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Brick Warp System – A Morpho-Static Paradigm

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Abstract

The present investigation proposes a new constructive and structural system in order to respond to the construction difficulties of double curvature surfaces. The objective is to initiate a brand new cycle of design and manufacturing in this field.

The aforementioned system has an internal logical which is framed by several design axioms. The static behaviour of the materials which could be used in this process is informed by the internal work produced by atoms in order to carry forces and loads. This determines the geometry of the architectural piece consequently giving a composite reason and an ethos to its consequent aesthetics. It being so, a mix of technological conditions, integrating digital design tools and serial production is then able to create a mass production system which allows for customization and productivity without loss of quality. This allows us to combine high levels of production with the special tailoring of constructive parts, enabling for a better design and constructive management of the projected double curvature surfaces while still guaranteeing a high level of productivity.

This method also considers the materials and their characteristics, dealing with the material phenomena of drying and curing, in order to optimize the milling task.

Such a "post-tensioning system" when compared to other systems is less demanding in terms of requirements for the construction of these geometries, and yet it will distinguish itself by its efficiency, easiness of construction, low cost, flexibility and adaptability to the manufacture of (parts for) double curvature forms and surfaces. Therefore, with this process it will be possible to successfully face the constructive and financial difficulties implied by this typology, hopefully more and more present in contemporary architecture.

Keywords: Double Curvature, Structural Morphogenesis, Digital Manufacturing, Digital Modulation, Digital Design, Parameterization

1. Introduction

The tectonics of curved structural forms is the main obstacle for their physical implementation. The compositional reason of double curvature structural forms must find its validation in the construction and manufacturing processes. These tools and materials correctly used will allow for their physical manifestation, enabling the Idea to rise to the status of Architectural form.

Today, the technological conditions for producing this formal universe present many constraints. Among them are the manufacture of the respective formwork, i.e., the modelling of the surface parts, associated with the use of centering, easels and/or scaffolding during assembly and fabrication. This clearly increases the costs and construction time periods, a context that contributes to the avoidance of these shapes in current architecture, reserved therefore for exceptional buildings, where costs and resources are not an equal obstacle.

Traditional design models presented difficulties in managing these curved shapes such as allographic representation, i.e., the fact that the person who conceives does not build, he only represents. These processes are in many cases a forgotten constructive dimension in architecture.

The new digital design paradigm defined by tools like CAD/CAE/CAM presents on the contrary an autographic representation design process where the person who conceives also builds at the same time. We can say that with digital tools, the designer also builds an object at specification albeit in a digital environment.

Digital tools and manufacturing technology have changed the relationship between the ideational processes and the subsequent production cycles. The alographic design paradigm established a more restrictive interaction between concept and construction. Digital tools however introduce a different workflow that results in an integrated and dialectic logic that involves both design and manufacture [1]. Because of this, the application of digital tools to architecture changes the paradigm of the correspective cognitive process, i.e., the (intertwining) way of thinking and conceiving an architectural artefact.

Project is no more a merely representative draft but it is turned into a digital artifact, defined by an information model, which is also a generative process of design and construction. The architectural object is turned into a precise number of rules and instructions that support both the design and the manufacturing process. Parametric algorithms create an interactive relationship between such different strata as concept, geometric logic, material properties and parts together with production and assembly methods as well as evaluating costs.

The digital artifacts produced according to this logic are more than a rhetorical figure of digital processes, they are assumed primarily as an architectural object. Researchers and the construction industry have been alerted to the benefits and the chances of this methodology. This allows not only to support the development of the ideational process in a creative way, but also the production of prototypes and full-scale architectonic artifacts, fast forwarding research for a post-industrial production processes [2]. And, also in reverse this helps, dialietically, to rethink the ideational process**.**

2. The double curvature construction processes

A double curvature form has a huge structural efficiency, but its production process is difficult and expensive. Labour costs associated with the production of concrete shells, since the 1970s made it unbearable to build using this type of geometry [3].

Figure 1: a) Candela´s construction formwork wedge b) Sustainable Urban Dwelling (SUDU) c) Armadillo Vault

Philippe Block had experimented these difficulties during the construction of his project: Sustainable Urban Dwelling – SUDU located in Ethiopia (see Figure 1b). Despite using a construction technique thousands of years old, the lack of a still knowledgeable and qualified workforce turned the manufacture into a challenge [4]. Felix Candela on the other hand in order to make shells out of concrete, developed several techniques to manufacture formworks which allowed the implementation of hyperbolic paraboloids from straight boards (see Figure 1a).

The use of digital platforms and the now available new tools design and manufacturing provide the basis for new solutions, allowing the construction of double curvature forms in reasonable time and at reasonable cost.

The partnership between Philippe Block Research Group and Escobedo Construction Company developed two different structures, without the use of mortar and prestress [5].

The first, in 2010, was the Chestnut Plaza Vault Park, a multi-purpose community space in Austin Texas, which was exhibited at the Venice Biennale 2012. The second, also exibited at the same exposition, but in 2016, was the Armadillo Vault with trusteeship, by the architect Alejandro Aravena (see Figure 2c). To build vaults from blocks, natural stone was cut with a diamond saw and then installed using a mechanical arm with four axes and the fabrication process was done in a pre-trial manufacturing installation.

Another innovative experience which combined digital manufacturing processes with traditional and natural materials, was the Cork Vault Pavilion design by Pedro Varela, Maria João Oliveira. Emmanuel designed and built for Concreta 2013 – Leça da Palmeira, Portugal (see Figure 2).

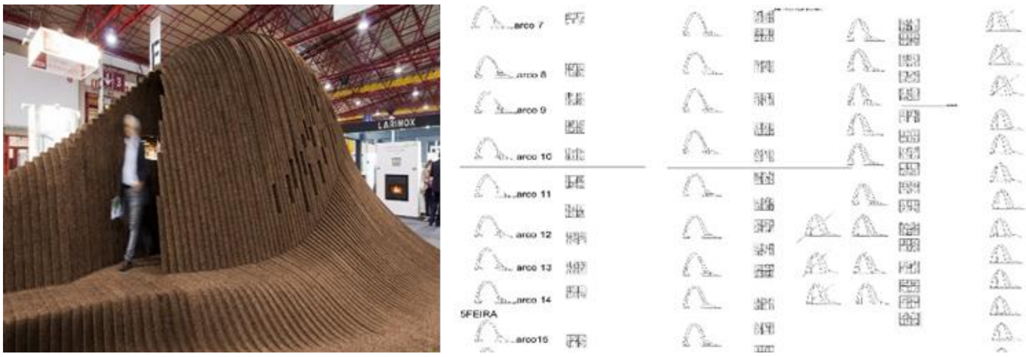

Figure 2: a) Cork Vault Pavilion Concreta 2013 b) Cork cutting path

They used black agglomerate cork boards with 100 mm thick, for purposes of manufacturing and assembly. The manufacturing pavilion took about 30 minutes to cut each set of 10 plates and all the manufacturing process took about 125 hours of cutting, the equivalent of up to 8 work days [6].

3. The proposed post-tensioning system for construction of curved structural forms through modular digital manufacturing

The system in question simplifies the construction and the fabrication of double curvature structural forms by eliminating the need for support systems during the production stage.

The application of post-stress to the vault´s voussoirs eliminates the applied external moment, generated by the self-weight, which is a consequence of the action of gravity on the material. The counter-rotation generated by the application of post-stress replicates the levels of compression that each voussoir would undergo, consequently eliminating the need for support systems in the construction phase.

The cable that is embedded and connected to the end pieces by brackets (said system in patent pending process N.º 2023005706077), works as a floating scaffolding. The axial tension efforts act by balancing the moment, which nullifies the rotation generated by the surface's own weight. The collapse of the surface would be induced without this stress. The absence of moment allows the shape profile to be constant, since the stresses are also constant along the surface.

The construction process is based on the previously customized voussoir´s assembly: as the parts are being placed, they are sewn together by a cable passing through them all, thus clamping and stabilizing the shape (see Figure 3).

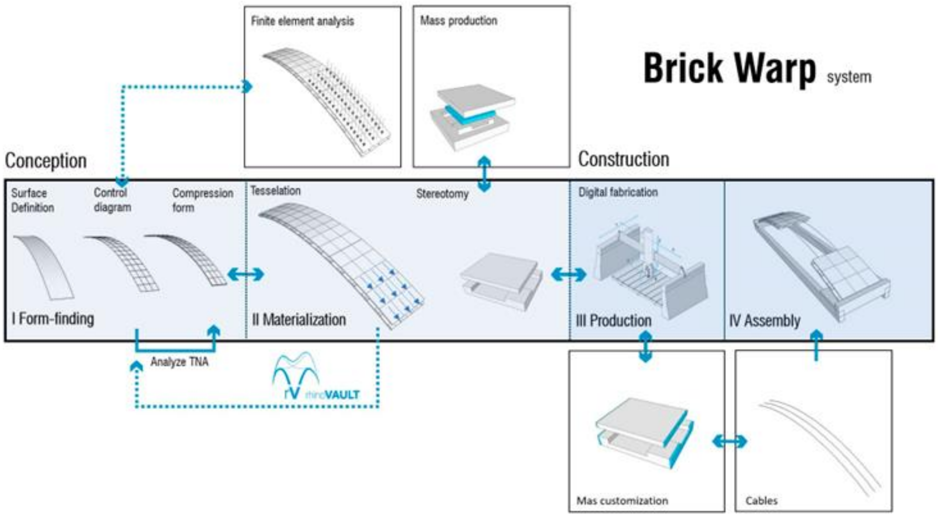

Figure 3: Brick Warp System workflow

The production process includes two stages, the first being a mass production system, where the part is made by clay injection into standard moulds. A serial manufacturing process is adopted in order to produce customized pieces which are then standardized without any loss of productivity. This is an important moment of the manufacturing cycle as it leads to cutting production and construction time and costs. Through the use of a parametric modelling tool it is possible not only to manage the process of creating a double curvature surface, but also to determine the stereotomy of the universe of parts that allows for its construction.

In the subsequent phase, pieces are tailored by a CNC milling machine, based on the data previously generated by parametric software. This cut will match the voussoirs of the surface, converting the standardized tiles on the necessary parts for assembling the projected surface.

The milling process produced by CNC allows for a large spectrum of techniques for cutting, such as the milling pocketing technique, which requires a 2,5D milling machine, considered in this case particularly suited for the universe of structural elements to be manufactured.

The part's geometric patterns are a direct consequence of the design form and the ensuing surface will be a synthesis of particular spatial intentions, structural behaviour, forces workflow, manufacturing processes, material properties, stabilization cables and correspective visual appearance, all of this managed by digital tools.

The constructive system now proposed, incorporating post-stress cables, will certainly allow to minimize the hand labour costs (in terms of time usage and specialization), and also cut manufacturing time because there will be no need for centering, formwork or scaffolding. Therefore, it can be argued that the said system defines an innovative production process based on mass customization series production.

4. Standardized pre-refabricated modules.

4.1. Standardized prefabricated modules.

The standardized pieces, i.e., the vault´s voussoirs, may present several tectonic versions, as these modular parts may have several base materials, such as reinforced concrete with bamboo (a.k.a., bamboocrete) or black cork agglomerate, etc. (the use of expanded or extorted polystyrene is hereby preliminarily excluded because of its environmental impact). Therefore, the production cycle must be adapted to the material properties as the pieces will certainly present different workability levels. Also, the different hardness and drying cure characteristics should be considered as a determining factor, not only on the choice of material but also in its milling or cutting process.

Assemblage joints have a great importance for waterproofing the surface of this constructive system. In order to avoid infiltrations, a valid recourse may consist in a cross-sectional geometry with a zig-zag. This allows to avoid a linear path to the rain which therefore makes it harder for it to penetrate the surface. This geometry could be further completed with a butyl element, facilitating the waterproofness of the system.

Figure 4: Mockup of the Brick warp system

4.2. Prefabricated ceramic modules

The ceramic parts have a set of characteristics that reveal great interest for this type of building elements such as weight, porosity, and also a large and time honoured know-how in these building materials and processes. In the construction of these vaults the material used is sturdy bricks. We can find examples of this in Alentejo, Portugal and in Catalonia, Spain, with a mixture of styles and construction processes, since the muslim occupation (initio 711 A.D. et fine 1249 in Portugal and 1496 in Castille, Spain).

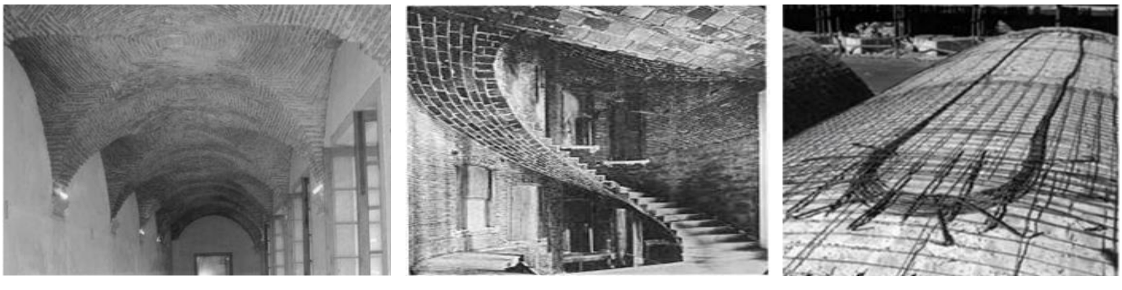

Figure 5: a) Vaults built in Moura – Portugal b) Stairs designed by Rafael Guastavino c) The double-curvature masonry vaults of Eladio Dieste

This technique consists of setting thin pieces of clay paste slabs through a mortar that binds and sets them (see Figure 4a). This process was the base to the work of modern designers as Eladio Dieste and Rafael Gustavino. Rafael was responsible for the introduction of this technique in the United States in the XIX century; he even went as far as patenting this method as Gustavino Vaults (Figure 5b). In the XX century Eladio Dieste after contact with this tectonic process, developed a method of his own for the production of reinforced brick coats, taking advantage of natural resources and the building tradition of his native country, Uruguai (see Figure 5c).

The ceramic parts have a lower weight ratio vis-a-vis concrete, the material normally used for the construction of this structural typology. Also the porosity of ceramics imparts the possibility of a higher hygrometric control which allows in turn for a more secure stabilization of the moisture content in the building [7].

The adoption of this material for the proposed system also has implications in the manufacturing process, because it makes it possible to start milling the parts before baking, thus taking advantage of the greater mildness of the material at this stage. This contributes significantly to the efficiency of this method, because parts are more easily cut, which permits accomplishing this task in a faster time and with less energy consumption.

After baking, the parts gain a chemical set of changes that enhance its physical stability, its strength, hardness and durably, which can be measured in centuries, as we previously acertained. All of which contributes to the suitability of this material for the manufacture of such surfaces.

4.3. Prefabricated concrete modules

Another possible material for producing the system's prefabricated modules may be found in the use of reinforced concrete, which may be proposed in different forms and compositions. This material also has a long tradition in the manufacture of shells, having as its main references Felix Candela, Heinz Isler and Pier Luigi Nervi. Recent innovations in this constructive technology make it more desirable, since they incorporate new materials in the composition, which not only increase their performance as well as reduce their impact in terms of weight and natural (sustainable) resources. We can consider in these cases materials such as reinforced concrete with bamboo (bamboo Reinforced Concrete).

Bamboo is a sustainable material which has a high rate of growth and is abundant, light, easy to carry and with relatively high strength and resistance levels. This material during its growth and development is subjected to natural forms of stress such as constant winds and other factors. In response to the environment, the material in question developed a hollow tubular structure that gives it a great resistance factor.

Taking these facts into account, The Future Cities Laboratory, a delegation in Singapore of the Teechnische Eidgenössische Hochschule (ETH) demonstrates the potential of this material to become in future an ideal replacement of reinforced concrete.

More so, we could add, the potential exists in places where steel cannot be produced (see Figure 6a) or lighter variations of it cannot be used or where its use is irrelevant, vis-a-vis the type of building, or where it may be ill advised for economic reasons.

As a technical curiosity, bamboo resistance tests prove it to be more suitable than most of other materials, including reinforced concrete with steel.

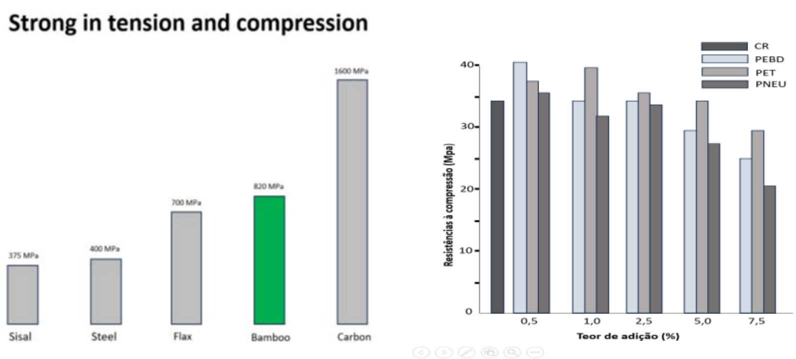

Figure 6: a) Material stress data b) Performance table of concrete added with recycled materials

This solution implies a lower use of energy in constructive solutions and also facilitating the milling process compared with other materials which are able to respond to tensile stresses. The inert used in the composition of concrete can also help dramatically to reduce the weight of prefabricated parts, if we use materials as expended clay or cork waste.

The increasing resistance of these parts may also involve the inclusion of milled PET bottles. The treatment given to this material allows it to be used instead of other polymeric fibres, replacing them with the same efficacy as its mechanical behaviour is revealed to be equal or even to excel it. Tests prove the resilience of reinforced concrete to compression after 28 days of curing, varying the fibre content, such as doped CR (dark gray) conventional concrete, PET (light gray) concrete additive with PET bottle fibres. It is apparent that concrete additive with PET has a superior performance in most of the solutions, since only a 7.5% content is lower in performance than concrete (see Figure 6b).

The use of these materials allows for further interest in analyzing an increase of the useful life of reusable materials, which otherwise would be looked as waist, in areas regarded as a dwell. Also, it should be taken into account the lower production costs of these parts, as this material appears to be fairly cheaper than the polymer fibres most currently used.

4.4. Prefabricated concrete modules

Cork is an organic material and Portugal is responsible for over 50% of the world's production. The cork industry is equipped with a set of characteristics that makes it very applicable to the universe, of material tectonics. One of these has to do with the fact that the material is an entirely natural product. Cork grows in layers in native (specifically called bark-) oaks, acting as coating for the tree, protecting it from heat, moisture and even fire [8]. The bark can also be used for many different purposes, from the most commonly known cork, to floor, wall and thermal paneling insulation, footwear, etc.

Unlike other organic materials its harvest doesn't involve the cutting down of the tree. Instead, it is peeled like an orange using special axes. Cork has the capacity to regenerate, so it is possible to exploit this feature throughout the lifespan of these trees, measured in centuries. This reflects the sustainability of the entire process.

The expanded cork agglomerate, known internationally as Insulation Cork Board (ICB) results from an operation where the cork is subjected to elevated steam temperatures, ending the aggregation process within an autoclave [9]. One of the features is that this can be done without adding any other material. This facilitates many downstream processes in environmental safety up to the recycling process, since it can be totally reusable or practically degradable.

Its physical properties are combined with a high adaptability to different manufacturing and construction processes. This material also allows the development of new and original products, as was evidenced by the investigation produced in the several International Cork Workshop: New Uses in Architecture held at the Lisbon Faculty of Architecture (FA-UTL) (see Figure 7).

The existence of a set of new materials able to be amalgamated with cork opens the possibility to generate new composite materials, the characteristics of which will be able to meet the demands of new construction processes up to aeronautical and space use.

Figure 7: cork board transformation process. International Cork Workshop: New Uses in Architecture, Lisbon Faculty of Architecture (FA-UTL)

In the 1960's this technology suffered a sharp decline; thanks to the survival of some small factories, it was possible to maintain the wealth of these techniques.

Tradition and tecnical know-how could be combined, mixing the old cork products with new materials making it possible to develop new constrictive processes based on cork and respective wastes. This material shows itself capable of meeting the objectives of this construction system given its lightness and its ability to be moulded and bonded, the intended approach goes through the reuse of waste resulting from the manufacture of other products.

For the implementation of the given constructive system, based on standardized elements milled by CNC machines, it is convenient to replace the regular cork boards for prefabricated cork tiles, that increases the efficiency of the production of the pieces that are the building system basis.

5. Morpho-stasis

Morpho–Stasis verifies the trilogy composed by Static, Aesthetics and Ethics [10]. In this conceptual methodology, the structural equilibrium is achieved by the geometric manipulation of the form, which allows atomic work optimization in the constructive process. This research field integrates the conception and construction of Structural Forms, increasing the structural performance of the architectural artifact, making them more efficient, less costly and faster to build. This allows for authorial enhancement of expressiveness, harmony, luminosity and lightness of the assigned space and also in the ways its limits are defined.

The present research intends to promote the use of new formal universes in Architecture and Design, simplifying processes and also minimizing economic, energetic and ecological impacts, i.e., it strives for better resource management.

Since structural shapes result from material modulation, knowing how to arrange the material in space in order for it to interact with gravity allows us to be able to generate, direct and redirect the path of any forces present. Therefore, the capability to manipulate its intrinsic capacity to transport charge through the work of the atoms of any given material increases the scope of formal architectural expression.

This allows for the physical manifestation of the conceptual paradigm set by morpho-stasis where conception is based on a compositional reason [11], or to put it simply, an aesthetic that is supported by structural ethics and a constructive cycle. The abstraction of the idea (i.e., the conceptual level) leads to the physical manifestation of the architectural object and this revelation is made through tectonics on a constructive level.

Therefore, the generation of form through structural principles (structural morphogenesis) depends on the technological condition and the management of its potential [12].

6. Conclusion: submission of contributions

The proposed construction and manufacturing process is characterized by an innovative manner which articulates digital tool design and classic manufacturing processes. It encompasses the new while not discarding acquired knowledge by combining a modelling software with mass production systems together with digital cutting processes in order to obtain a higher efficiency in double curvature production.

In order to optimize the production method and reduce production costs, a surface is made by standard pieces customized in a milling machine. The use of cutting tools is limited to the maximum, namely the assemblies, thus reducing the wear of expensive machines, milling time and energy costs.

The characteristics of materials and their production processes have been taken into account in order to optimize not only the production of standard parts but also its efficiency in the system. Taking advantage of the material drying process, the milling process is performed before the baking of the parts, this detail turning the milling easier and making all the process more efficient and inexpensive.

Another important aspect to be also taken into account is the dispensation of supporting infrastructure such as formwork, centering and scaffolds, which minimizes costs and production time, this efficiency all resulting from assembly design.

The interactive nature of the design and production is supported by a digital platform (Rhinoceros/Grasshopper) which makes it possible to articulate the form finding process, material properties and fabrication processes.

This structural and constructive system may be very well taken into account as a worthwhile answer to the difficulties of the double curvature construction cycle, since it demands less equipment, fewer costs and less workers with fewer qualifications. The simplicity of this building system, requires lower labour qualification compared with almost any traditional construction method we can confront it with. The mounting methods also improve the efficiency reducing the time and the number of persons engaged in construction tasks.

Finally, the validation of this research allows the possibility of collaboration between academia and industry.

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References

[1] Malé-Alemany, M. Sousa, J.P., "Hyper [D-M] Process", *in Proceedings of the 20th Conference on Educationin Computer Aided Architectural Design*, eCAADe , Graz, pp. 343-346, 2003.

[2] Williman, J., Gramazio, F., Kohler, M. and Langenberg, S., Digital by Material In Brell-Çokcan, S and Braumann, J, (eds) Rob | Arch 2012, *Robotic Fabrication in Architecture, Art, and Design*, Springer-Verlag, Wien, pp. 12-27, 2013.

[3] Bagrianski, Serrguei, 2010 [Online] Princeton University. http://formfindinglab.princeton.edu/people/serguei-bagrianski. [Acess15 December 2023]

[4] Group Research Block (2010) [Online] ETH. Available: http://www.block.arch.ethz.ch/brg/research/appropriate-construction-for-africa [Acess15 December 2023].

[5] Group, Block Research (2013) [Online] ETH. Available: http://www.block.arch.ethz.ch/brg/research/digital-stereotomy [Acess15 January 2021].

[6] Varela,P.A, Paio A., Sousa J.P., *The Cork Vault Pavilion, Interna-tional Conference of the Architectural Science Association* [Online] 2014 Available: http://anzasca.net/wp-content/uploads/2014/12/08_31_191.pdf [Acess15 December 2023].

[7] Pedreschi, Remo ; Theodossopulos, D., *The Duble Curvature Masonry Vaults of Eladio Diest, Structures an Building* [Online],vol.160 Available: http://www.arct.cam.ac.uk/Downloads/ichs/vol-3-2451-2468-pedreschi.pdf [Acess15 December 2023].

[8] Pereira, H., "Cork: Biology, Production and Uses", 2011 [Online] pp.45-47Available: https://www.google.pt/?ion=1&espv=2#q=%5B7%5D+Pereira,+H.:+Cork:+Biology,+Production +and+Uses.+Elsevier,+Amsterdam. [Acess15 December 2023].

[9] Fortes, M.A., Rosa, M.E. and Pereira, H. (Eds.): *A Cortiça. IST Press, Lisbon*, p 26. Group, 2003.

[10] Basto Diogo, A. Carvalho, C. Morais, A., "Modular fabric tensile structures". In: *Alicja Maciejko (eds) Human Factors in Architecture, Sustainable Urban Planning and Infrastructure. AHFE 2022 International Conference*. AHFE Open Access, vol 58. AHFE International, USA.http://doi.org/10.54941/ahfe1002335, 2022.

[11]Mahfuz, Edson, "Ensaio Sobre A Razão Compositiva", *UFV, Impr. Univ. Belo Horizonte, AP Cultural*, 1995.

[12] Basto Diogo, A. Morais, António "Adaptive Textile Mold System for Double Curvature". *Proceedings of AHFE 2021 Virtual conferences on Design for inclusion, Affective and Pleause Design Interdisciplnary Practice, and Human Factors for Apparel and Textile Engineering*, July 25-29, 2021, USA, Spinger, 2021.