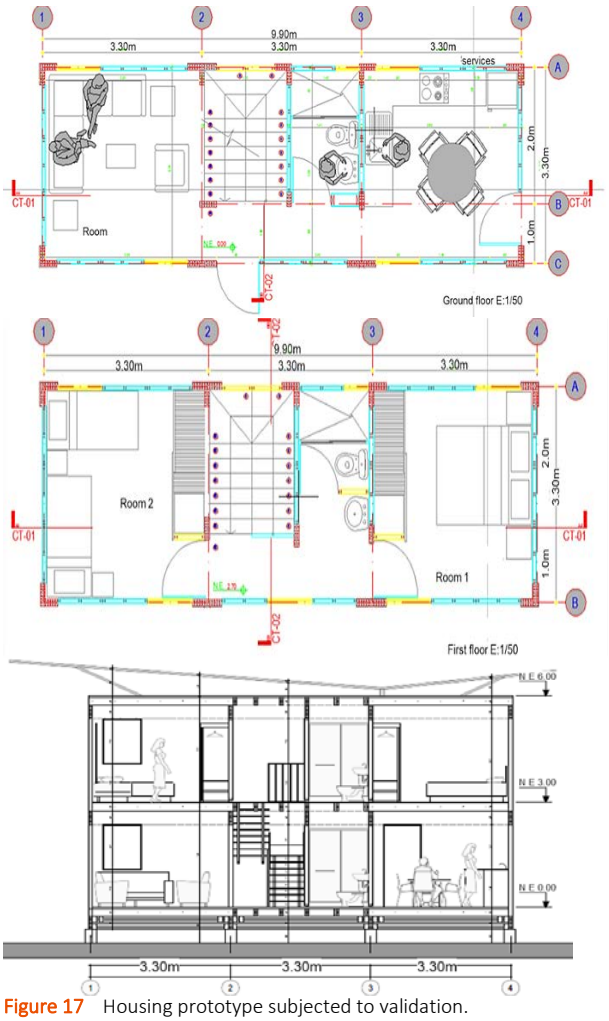


Figure 17 Housing prototype subjected to validation.

The design of wood elements and the joining devices required to form structures will be carried out according to the criteria of limit states established in the Standards on Criteria and Actions for the Structural Design of Buildings, which establishes the requirements that must be met in regarding safety and behaviour in service conditions. When designed according to the ultimate limit states, loads are multiplied by load factors or safety factors (γ, Ψ) usually greater than 1.0. The magnitudes obtained depending on the type of combination of the loads.

The design may be carried out by means of analytical or experimental procedures. In the design by analytical methods, the internal actions will be determined considering that the structural elements and the structures have a linear elastic behaviour.

The values of the resistance of calculation of the wood Rd, are obtained from the characteristic value of said properties, by means of the following equation:

$$R_d = K_{mod}\left(\frac{X_K}{\gamma_w}\right) \quad (1)$$

Where: γ_w is the coefficient of reduction of the properties of the wood and K_{mod} is the modification coefficient that takes into account the influences not considered by γ_w.

The K_{mod} modification coefficients affect the calculation values of the properties of the wood depending on the load combinations, the moisture content, and the possible use of second quality wood. The modification coefficient is:

$$K_{mod} = K_{mod1}\, K_{mod2}\, K_{mod3} \quad (2)$$

Where the partial modification coefficient K_{mod1} takes into account the load combinations and the type of material used. The partial modification coefficient K_{mod2} takes into account the moisture content and the type of material used. The coefficient of modification K_{mod3} takes into account whether the wood is first or second category. In the case of wood of second category admit a K_{mod3}= 0.8 and if it is of the first category it is considered a K_{mod3}= 1.0. (ABNT, 1996).

For the modelling K_{mod}=0.6. Below is the housing three-dimensional model analysed in its initial configuration (Figure 18).

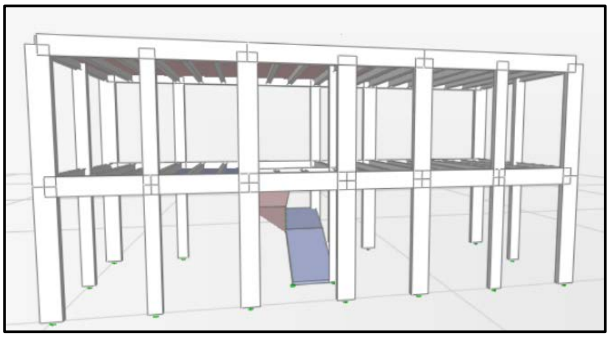


Figure 18 Original model in SAP2000 .

In the Table 5, it can be observed that the maximum axial force obtained in the simulation is below the value of the elastic load obtained in the tests.

Table 5 Loads of the supporting panel in ABAQUS and SAP2000.

Column Panel	Test	Level 1	Roof
Axial Force KN	128t	10.01	4.30
Beam Panel	Test	Level 1	Roof
Deflection Admissible 165/200=0,825 (cm)	0.4	0.3	0.2

For the beam panel, both the deflection and the bending moments check at the level of pre-dimensioning and structural analysis.

The figure 19 shows the lateral displacement of the house under seismic analysis.

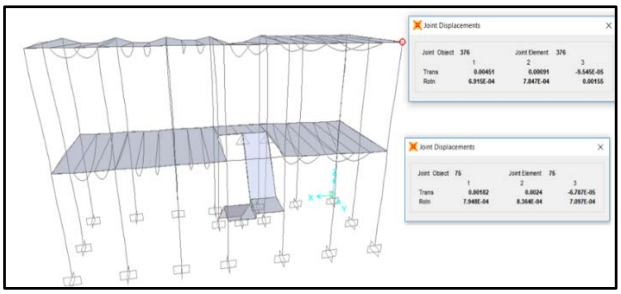


Figure 19 Deformed structure subjected to lateral displacement SAP2000.

With respect to the moments and axial forces, there are no variations between the analysis under service and seismic loads. However, it is possible to determine the drift of the structure at the end of the simulation; it has a value of 0.012, complying with the limit drift given by COVENIN 1756-01 for elements susceptible to being damaged by deformations of the structure, which is equal to 0.018.

10. FINAL CONSIDERATIONS

The Tenso-Wood System constitute a viable alternative in the sustainable construction of houses under the criteria of rationalization and prefabrication.

The design of the tensed wood building system met the main objectives established for the project, which sought in principle to provide an effective, efficient and quality solution for the massive construction of housing, as well as develop a design taking into account sustainability criteria; adapted to technological resources and affordable materials in developing countries. Under these criteria, a feasible proposal was conceived that implements a minimum amount of standardized construction components, namely: two types of load-bearing panels, two types of beams and two types of fittings for connections, for the construction of multiple structural configurations. On the other hand, the validation of the productive processes of the components allowed to verify that the simplicity of these will allow an easy technological appropriation by the population in general, guaranteeing good constructive quality.

The models realized by means of finite elements, proved to be more rigid than the models tested (smaller displacements than the real displacements). Since the stresses in the wood are very low, the results of the load-displacement curves are strongly influenced by the initial slope of the wood's stress curve, with a very wide range of results.

A prototype proposal, a modular system from an architectural design grid of 3.30 m x 3.30 m with 3.00 m in height, in order to reduce the number of panels of enclosures that allow to be used. This allows us to play with the configurations of the load-bearing elements, and thus be able to unify the design process in plant distribution, constructive rationalization and ease of assembly in the details of the joints between panels.

The theoretical simulations of the experimental tests with the model of Finite Elements S4R5 Nonlinear of ABAQUS approached quite well, since it was possible to reproduce the distortion of the geometry. Thus, it was possible to define the adjustment parameters, which are: the size of the finite elements, theoretical thickness of the finite elements, theoretical constitutive relation of the steel and the minimum size of the increment to be specified between iterations to achieve the numerical convergence of the model.

This constructive system aims to be industrialized, therefore modular, prefabricated and whose manufacturing processes must be conceived within the environmentally integrated design and what has been called the appropriation of technology by the communities involved in housing solutions. From a structural point of view, the rules and calculation procedures necessary for the panels to be used in seismic areas were contemplated, so that people can live in a tropical environment as dignified and as comfortable as possible, as well as in full balance with nature.

The Tenso-wood panels are a viable alternative in the construction of houses under the criteria of rationalization and prefabrication using ecologically sustainable technologies. Through the experimental program it was possible to validate in a favourable way the constructive process of the panels and their structural behaviour. Regarding the construction of the panels, the use of bolts guarantees that the wooden slats behave as a solid and stable structural element, since in the experimental tests no separations between slats or bolt failures were observed. Likewise, in the test of the frame, the rigid

condition of the connections was verified, since the screws and the plates remained in place. Fulfilling one of the purposes of this research, which is to achieve an easy and appropriate manufacturing process. The maximum loads supported by the components, deformations and failure modes observed in the tests, allow concluding that these could be used as structural elements.

ACKNOWLEDGEMENTS

This project has been developed in the Housing and Habitat Research Center of Los Andes University (ULA-Venezuela). Project No: A – 760-10-09-C of FONACIT and CDCHT-ULA. Likewise, the collaboration in the realization of the experimental tests, of the Laboratory of Forest Products, the Laboratory of Materials and Tests of the Faculty of Engineering, and the Laboratory of Structural Mechanics of Lisandro Alvarado University (UCLA - Venezuela), should be highlighted.

REFERENCES

1. AMERICAN NATIONAL STANDARD ASD/ LRFD. Design specification for wood construction. 2005.
2. ARRIAGA, F.: "Madera aserrada estructural". AITIM. Madrid, 2003.
3. Associación brasileira de Normas Técnicas. ABNT. Projeto de estruturas de madeira. Rio de Janeiro, Brasil. 1996.
4. ASCE7-16 Minimum Design Loads and Associated Criteria for Buildings and Other Structures. Minimum design loads for buildings and other structures. ASCE standard, ASCE/ SEI 7-16: Reston, Virginia: American Society of Civil Engineers, 2017.
5. AUGEARD E., MICHEL L., FERRIER E. Experimental and analytical study of the mechanical behavior of heterogeneous glulam–concrete beams and panels assembled by a specific treatment of wood. Construction and Building Materials 191, pp 812–825. 2018.
6. BRETTSTAPEL. Construcción, recuperado en marzo 2012 de http://www.brettstapel.org
7. CTE. Documento básico SE-M. Seguridad estructural: estructuras de madera. Ministério de Fomento. Madrid, octubre de 2009.
8. CSI, Analysis Reference Manual for SAP2000. Computers and Structures inc., Berkley, California, USA. 2015.
9. CHEN H.L., VENKATESH G., GANGARAO H.V.S., Stephens J.E. Dynamic Characterization of Posttensioned Rods in Stressed Timber Systems. In: Nowak A.S. (eds) Bridge Evaluation, Repair and Rehabilitation. NATO ASI Series E: Applied Sciences, vol 187. Springer, Dordrecht. 1990.
10. DYKEN, T. Monitoring of Norwegian timber bridges. Proceedings NVF timber bridges. Nordic roads association, Norwegian public roads administration. Hamar. 13 pp. 2005.
11. FEDERAL EMERGENCY MANAGEMENT AGENCY FEMA. Quantification of Building Seismic Performance Factors, FEMA p695.Washington D.C., USA. 2009
12. FERREIRA, O. et all. Madeira: Uso Sustentável na Construção Civil. Instituto de pesquisa tecnológica, São Paulo. p 17. 2003.
13. FOREST PRODUCTS LABORATORY. Wood handbook—Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p. 2010
14. PAJCHROWSKI, G., NOSKOWIAK, A., LEWANDOWSKA, A., & STRYKOWSKI, W. Wood as a building material in the light of environmental assessment of full life cycle of four buildings. Construction and Building Materials, 52, 428–436. doi:10.1016/j.conbuildmat.2013.11.066. 2014.
15. GIULIANO, M.P., DECHENT SILVA, R. Manual de diseño, construcción, mantención y monitoreo de tableros de madera tensado. Universidad de Concepción, Facultad de Ingeniería Civil. Concepción, Chile. 157 pp. 2011. Recuperado el 3 de febrero de 2012 de http://www.cttmadera.cl. 2011.
16. GUBANA A., MELOTTO M., "Experimental tests on wood-based in-plane strengthening solutions for the seismic retrofit of traditional timber floors", Construction and Building Materials, Volume 191, Pages 290299, http://www.sciencedirect.com/science/article/pii/S0950061818323651. 2018.
17. HARTE, A.M., 2017. Mass timber – the emergence of a modern construction material. Journal of Structural Integrity and Maintenance [on line], vol. 2, no. 3, pp. 121-132. ISSN 2470-5314. DOI 10.1080/24705314.2017.1354156. Disponible en: http://doi.org/10.1080/24705314.2017.1354156.
18. HEMPEL, R. Sistemas constructivos de madera sólida, Universidad del BioBio, Concepción, Chile. 2009.
19. HEMPEL R., POBLETE C. Cuaderno de la edificación en madera N°7: Sistemas estructurales en madera. Concepción, Chile: Universidad del BioBio. 1994.
20. HOADLEY, R.B. Understanding wood. The Tauton press. Newtown, USA. 2000.
21. HUAIQUILAF, B. Estudio experimental del comportamiento reológico de tableros tensados de madera pino radiata endurecida. Memoria de título, departamento de Ingeniería Civil, Universidad de Concepción, Concepción, Chile. 138 pp. 2004.
22. HERRERA, J., GODOY, L. Aplicación de la mecánica de materiales a la madera, Universidad Nacional de Córdoba, Córdoba, Argentina. 2010.
23. JUNAC. Manual de diseño para maderas del Grupo Andino. Junta de Acuerdo de Cartagena. Lima, Perú. 1985.
24. KOPPELHUBER, J., BAUER, B., WALL, J. y HECK, D.. Industrialized Timber Building Systems for an Increased Market Share - A Holistic Approach Targeting Construction Management and Building Economics. *Procedia Engineering*, vol. 171, pp. 333-340. ISSN 18777058. DOI 10.1016/j.proeng.2017.01.341. 2017.
25. QUEIPO DE LLANO, J; MOYA, B.; GONZÁLEZ, R.; LLINARES, C, VILLAGRÁ, V.; GALLEGO, G. Guía de construir con madera. unidad de calidad en la construcción. Instituto de ciencias de la construcción Eduardo Torroja. Consejo Superior de Investigaciones Científicas (CSIC).2010.
26. National Design Specification (NDS) for Wood Construction was developed by the American Wood Council's (AWC) Wood Design Standards Committee and has been approved by ANSI as an American National Standard. 2018.
27. NORMA COVENIN 2002-88. Criterios y acciones mínimas para el proyecto de edificaciones. Mindur. Caracas, Venezuela. 1988.
28. NORMA COVENIN MINDUR 1756-01, Edificaciones sismorresistentes parte 1: Articulado. Caracas, Venezuela. 2001
29. SAP2000. Computers and Structures. https://www.csiamerica.com/products/sap2000.
30. PADT-REFORT 1984 Manual de Diseño para Maderas del Grupo Andino. Junta del Acuerdo de Cartagena, Lima Perú. 591 pp
31. PAJCHROWSKI G., NOSKOWIAK A., LEWANDOWSKA A., STRYKOWSKI W. 2014. Wood as a building material in the light of environmental assessment of full life cycle of four buildings. Construction and Building Materials 52, pp. 428–436.

32. POLLOCK, D., T., WILLIAMSON, Y D., GROMALA, 1995. Evolving design methods. Chapter 4.
33. ROBLES, F. Manual para el diseño de estructuras de maderas, sección Nº 3. Laboratorio de Ciencia y Tecnología de la madera. Distrito Federal, México. 1990
34. UGALDE, G. Diseño y construcción tablero de madera tensado para el puente cautín. Memoria de título, departamento de Ingeniería Civil, Universidad de Concepción, Concepción, Chile. 183 pp. 2004.
35. VARGAS-MOSQUEDA, M., UZCÁTEGUI, M., PICÓN, R., MONTILLA, S. Evaluation of structural stressed wood used for construction. Revista Ecodiseño y Sostenibilidad. Número 7(1).2015.
36. VARGAS-MOSQUEDA, M., Preliminary design of Tenso-Wood System. Structural Timber System for housing. +Arquitectura +Diseño: Investigaciones de la Facultad de Arquitectura y Diseño. ULA. Universidad de Los Andes. Mérida, Venezuela. 455 pp. 2015.