TIMBER ROOF LAMINAR COVERS IN URUGUAY, DESIGNED AND MANUFACTURED BY CAD-CAE-CAM PROCESSES

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ABSTRACT: The use of wood in building construction is growing in Uruguay. That is why the design of innovative building materials and components, and the incorporation of new technologies in the productive processes that add value to the national raw material, is a priority. In the last decades, our country has made a great investment increasing forested areas and updating the technology applied to this industry sector. In consequence, there is a suitable timber production to be used in building construction. One of the Forestry Sector Plan goals established by the Industry, Energy and Mining Ministry of Uruguay (MIEM) for the timber sector, is the promotion of the use of wood in the local market. This is because wood products incorporated to the building industry promote investments in the production chain, adding value to materials and increasing the technological development.

The main objective of this research is defining a parametric modeling and computer-aided manufacturing procedure (CAD-CAE-CAM) of laminar structures with complex forms, based on wood products, adapted to the technology and the conditions of our environment for being used in educational buildings.

For this purpose, form-finding experiments with origami techniques are carried out in order to select those more suitable for laminar structures. Then, these forms are adjusted by applying optimization factors, considering the interrelation with different building aspects.

The relevance of the proposed models is corroborated with institutional productive actors, linked to the construction of educational buildings.

The detailed design of some selected laminar roofs that have been considered appropriate to be included in educational buildings is done. Applying the developed procedure, at least 5 small-scale prototypes and 5 full-scale modules of this kind of roof covers are manufactured. These prototypes are tested in order to determine their mechanical properties. The structural performance of these solutions is determined from theoretical calculations, and correlation analysis between calculations and the results obtained from mechanical resistance tests.

In this way, we intend to verify the relevance of the laminar structures constructed with timber panels, designed and manufactured from CAD-CAE-CAM processes, as a solution to be incorporated to the construction of educational buildings in Uruguay.

The development of a CAD-CAE-CAM methodology for the manufacture of laminar roof covers of timber products, will allow our University to offer a new productive service to the market, as well as to promote the use of national materials with incorporated engineering.

KEYWORDS: form-finding, origami, complex forms, optimization, prototypes

1 INTRODUCTION

In recent decades, a large number of structurally optimized complex shaped structures have been constructed.
The current technology allows to design and produce structures taking full advantage of the properties of the materials and related to this the wood products have a prominent role.
The advance of parametric modelling and computer-aided manufacturing methods (i.e. cad-cae-cam methods) has enable the design and elaboration of optimized construction components with complex morphologies, impossible to be developed with traditional methods. It implies a strong reduction of labour and production time costs. Computer-controlled cutting machines (for example, lasers and CNC routers), 3D printers and modelling and structural calculation software are increasingly powerful. At costs that are quickly amortized, they provide benefits hardly imagined a few decades ago [1]. For this reason, a great growth of CAD-CAE-CAM methods is foreseeable in Uruguay. It is probable, also, that the cost of these machinery will decrease in the short and medium term, so it will be increasingly attractive for companies to have this technology that allows the manufacture of architectural components with complex shapes in very short deadlines and without the participation of specialized workforce. For these reasons, it is considered feasible for the local market to adopt such structural solutions in the short term. On the other hand, the formal potential of such structures is beyond doubts. However, there are currently no relevant practical applications in the construction industry in our country. For this reason, it is considered essential to develop methodologies adapted to our environment, to our building needs, to national materials, to our technological availability and to local construction costs.

2 METHODOLOGY

A computer aided modelling and manufacturing method is developed, adapted to the structural materials derived from national timber and to the technology available at the Digital Manufacturing Laboratory (labFabMVD) of the Architectural School in the University of the Republic (FADU-UdelaR), Uruguay. Analogical and digital form-finding experiments, are carried out in order to find a series of optimal forms for the construction of laminated roofs made of timber-derived panels. A series of optimization factors are applied to these forms and a catalogue is prepared.
The architectural potential of this constructive and structural typology is explored through experimental teaching in courses at the Architecture School (FADU-UdelaR).
The relevance of the results achieved in these activities is verified through a series of interviews with experts and technicians in charge of design and construction of public educational buildings.
On the other hand, tests are carried out to determine the density, flexural strength and elastic modulus of plywood boards manufactured in Uruguay with pine and eucalyptus.
Based on some of the structural forms that have been found and optimized, the complete project of an educational building roof with national plywood boards is carried out.
The relevance of the developed CAD-CAE-CAM method is verified through the manufacture and assembly of prototypes that are subjected to mechanical resistance tests. Small-scale prototypes of complete roofs and partial modules at full scale are constructed. The results obtained in the tests are compared with the theoretical mechanical characteristics of the laminar roofs.

3 RESULTS

3.1 FORM-FINDING EXPERIMENTS: MOTIVES, BASIC PATTERNS AND SHAPE OPTIMIZATION

Through a series of form-finding experiments, optimal forms for the construction of roof laminar covers are found. By using origami techniques, analogical scale models are made, simulating the physical properties of different 3D morphologies, with different structural systems, with the aim of compositionally exploring resistant shapes, of understanding their structural functioning [2,3,4] and of defining mechanisms for its optimization.
A basic motif or cell is a simple line drawing, which contains the information needed to fold a piece of paper: valleys and mountains. A basic pattern is a way of folding a sheet of paper that arises from the repetition of a motif, with a regular rhythm [5]. The basic patterns can be moulded through the application of manipulation mechanisms, with the aim of exploring their plastic and architectural potential (structural and constructive). In this way, manipulated or complex patterns arise.
The manipulation mechanisms consist of alterations of some of the geometric characteristics of the folding pattern, which cause distortions in its rhythm. They can be classified into:
1- Lengthening: proportions of the pattern motifs are modified, obtaining variations in its rhythm.

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2- Rotations: angles or inclinations of the pattern motifs are modified.
3- Symmetries: motives or groups of pattern motifs are repeated by reflection.
4- Polarizations: pattern motifs are organized or ordered through turns around fixed points or poles.
5- Glide reflection: pattern motifs are organized or ordered through translations.
6- Combinations: coupling of two or more basic or manipulated patterns.

3.2 CATALOG OF BASIC AND OPTIMIZED FORMS

The result of the morphologic study of folding patterns is organized in a catalogue. The following categories are distinguished:

1- Linear progressions: those basic patterns whose motifs are progressions of parallel valleys and mountains. Depending on their rhythm, they can be classified into accordion, knife or box pleats. When the motifs define an alternate succession of valleys and mountains of equal proportion, an accordion pleat is generated (as e.g. in Figure 1). This is one of the simplest basic patterns. When the succession of valleys and mountains do not maintain the same proportion, knife pleats arise (as e.g. in Figure 2). If the motifs define a valley-valley-mountain-mountain sequence, a box pleat folding is generated.
2- Helix and spiral pleats.
3- V-pleats (as e.g. in Figures 3, 4, 7, 10 and 11).
4- Other tessellations with complex motifs: lattice pleats, rotating triangles (as e.g. in Figure 6), squares and hexagons, fractured flowers, V-mountains, etc.
5- Arches and vaults: X-form Spans (Yoshimura pattern) (as e.g. in Figure 5), rhomboid-form Spans, simple V-fold Spans, square corner V-fold Spans, fishbone, etc.
6- Pyramids and domes: inverted boxes, paraboloids, pyramidal accordions, X-form Span lattices, V-fold pyramids (as e.g. in Figure 9), radial X-form Spans, cylindrical accordion, knife or box pleats, etc.
7- fitted motifs: triangular, quadrangular base motifs, etc.
8- Other explorations: kirigami, kaleidocycles, volumetric V-folds, curved folds, etc.

In different morphological categories found, it is valued:
A- Its geometric stiffness (the ability to oppose being deformed or curved) or its flexibility (the ability to deform or bend), when manipulated in different directions outside the fold planes. It is an index of its potential to be used as a structural or resistant morphology. It is also an index of its potential to be used in the design of mobile structures.
B- Its manipulation potential, that is, its capacity to be altered or distorted through the application of different manipulation mechanisms. It is an index of its adaptability to generate optimized and complex geometries.
C- The conservation or loss of flatness during manipulation. This characteristic is decisive of the procedures and materials with which the form can be manufactured and constructed.
D- Its systemic potential. It is an assessment of its capacity to solve problems associated to the materialization of architectural systems.
After the analogic formal exploration, a digital exploration was performed through origami simulations with Grasshopper (as e.g. in Figure 8), a plug-in incorporated in Rhinoceros 3D. To program the simulation of the folded shapes with Grasshopper, Crane plug-in, created by Kai Suto and Kotaro Tanimachi, was used. This plug-in allows the creation of an origami pattern (C mesh) and then the simulation of its folding. This tool is an intermediate step between the analogic design and the parameterization of the forms, and allows to develop form-searching processes. The patterns obtained from the analogic catalog were digitally simulated and scaled. Optimization criteria were then applied. This process allows to evaluate the static behavior of shapes, and to make successive modifications in the folding patterns.

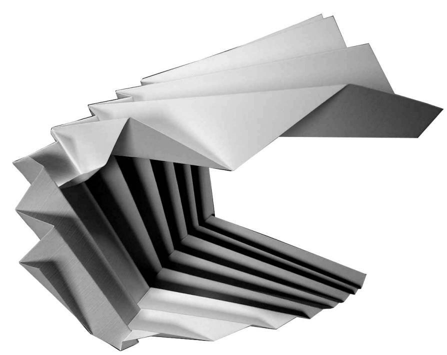

Figure 1: *Polarized accordion with two square corners*

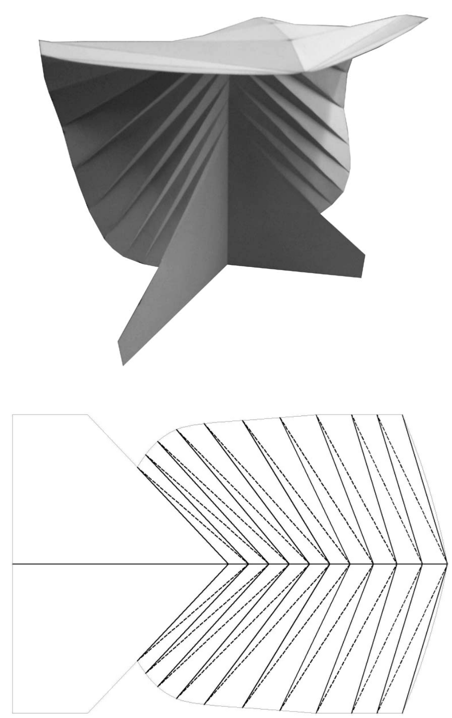

Figure 2: *Lengthened symmetrical knife pleat*

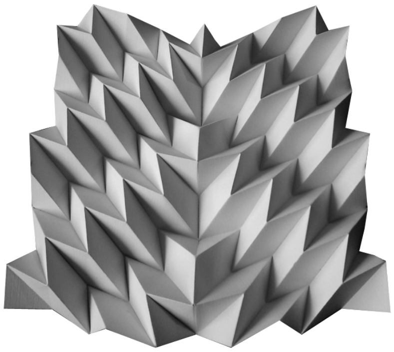

Figure 3: *Rotated and glide reflected V-pleats*

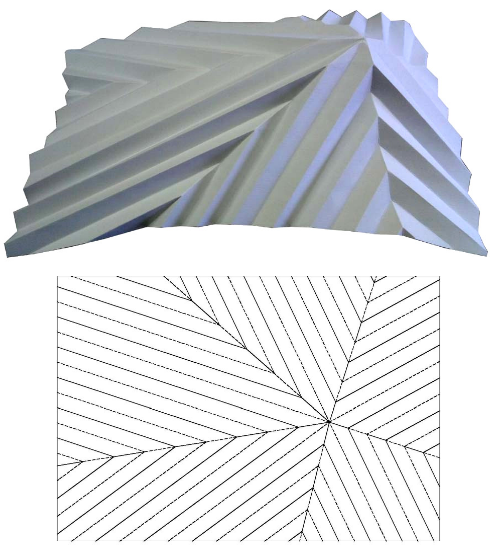

Figure 4: *Polarized V-pleats*

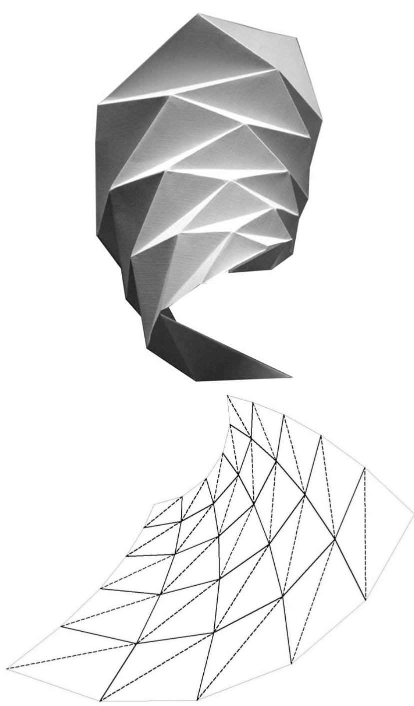

Figure 5: *Lengthened X-form Span*

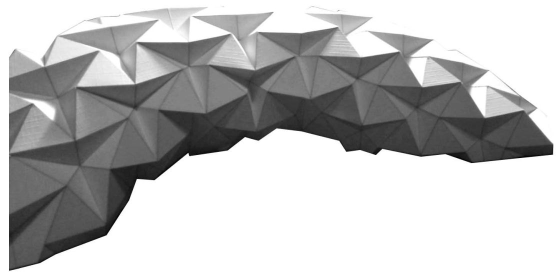

Figure 6: *Rotating triangles*

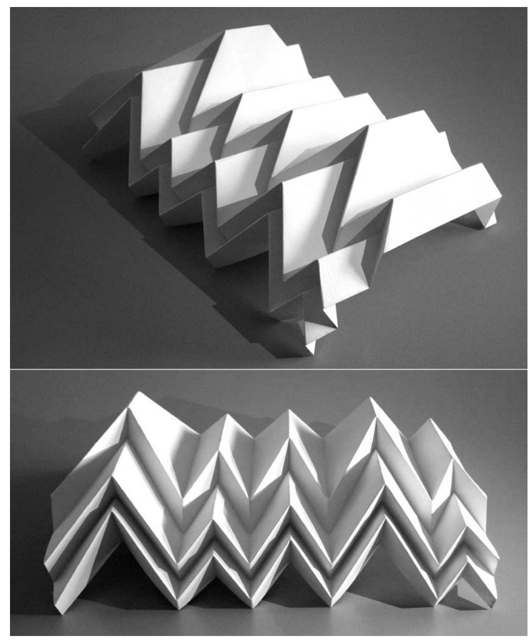

Figure 7: *Lengthened and glide reflected V-pleats*

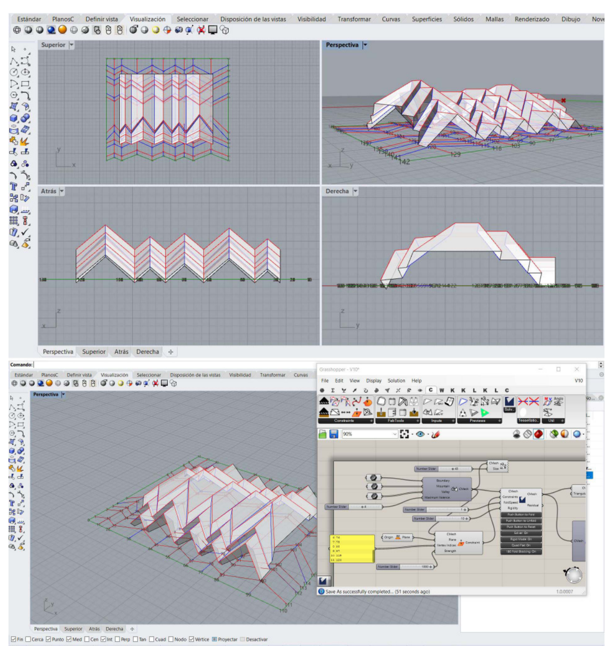

Figure 8: *Form-searching process through origami simulations with Grasshopper*

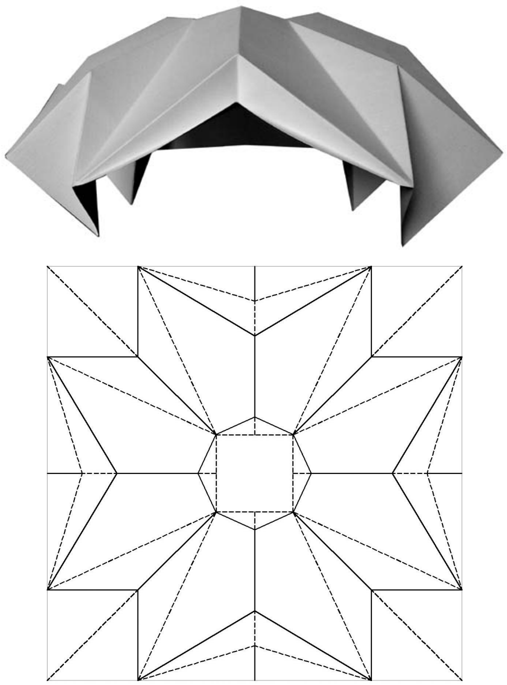

Figure 9: *V-fold pyramid*

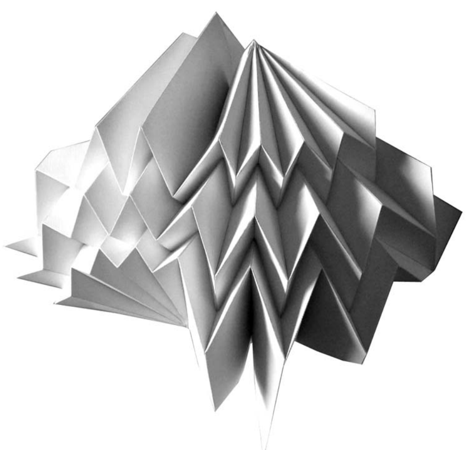

Figure 10: *Polarized V-pleats with two poles*

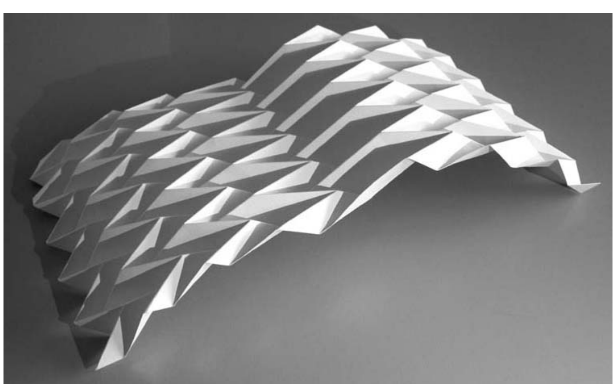

Figure 11: *Lengthened V-pleats*

3.3 MATERIAL

It is decided to work with plywood boards manufactured in Uruguay with raw material from renewable forests with a forest management plan: *Pinus elliottii, Pinus taeda* and *Eucalyptus grandis*. These plywood boards are composed of sheets, 2 mm to 5 mm of thickness, of pine, eucalyptus or both. Currently, there is only one company that manufactures these plywood boards in Uruguay, in thicknesses of 12 mm, 15 mm and 18 mm, and dimensions of 1,22 m x 2,44 m. These plywood meets international local quality and environmental requirements. The plywood panels meet the standards of PS1, as certified by the TPI USA Agency and the standards of EN 13986 (CE2+) [6], as certified by the Exova BM Trada. The declared properties of the product are based on the following Harmonised Technical Specifications: EN 13986:2004 +A1:2015, Wood-based panels for use in construction – Characteristics, evaluation of conformity and marking and EN 636:2012+A1:2015–Plywood –Specifications [7].

Plywood boards available in the local market will be characterized by the determination of some of its properties, such us moisture content, density, flexural strength in the board plane, flexural strength perpendicular to the board plane, compressive strength in the board plane, tensile strength, water vapour permeability and thermal conductivity.

Some measures due to the current health emergency situation in our country are causing delays in project´s development timeline; especially it had an impact in the implementation of the laboratory tests. Anyway, to date it has been possible to do tests for determination of edgewise bending properties (see Figure 12), tensile strength according to UNE-EN 789 [8] (see Figure 13), and thermal conductivity according to ISO 8302. [9]

Figure 12: *Flexural strength test of plywood board*

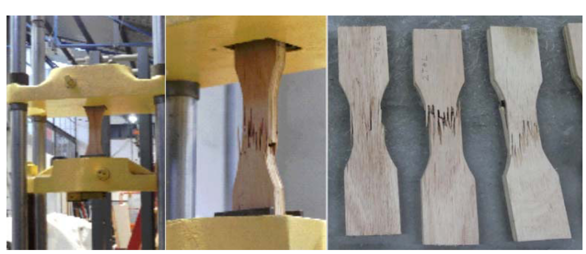

Figure 13: *Longitudinal tensile test of plywood board*

3.4 PARAMETRIC MODELING PROCEDURE AND COMPUTER-ASSISTED DIGITAL MANUFACTURING (CAD-CAE-CAM PROCESS

The definition of a parametric modelling procedure implies generating an algorithm in which all the elements or parameters involved in the morphological conformation of the laminar cover(s) are interrelated. The numerical indeterminacy between singular and / or plural is due to the fact that the parametric modelling procedure makes it possible to design a process by which "n" elements can be obtained from the algorithmic definition and from which, the sample that best approximates the conditions set as optimal, is "extracted". Once the sample is materialized, it can be analyzed and tested. In a parametric modelling process the form itself is no longer drawn, but rather a process is defined, through which the form is generated. It can, therefore, be adjusted and modified through the manipulation of the parameters that define it.

3.4.1 Definition of the parametric procedure

The definition of this procedure implies:
1- Choice of an algorithmic programming framework; it is decided to work with "Grasshopper" plug-in, which is a very intuitive visual programming language, widely used in the academic activity related to design, and free available.
2- Determination of parameters and components; it implies defining the elements involved in the process as well as the type of relationship established between them (mathematical, geometric, vectorial, or logical relationships) and that will be carried out through the components responsible for executing actions.
3- Adoption of one of the folded morphologies found from the origami technique.
4- Choice of software that models and calculates three-dimensional surface structures with complex geometry using the Finite Element Method [MEF]. It is decided to work with RFEM 5 software, by Dlubal (see Figures 15 and 16).
5 - Definition of the material elements that will shape the laminar covers, and the unions or fasteners between its different components and between them and their supports. We work with 120 cm x 240 cm boards of national plywood, with thicknesses up to 18 mm. The joining and fixing elements are made using tongue and groove fits, according to the dimensions defined by the surface of each board [10,11].
6- Selection of output elements; referred to the geometric elements needed to materialize the form, generating the information inputs of a CAD-CAM system.

3.4.2 Initial conditions

Spatial morphology: forms found from folding strategies. Technique: origami. Type of Digital Manufacturing Technology: subtractive technology CNC router. Materials: 1.22 m x 2.44 m plywood boards, with 18 mm thickness. Assembly of components: mortise and tenon joints with bevel angles.

3.4.3 An example: parameterization of a selected form

Rigid folding systems inspired by origami allow the development of complex structures governed by few variables. An algorithm proposed to the definition of X-form Spans is described below:
1) definition of an A base module, structured from a rectangle of 2:1 ratio. It is important to generate as many dimensionless relationships as possible when defining a parametric method.
2) construction of a parallelogram of the rhombus type, joining the midpoints of the sides of the A base module. The initial rectangular figure is turned off.
3) Geometric definition of the rhombus major diagonal to be used:
03.1) as a rotation pivot of the resulting triangles according to an Ω angle in a range of 1 to 179 degrees (the range in that domain is restricted to avoid "graphic aberrations").
03.2) as a rotation center. One of its extremes is identified as Point 01, and the other as Point 03.
The original A base rhombus has only one degree of freedom. In the next step a copy of the original base rhombus is created, which is designated as B module. A translation is applied to this module, along the z axis, so that point 01 of the copied module coincides with point 03 of the original module.
4) creation of B module from a copy of A module.
5) translation of B module, with a vector equal to the length of the major diagonal of A module, along the z axis.

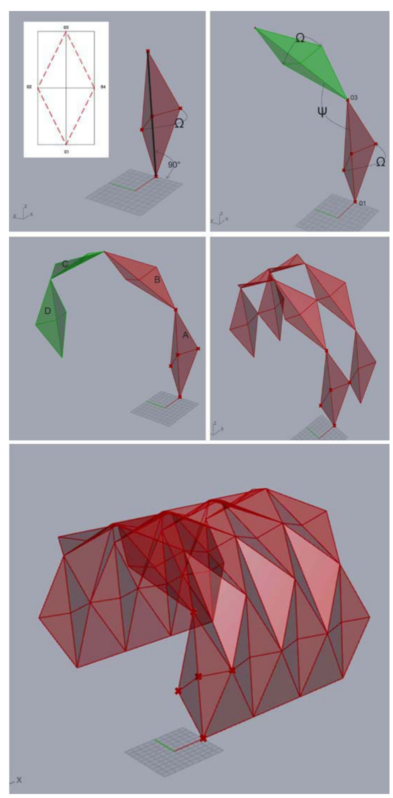

Figure 14: *Parameterization of X-form Spans using Grasshopper software.*

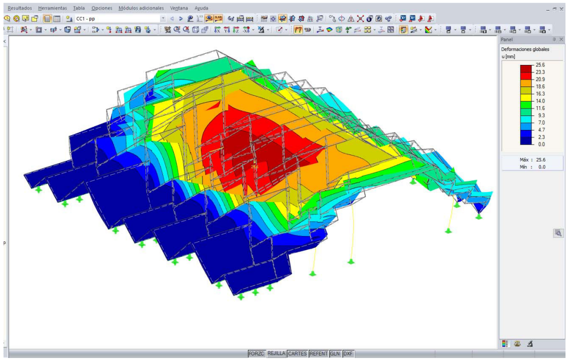

Figure 15: *Deformations of a roof with V-pleats, using RFEM 5 software.*

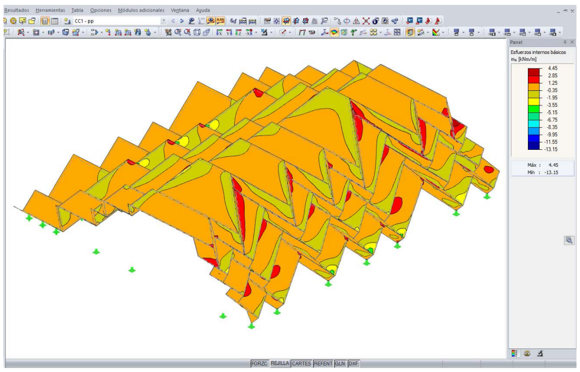

Figure 16: *Basic internal forces:* m_x *of a roof with V-pleats, using RFEM 5 software.*

6) rotation of the B module along the y axis, with an angle ψ (in a range of 0 to 180 degrees).
7) symmetrical copy of the A and B base modules, according to the y axis. The first portico is defined, based on the folded modules A, B, C and D (Figure 14).
The following steps are: make "n" copies with translation of the portico according to the x direction, with a vector equal to the length of the smaller diagonal of the initial A base module, and sew the resulting gaps between the modules following the previous translation.

3.5 SURVEYS

In the framework of the research, a preliminary survey is carried out with the purpose of collecting the opinions of experts in educational building design.
This survey seeks to obtain information about the advantages and disadvantages of this type of roofing compared to other constructive solutions from different points of view (environmental adequacy, health and hygiene, safety of spaces against intrusion, thermal and acoustic performance, aesthetics, fire protection, durability and maintenance, structural integrity and tightness, etc.) for different kinds of educational spaces (classrooms, conference rooms, auditoriums, gymnasiums, swimming pools, libraries, etc.).
Starting from an environmental point of view, we ask about the suitability of this material for the construction of medium and large-scale roofs in our country.
On the other hand, we consult about technical aspects to be considered, such as recommended materials or accessories (insulating materials, support or joint elements, etc.), possible interference with installation systems (lighting, heating, cooling, ventilation, etc.) and critical points to be considered.
Finally, ask for an assessment in the architectural attractiveness of these kinds of roof, in the development potential they have in our country and in the personal interest in this matter.

In general, as result of the opinion research, the incorporation of wood in building construction and its promotion is well accepted. However, some people have reservations about its future use and others warn of the need to ensure some aspects.
While noted the warmth and adaptability that wood brings to spaces, it is very important to control its quality, use wood with correct moisture content and protect it from insects as well as from the action of humidity and the sun. In addition, related to design of wood structures special attention must be paid to the joints between the parts and between these and other structural elements.
Timber, as a national and renewable material, is associated with the concept of sustainability. However, its use is not usual in our country. Faced with this point, some feel that it is a cultural issue because we are not prepared for design, calculation, maintenance and use of buildings that include this material.
For the specific case of wooden roofs to cover medium scale spaces in educational buildings in our country some advantages and disadvantages are mentioned.
The former include good weight/resistance ratio, aesthetic quality (although it would have to be evaluated over time), thermal and acoustic properties and, in the future, probably, cost convenience. It also mentions the flexibility for different uses from the point of view of design and its possibility of adaptation to existing premises.
Maintenance is identified as the main disadvantage. Especially in public buildings, preventive maintenance is a problem because, in general, it is very difficult to obtain resources for it. As critical points in design are identified joints, terminations, fire protection, water tightness and assembly.
For design, from the point of view of thermal insulation, it is suggested to use different materials, such as expanded polystyrene, polyurethane, glass wool, both in its rigid versions and as a blanket, or cellulose projected with fire retardant.
In general, for this type of roof it is convenient that the installation systems (lighting, heating, cooling, ventilation, etc.) are not housed inside. If this is not the case, a detailed design of passes and access points is required, as well as an exhaustive analysis of interferences and an adequate specification of means of fastening or supporting the elements of the installations.
Finally, it is concluded that in relation to educational buildings, there is a trend towards the use of multi-layer panels as a solution in upper horizontal enclosures. In this sense, laminate roofs would be an option to consider, emphasizing also their great potential from the aesthetic point of view.

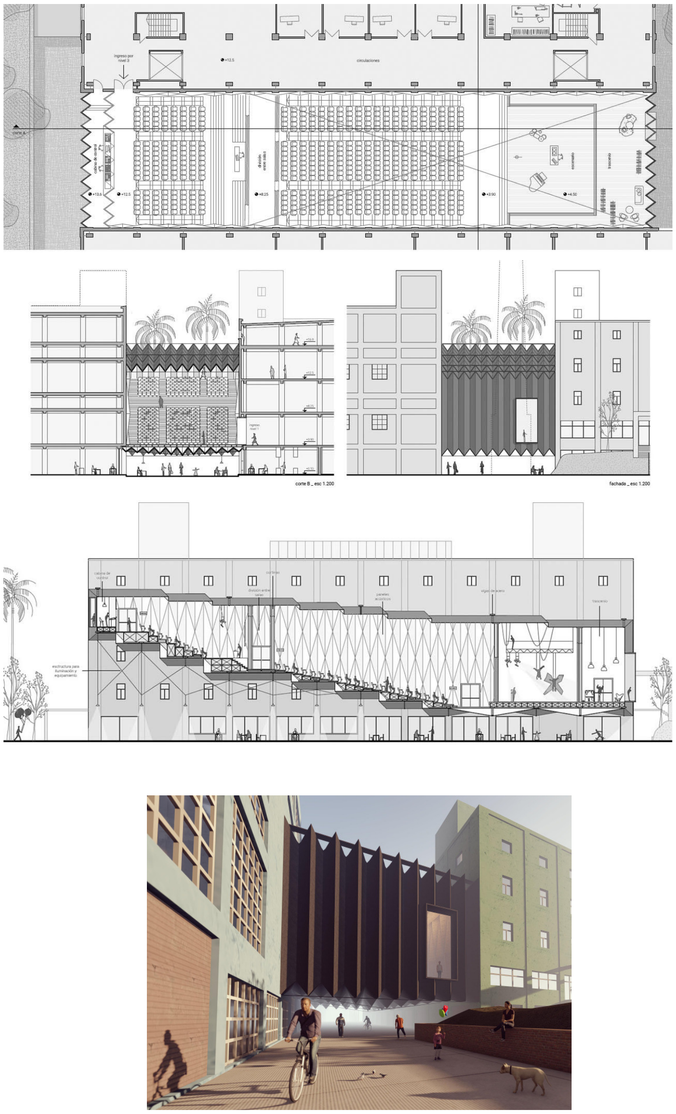

Figure 17: PTI-Cerro Auditorium. Authors: Agustín Dellepiane and Victoria De Vida.

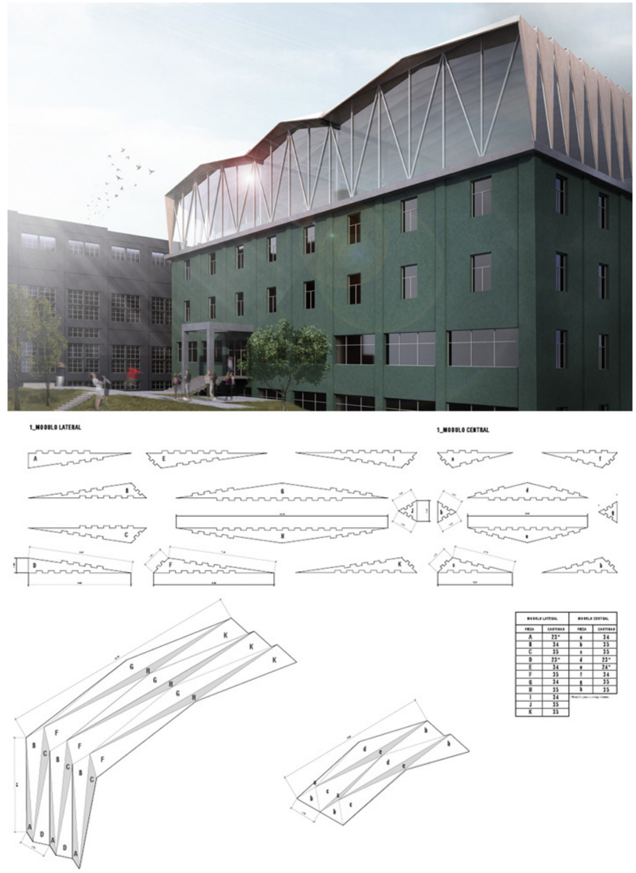

Figure 19: *Research Center. Authors: Giuliana Rodríguez and Joaquín Roybal.*

Figure 18: *Roof over Access hall, court, vehicular traffic and dining room terrace. Authors: Gonzalo Castelló and Lorena Tovagliares.*

Figure 20: *Kinder garden. Authors: Joaquín Molina and Fiorella Campos.*

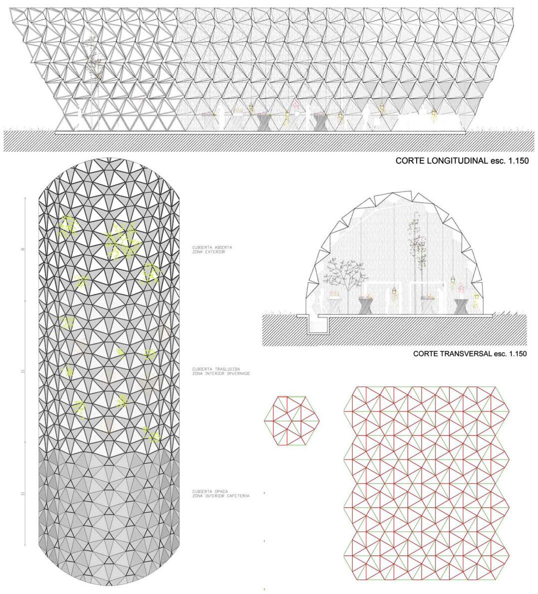

Figure 21: *Greenhouse. Authors: María Cabrera, María Clara Puppo and Lucía Reolón.*

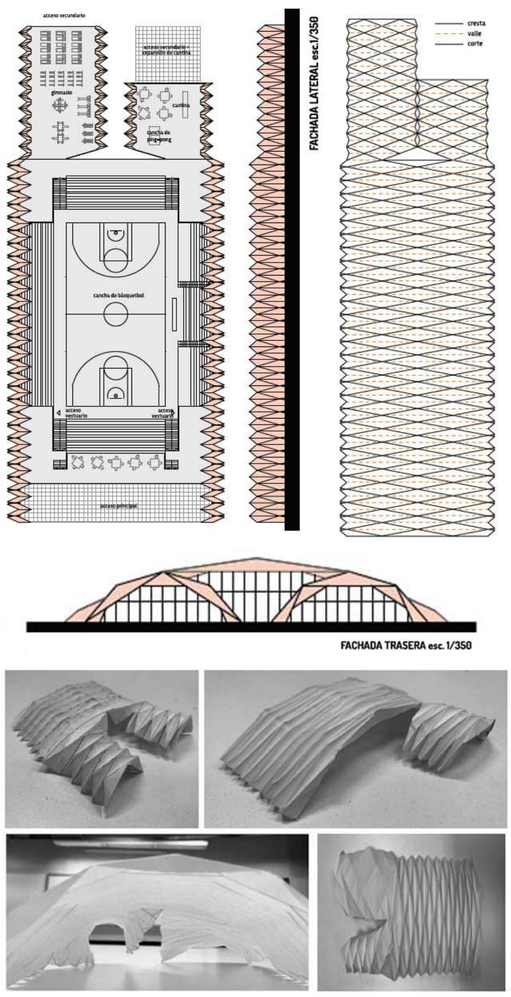

Figure 22: *Sports Center. Authors: Martín Barizo and Bruno Dutra.*

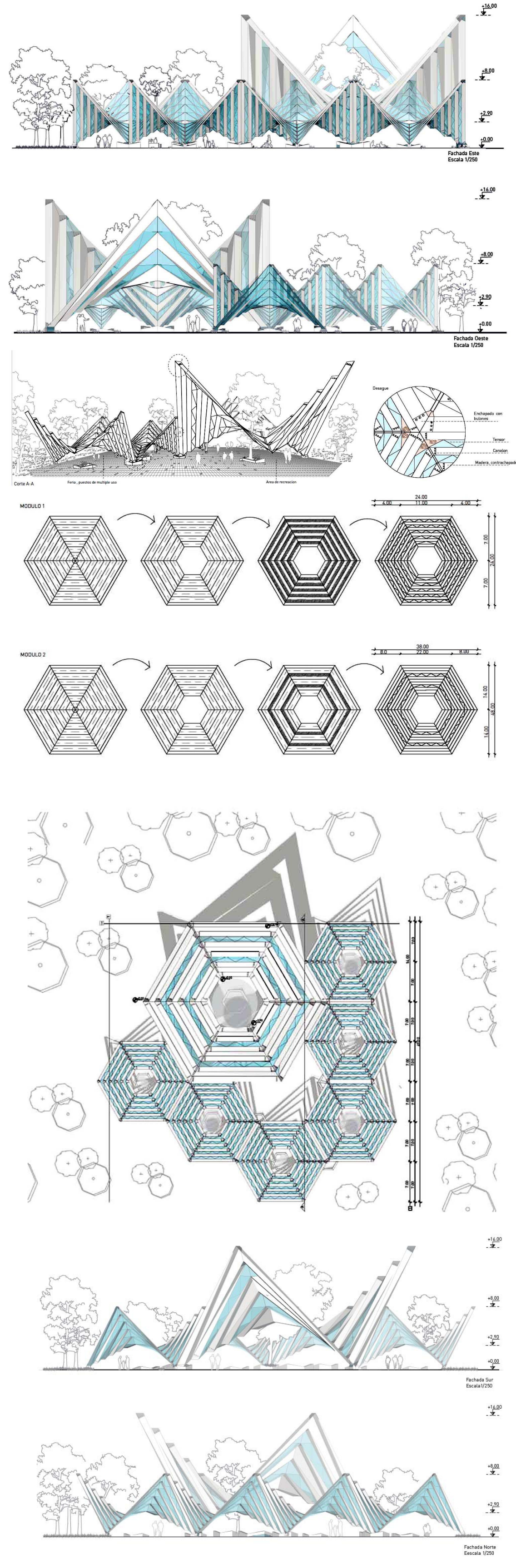

Figure 23: *Fair roof. Authors: Adriana Riverol and Nicolás Kamplin.*

3.6 EDUCATIONAL EXPERIENCES

In order to explore the architectural potential of folded timber structures as a solution for medium or large-scale roofs in educational buildings in Uruguay, during the first half of 2019 we collaborated in the dictation of the course "Specific Projects: Holistic explorations - timber" (FADU-UdelaR).

This course was structured in two curricular activities that complemented each other, while contributing to the research: 1- The development, at the existing structures in the Industrial Technology Park (PTI-Cerro) in Montevideo, of an architectural schedule that complements the educational activities carried out there today. 2- The design of medium or large-scale folded structures with panels derived from timber. This activity was based on the hypothesis of incorporating an architectural schedule to the educational complex PTI-Cerro that investigates its spatiality, based on the resolution of a timber roof designed and manufactured with environmental technology. With this incorporation, it is intended to restructure the architectural functions that are currently performed on the site and to explore a new profile for the educational center. Figures 17 to 20 shows some images of the students´ work.

Furthermore, during the course "Laboratory of structural morphologies" (FADU-UdelaR), in the second semester of 2019, we worked on the design of laminar structures with timber-derived panels, from form-finding experiments with folded paper. In this course, an exercise that promoted the experimentation with paper folding techniques was proposed, with the aim of finding appropriate ways to solve architectural and structural problems.

Students constructed physical models that allowed to visualize the found morphologies, as well as to analyse their stiffness and strength. Then, they developed an architectural-structural application from the results obtained in the previous form-finding experiments. Figures 21 to 23 shows some images of the students´ work.

4 CONCLUSIONS

We believe that the development of our own CAD-CAE-CAM methodology for the design and construction of laminar structures, through collaborative work between the Construction Institute (IC, FADU-UdelaR) and the Digital Manufacturing Laboratory (labFabMVD), will allow our University to offer a new service of modelling and manufacturing architecture, as well as promoting the use of national products derived from timber in local industry.

The surveys carried out allow us to verify the relevance of medium and large-scale timber roofs as a solution for the construction of educational buildings in our country.

The catalogue made with the structural morphologies found and optimized, allows us to appreciate the range of architectural solutions that can be modelled and manufactured with CAD-CAE-CAM methods, while the work carried out in the Architectural School courses (FADU-UdelaR) "Specific Projects: Holistic explorations - timber" and "Laboratory of structural morphologies" allow a first visualization of the architectural potential of this constructive and structural solutions.

We believe that the executive projects we are now developing, and the prototypes that we will manufacture, will allow us to verify the relevance of the proposed CAD-CAE-CAM method.

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