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HARDWOOD GLULAM IN COMPLEX STRUCTURES: DESIGN AND CONSTRUCTION OF THE MACA MUSEUM IN URUGUAY

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ABSTRACT: This work presents the process of structural design, fabrication, and construction of the MACA museum in Uruguay, with a focus on the use of hardwood species. The main room of MACA museum (1600 m^2) is a 3D complex structure made of Red Grandis (*Eucalyptus grandis*) glulam. The structure was designed by 19 bi-hinged frames, made up of inclined columns of 15 m of maximum height and curved beams of variable cross-section up to 27 m long. Given that Uruguay's first forest plantations date in the '90s, there is not yet a structural timber industry. The first timber standards were approved in 2018, and even Europe lacks a harmonized standard for the manufacturing of hardwood glulam. This paper presents the state of the art in hardwoods glulam and focuses on the difficulties and opportunities associated with the use of a hardwood species. In addition, it contemplates the importance of coordinated work between the academy and the industry (architects, structural engineers, and constructors) in the development of the design, manufacturing, and construction of the complex hardwood glulam structure of the MACA museum.

KEYWORDS: *Eucalyptus grandis*, hardwood, glulam, timber industry, structural design, construction, New European Bauhaus

1 INTRODUCTION

1.1 SOLID TIMBER OF HARDWOOD SPECIES WORLDWIDE

By 2030, the global production of coniferous (softwood) sawn wood is expected to increase at an annual rate of 1.8% [1]. Approximately 50% of this timber will be used for construction purposes as a substitute for steel, concrete, and masonry. The other 50% is destined for other uses of solid timber, such as packaging, furniture, or carpentry. In an analysis of the volume production of softwoods and hardwoods worldwide, according to data obtained from FAOSTAT, all the continents, except Asia, produce a higher volume of softwood species (Fig. 1).

This higher use of softwoods can be also observed in Europe, where while the production of coniferous sawn wood maintained an increasing trend over the years, the production of hardwood (non-coniferous) remained constant. Fig. 2 shows the graph of solid wood volume production from 2000 to 2020, generated from the FAOSTAT database.

In addition, the growing interest in sustainable low-carbon biobased materials for construction implies that the trend in demand for mass timber (glued laminated timber -GLT or glulam- and cross-laminated timber -CLT-, among others), continues increasing worldwide, mostly focused on softwood species [1].

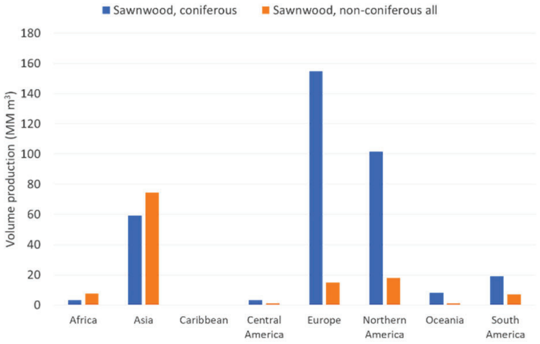

Figure 1: *Sawnwood volume production per continent (data obtained from FAOSTAT, 2022)*

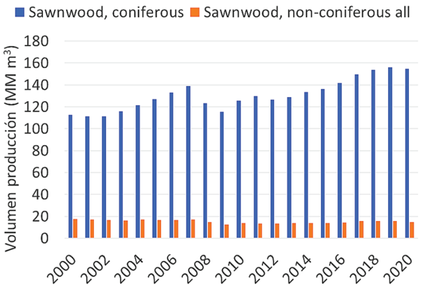

Figure 2: *Sawnwood volume production between 2000 and 2020 in Europe (data obtained from FAOSTAT, 2022)*

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Under this panorama of increasing coniferous´demand for construction, is when the possibility of considering hardwood for structural use arises. Traditionally, hardwood prices were higher than those of softwoods due to, among other factors, the higher energy consumption in drying. However, softwood sawnwood prices have increased considerably in the last few years. As an example, in the US the prices increased more than double from 2010 to 2018, to nearly quadruple by September 2020, decreasing again to values close to those of 2010 at the end of 2020 [2].

1.2 OVERVIEW OF THE HARDWOODS GLULAM IN EUROPE

According to the European standard prEN 1912:2021 [3] data, most European countries have national softwood timber visually graded for structural use, and only five countries (GE, FR, BE, ES, and IT) have graded hardwood sawn wood (ash, beech, poplar, Southern blue gum, shining gum, and sweet chestnut), as shown in Fig. 3. Although this shows the current reduced interest in hardwoods for structural use, the number of species and countries has increased slightly since the previous version of 2012 [4].

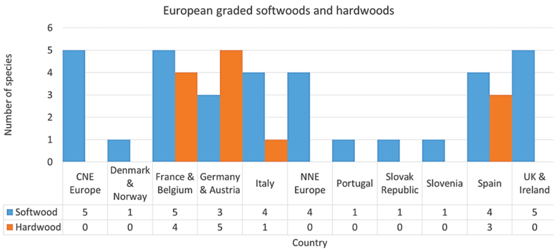

Figure 3: Softwood and hardwood species visually graded for structural use in Europe (data obtained from [3]*)*

Current European standards for engineered wood products (EWPs), such as GLT [5], CLT [6], or laminated veneer lumber (LVL) [7] are focused on softwood species, and harmonized European standards for hardwood species are not yet developed. The draft of the European standard about hardwood GLT is under development since 2014 [8], but there is not yet a consensus on the manufacturing requirements which contemplate the variability of the hardwood species. Therefore, it´s not possible to obtain the CE marking via the harmonized European standards, which is mandatory under the Construction Products Regulation (EU 305/2011) [9]. The European Technical Assessment (ETA), which is the basis for a Declaration of Performance (DoP), offers a voluntary route for the manufacturers to obtain the CE marking for hardwood glulam and other novelty products. In the absence of EN standards, European Assessment Documents (EADs) are the technical specifications developed by the European Organisation for Technical Assessment (EOTA) as the basis for the ETA certifications. The ETA for hardwood glulam can be obtained from the EADs for hardwood glulam production number 130010-01-0304 [10] and 130320-00-0304 [10], depending on the species.

Although there are several manufacturers in Europe able to produce hardwood glulam, only four (one in Germany, one in Austria, and two in Spain) obtained the CE marking throughout the ETA certification, according to the EOTA database [11]. Other alternatives are to go to the market using the report of the experimental test results from an external laboratory, and under the responsibility of the manufacturer, as presented in this paper.

1.3 EUCALYPTUS GLULAM IN SOUTH AMERICA

In the South American context, glulam production is mainly concentrated in Chile, with some industries in Argentina and Brazil, and a factory under construction in Uruguay. However, only Brazil has been manufacturing hardwood glulam beams for structural use for years. The company ITA began eucalyptus glulam production in 2008 and built some long-span structures, such as the Haras Polana with a cantilever of 12 m or the Iporanga Convention Center with a span of 14 m [12], Fig 4. However, the lack of standards and marketing strategies has slowed down the development of the glulam industry in the country, although the recent development of standards and the interest of new companies to produce glulam will probably increase the current production capacity by tenfold [13].

***Figure 4:** Eucalyptus glulam structures in Brazil* [12]

1.4 FOREST AND TIMBER INDUSTRY IN URUGUAY

During the 90s, Uruguay's forestry sector experienced significant growth and currently, there is 845,000 ha of planted forests. *Eucalyptus spp*. covers 71% of the planted area, with approximately 600.000 ha, from which 42% corresponds to *Eucalyptus grandis* and *Eucalyptus saligna.* and 17% to Southern blue gum (*Eucalyptus globulus). Pine spp*. covers 18% of the planted area, most of them of Loblolly and Slash pine (*Pinus taeda* and *Pinus elliottii)* [14]. The annual production of *E. grandis* is 11.2 million m^3 of roundwood, which is primarily used by the pulp industry and energy sector. The trees used for this purpose are typically between 10 and 12 years old. Approximately 1.2 million m^3 from the annual average supply are intended for mechanical transformation, with trees between 18 and 24 years old [15]. With growth rates of $30m^3ha^{-1}yr^{-}$, *E. grandis* becomes a promising raw material for glulam production in Uruguay.

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Since timber is not a traditional construction material in Uruguay, the standards focused on structural timber are very recent. The first standards of timber grading for eucalyptus [16] and pine [17] were approved in 2018, while the standard with the requirements for glulam production [18] was approved in 2019, even though there is not yet a local manufacturing industry for structural products. However, the Uruguayan company *Urufor* has a large tradition in manufacturing laminated Red Grandis (a genetically improved variety of *Eucalyptus grandis*) products for non-structural use, but aesthetics and carpentry use, mainly for exportation. Regarding the national pine industry, the first manufacturing company of glulam and CLT is currently under construction, and it will start to produce in 2023 (*Arboreal*). According to the Uruguayan Technical Standard UNIT 1262 [16], mechanical properties of *E. grandis* sawn wood visually graded are $f_{m,k}$=21.4 N/mm^2, $E_{0,m}$=11960 N/mm^2 and ρ_k=386 Kg/m^3, which could be assigned to a strength class C20 of the European standard EN 338 [19]. Under the lack of a national structural code for designing timber structures in Uruguay, Eurocode 5 [20] [21] has been adopted as the reference code.

1.5 OBJECTIVE

This paper focuses on the importance of coordinated efforts between academia and industry (including architects, structural engineers, and constructors) in the design, manufacturing, and construction of complex and aesthetically pleasing hardwood glulam structures. Specifically, it examines the Atchugarry Museum of Contemporary Art (MACA), which features beams with spans of up to 27 meters and is aligned with the criteria of the New European Bauhaus (NEB).

2 CASE STUDY: MACA

2.1 ARCHITECTURAL DESIGN

MACA museum is situated in Maldonado, Uruguay, and was devised by the sculptor Pablo Atchugarry, throughout the Pablo Atchugarry Foundation. The main building, destined for the sculptures showroom, consists of a 3D curved structure with a floor area of 1600 m^2, designed by Carlos Ott Architect (Fig. 5). It was initially thought to be solved with a steel structure, but it turned to be a timber structure (Fig. 6) after a positive technical feasibility study carried out by some of the authors through the Faculty of Engineering of Universidad de la República.

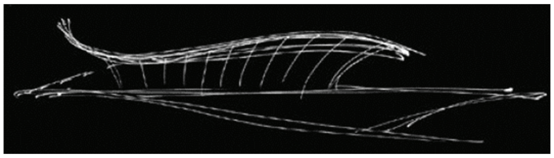

Figure 5: *Architectural sketch of MACA (Source: Carlos Ott)*

Figure 6: *3D rendering of MACA (Source: Carlos Ott)*

This study was focused on the pre-dimensioning of the frames, estimation of wood volume, analysis of the potential glulam suppliers, possibilities of transportation to Uruguay, and construction logistics.

2.2 STRUCTURAL DESIGN

The continuation of the engineering work from the feasibility study developed at the University was made through the creation of a timber engineering study named *Oak Ingeniería*, which was responsible for converting the architectural design into a timber structure, respecting the three-dimensional shape of the envelope.

The initial structural design was solved by 19 bi-hinged frames, made up of inclined columns of 15 m of maximum height and curved beams of variable cross-section up to 27 m long. It was initially designed with softwood glulam of strength class GL24h and the frames were composed of double columns connected to the curved beams by mechanical fasteners (Fig. 7). The design was made looking for a simple solution that could be provided by as many international companies as possible during the tendering process, and which implied a softwood wood volume of 237 m^3. The international tendering was won by the French company *Simonin SAS* with an initial solution using spruce glulam.

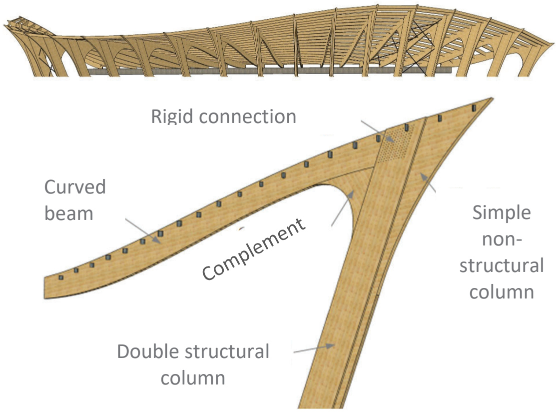

Figure 7: *BIM model of the preliminary softwood structural solution*

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2.3 MATERIALS AND GLULAM MANUFACTURING

Since MACA was intended to become an iconic structure and building for the country, the involved actors proposed the option to use local wood for its construction, with the aim to give a local character to the design. Red Grandis was selected for the structure, mainly because of its aesthetics and color, which differ from the most common softwood species used in structures. The tradition and expertise of the company *Urufor* sawing, sorting, and drying this species was key for the selection. 350 m^3 of dried Red Grandis boards (Fig. 7a) of 25/28 mm of thickness were provided by *Urufor* and sent to the *Simonin* facilities in France for glulam manufacturing (Fig. 7b).


(a) (b)

Figure 7: *Red Grandis boards and glulam at Simonin facilities*

The initial environmental cost of this business model was accepted thinking that this iconic building would contribute of promoting the use of local wood for structural purposes. Also, it would allow evaluating of a potential future hardwood-based timber industry, which could provide local structural glulam in a more environmentally friendly solution.

The manufacturing of hardwood glulam implies the reduction in the thickness of the lamellas with the aim to ease the drying process and saving costs. The thickness of the lamellas after the board planning resulted in 20/23 mm in the case of Red Grandis, much lower than the common thickness in softwood, which usually varies between 35 and 45 mm for curved and straight beams, respectively. The increase in drying time of *E. grandis* of 25 mm of thickness versus *Pinus taeda* of 40 mm of thickness corresponds to a factor of 4.25 [22]. In addition, the reduced thickness implies that the number of glue lines increased by 1.6 in the case of lamellas of 25 mm of thickness than that of 40 mm and, therefore, a higher amount of adhesive is required. Both factors have a direct incidence on the hardwood glulam cost.

Under the lack of a specific standard for glulam production, the manufacturing process followed the requirements of standard EN 14080. The initial type testing and the factory production control were made through an agreement with the industrial technical centre *FCBA* to ensure the mechanical properties and the gluing quality. In addition, an internal delamination control according to method C of EN 14080 was made.

The characteristic values of the mechanical properties of the boards and the bending strength of the finger joint ($f_{m,j,k}$) were obtained from experimental tests, resulting in three hardwood strength classes depending of the visual quality: D18 ($f_{m,j,k}$=22 N/mm^2), D20 ($f_{m,j,k}$=36 N/mm^2), and D24 ($f_{m,j,k}$=30 N/mm^2). The values were like those declared for sweet chestnut or Poplar nigra (D24 and D18) and for the lower visual qualities of beech (D18, D24) from France [3]. Glulam beams were manufactured using a Melamine Urea Formaldehyde (MUF) adhesive for hardwood species and results from the initial type testing on full-scale glulam beams resulted in the strength classes named GLD20h (ρ_k= 475 Kg/m^3), GLD24h (ρ_k= 485 Kg/m^3), and GLD28h (ρ_k= 530 Kg/m^3) for the lamellas of strength classes D18, D20, and D24, respectively. The obtained hardwood strength classes were like those of softwood species in terms of bending strength and modulus of elasticity, but with higher values of density.

As a comparison, densities resulted in values 1.3 higher than those of softwood for GL24h and GL28h. These results also showed the increase in the density of Red Grandis, the *Eucalyptus grandis* genetically improved by *Urufor*, with respect to that declared in the Uruguayan standard UNIT 1262 [16].

2.4 STRUCTURAL REDESIGN

The change from a softwood to a hardwood species during the tendering implied a revision of the initial structural design. Not only the cross-section of the members had to be modified, but also the configuration of the frame with the aim to reduce the total wood volume and, in this way, to partially compensate for the higher costs of hardwood versus softwood glulam. The double columns that braced the beams were substituted by simple columns joined by a high resistance connexion of glued bars that support the corresponding bending moment. This connection was solved with the Resix system, patented by *Simonin,* which benefited from the higher timber density of Red Grandis with respect to the softwood species. With the aim to facilitate the transportation of the glulam beams from France to Uruguay, with a total span of up to 27 m, they were manufactured in two parts, joined *in situ* generating a rigid connection with this *Resix* system. Each of the 19 bi-hinged frames consisted of the connection of seven glulam pieces, as shown in Fig. 8, with parts 1, 2, and 3 constituting the main structure of the portal frame. The columns were divided into two parts with the aim to separate the parts located in the interior from those in contact with the weather environment. The objective was that the exterior part of the columns could be repaired or replaced easily in the case of damage due to weather exposure, without affecting the structure of the bi-hinged frame. Fig. 9 shows the final configuration of the frames and the detail of the rigid Resix connection.

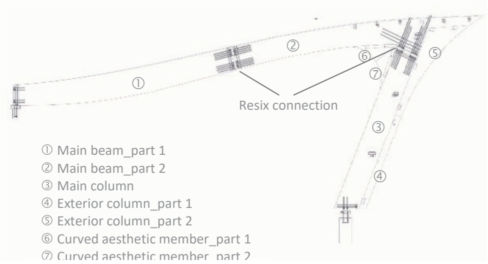

Figure 8: *Scheme of one of the bi-hinged frames*

Figure 9: *Final design of the frames and rigid Resix connection*

The BIM model was modified according to this final design and all the notches were designed to be manufactured by a computer numerical control machine (CNC), which was the key to the successful building process over 10,000 km away from the manufacturing company. Fig. 10 shows the machining of the main beams for the Resix connection and the location of the purlins.

Figure 10: *CNC machining in the beams and purlins*

2.3. CONSTRUCTION PROCESS

The timber structure was erected by *Simonin France* in collaboration with the Uruguayan building company *Atchugarry Arquitectura y Construcción*, which served for the local training in timber construction. With a total of 196 m^3 of Red Grandis glulam (48 m^3 for the purlins, 68 m^3 for the columns, and 80 m^3 for the beams), the construction process started in October 2020 and the MACA Museum was inaugurated in January 2022.

The complex 3D design of the building implied that each glulam piece is different from the other, resulting in a total of 322 purlins, each one with a unique cross-section, length, and angle of insertion on the beams, which also implied the design of unique steel fasteners for each member. Different stages of the construction process are shown in Fig. 11.

Figure 11: *MACA construction process*

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During the construction process, black stains were observed on the hardwood timber structure associated with the rains that occurred during the installation of the steel structure for the envelope. It was caused by the contact between the natural wood tannins of the Eucalyptus diluted in water with the oxidized iron contained in steel filings, a problem that doesn´t occurs with softwood species. After different tests developed in the frame of a Master Engineering thesis [23], they were removed by applying oxalic acid, as shown in Fig. 12.

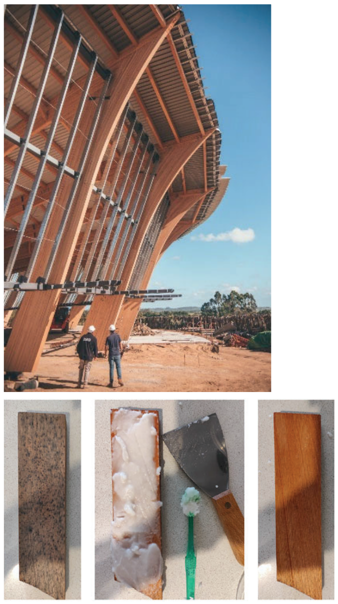

Figure 12. *Steel structure for supporting the envelope and experimental tests with oxalic acid to remove the stains* [23].

Fig. 13 shows images of MACA museum once finished.

Figure 13: *Images during the construction process of MACA*

3 ALIGNMENTS WITH THE NEB VALUES

The design and construction of the sculptures hall of the MACA museum were aligned with some of the New European Bauhaus (NEB) values, launched in 2021 by the European Commission.

1) Together

According to Pablo Atchugarry, owner and developer of the museum, the intention of MACA, located in a 40-hectare greenery field, which is also an international sculpture park, is “to be a bridge for local and international art, an open and free museum where the art can be available all the year”. To reach his objective, a collaborative design work process between the owner and the architect in the first stage of the project conception, and then with the academy, engineers, providers, manufacturers, and constructors, made it possible for MACA to become a reality.

2) Sustainable

During the collaborative design work process, the building´s structure was converted from steel to wood. With a total structural wood volume of 197 m^3, the content of biogenic carbon, which was calculated according to EN 16449, was 148 tn. This calculation doesn´t consider the influence of transportation, which would affect the result because the wood made a round trip between Uruguay and France due to the lack of national glulam manufacturers, as had been the case of steel, usually imported from China because of the lack of national steel industry. *Eucalyptus grandis* provided by Urufor comes from sustainable forest management, certified by FSC [24].

3) Beautiful

The 3D building’s shape and the aesthetics of Red grandis wood made the MACA museum cited by several international institutions and magazines as a monument to timber architecture or highlighted its aesthetics [25] [26] [27] [28] [29]. In addition, it was selected as one of the best museums of 2022 worldwide by the Conde Nast Traveller magazine [30].

4 CONCLUSIONS

This paper presents the design, fabrication, and construction of the MACA museum's structure, with a focus on the challenges and opportunities that arise when using a hardwood species. The successful implementation of the project was only possible due to the collaborative efforts of all stakeholders from the outset. The architectural and engineering design was developed through an iterative process between the owner, architects, and engineers, with close collaboration with the wood supplier and the manufacturing company. The outcome was a flawless building process, with only one purlin requiring modification due to a human error in the digital order of the CNC machine.

The final redesign with Red Grandis, with values of density 1.3 higher than that of a GL24h from softwoods, resulted in a reduction of 41 m^3 in total wood volume with respect to the initial solution in spruce. However, the increased cost of this hardwood glulam with respect to a softwood (4.25 times the drying time and 1.6 the amount of adhesive), coupled with transportation costs for manufacturing in another continent, didn´t offset the volume savings. Nonetheless, the choice of Red Grandis, a sustainable and local raw material, resulted in an aesthetically pleasing building, where the wood's natural color and curved building´s structure highlight a unique design in South America, as a result of a collaborating design, complying with the NEB values.

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