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Kirucrete System

Standard system for biuilding concrete shells

[Alexandrino José Basto Diogo, António Morais]

***Abstract*— this article aims to explore new construction processes, capable of facilitate and optimize the production cycle of structural forms based on the double curvature.**
We intend to explore the potential of an adaptable rigid formwork system capable of producing sinlastic and anticlastic surfaces.
An integrated approach that takes into account the generation of form, structural mechanics, and its construction process, in order to generate architectural artifacts of great structural and constructive efficiency, with a strong artistic expression.
This system combines cable net with cut linear pieces in a way that material bends .
The system is based on a cable network supported by a frame and covered with an adaptive formwork covered with shotcrete.

***Keywords*— Duble curvature, Concrete shells, Constrution logistiscs, Cable net, Formwork, Structural shapes.**

I. Introduction

The concrete shells when well designed have a structural efficiency resulting from the membrane effect; can allow large spans a large material saving.
However, the production cycle proves to be very demanding in terms of infrastructure and labor work.
Rigid formwork normally used in the construction of these surfaces, prove to be difficult to produce requiring specialized and intensive labor, not being possible to reuse falsework.
The amount of labor and production costs associated turn difficult the use of these shapes, although all the plastic, spatial and structural potential, therefore these structural type are excluded from the architecture today.
It is however possible to adopt a production process that allows to minimize the costs of traditional processes for the production of shells.
To solve the limitations of the traditional production process, we adopt an adaptive formwork mass produced which doesn't require falsework.

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The system does not require such intensive labor, or skilled labor, the production is faster and is particularly suited to product sinlastic and anticlastic surfaces.

II. Objectives

his work is part of a line of research of the technology department of the Faculty of Architecture of Lisbon aims to develop technological solutions that give a solid response and consistent with the challenges posed by the implementation of the architectural idea.
The solutions are developed according to the principles of efficiency, ease of production, cost and robustness. It aims to establish partnerships with industry to leverage the economic impact and technological solutions and exponentials the spread of solutions.
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III. Context

The earlier reflection suggests that one of the decisive factors in the production of Shell concrete is the formwork system used, a study of these processes allows us to split these methods into large families.
We have three main categories rigid formwork made from wood boards, flexible resorting to the use of fabrics membranes and a hybrid system utilizing small rigid parts articulated to a cable network.

IV. Historical overview

A. *Flexible formwork*

The British engineer James Hardress of Warenne Waller (1884-1968), was the first to apply to fabrics in the construction of concrete shells. He developed a building system based on light parabolic arcs that could be transported, made of wood or steel.
The arches were placed in parallel and then lined with sackcloth which is subject to a slight tension, the weight of coating mortar generates a ripple that characterizes this process and acts as a lost formwork.

Figure 1. Warehouse of Chivas distillery. .(https://www.theguardian.com/business/2013/jun/14/whisky-speyside-chivas-brothers-scotland)

The system was competitive for their low production costs; its implementation did not require an intensive labor.

Waller patented the system Ctesiphon in 1955, in the late 70 system it had been used in over 500 structures throughout the world. One of the examples and the warehouse of the distillery Chivas has a height of about 30m and 150m span, the thickness of the shell is an impressive slenderness with only 6.4 cm, measuring the tissue between the spans 2,54m [1].

Figure 2. Eindhoven prototype, mesh casted with shotcrte. (*http://www.arnopronk.com/bestanden/PaperArno%20pronk-def%20_3_.pdf)*

The Eindhoven University of Technology in 2006 developed a set of experiences based on the screen on concrete projection method, having been made a prototype of 7m high by 2.5m wide and a thickness of 7cm.

The analysis of the implementation process revealed that the projection of concrete may change the shape of the surface [2].

The University of Brussels built 10 prototypes with a span of 2m and 5cm thick, made from shotcrete tensioned on the screen.

After the concreting the original surface varied between 5% and 58%, this variation was due to the sliding of the attachment points as well as the dynamic effect induced on the surface by the concrete projection. [3].

B. *Concrete additive latex*

Latex Polymer when added to mortars in the coatings process, provides sealing and elasticity to the surface. Suitable for creating bonding layers, repair mortars, screeds for floor wear-resistant, waterproof mortar for concrete, mortar resistant to chemical effects, plasters with high strength and impermeability.

The "roof Nez" How is affectionately called, and which owes its name to its designer, George Nez.

This coverage is characterized by low production costs and a remarkable resistance and waterproofness, is constructed by applying concrete added with latex on a screen support, this process reveals despite its simplicity is highly effective.

Figure 3. Roof Zed Construction process. *(*http://greenbuildingelements.com/2012/03/01/george-nez-habitat-pioneer-who-builds-the-roof-first-george-nez-habitat-pioneer-who-builds-the-roof-first/)

Tests conducted by the bureau of parks in the United States, in Knott Laboratory in Denver, show that this coverage has a high performance compared with normal covers, resisting four times to cold and heat.

The cover has a thickness of 1 cm but has sufficient strength to support a truck parked on it.

The process consists in fixing on the suport elements a screen whose core consists in fiber glass then was poured concrete composed by sand, cement, water and latex [4].

Figure 4. Latex concrete roof made in Ethiopin by the Architecture Institute. (*http://www.hebel.arch.ethz.ch)*

In Ethiopian the Architecture Institute in collaboration with ETH Zurich institute.
Prototype of a concrete additive in coverage with latex, this project was coordinate by the associate professor at ETH Dirk Hebel. [5].

C. *Rigid formwork*

Félix Candela adopted double curvature as his election formal universe, the result of his professional practice in which join the cycles of design and construction developed a set of construction techniques that enabled the construction of his vast work.
His vast knowledge of the hyperbolic paraboloid geometry allowed him to design a formwork system based on conjugated linear elements with parts wedge.

Figure 5. Candela´s innovative formwork construction. *(http://www.peri.com/en/projects/cultural-buildings/restaurante-florante-submarino.html)*

To optimize the constructive process, conceived a constructive strategy that used formwork boards with a thickness of ½ inch (1.27 cm) by placing wedges between them to get the desired curvature [6].

D. *Prestressed masonry*

Eladio Dieste developed a set of technical and structural morphologies thanks to an interdisciplinary approach that embraces the structures, materials and architecture.
Their work is based on the relationship of structure and form, his architecture is a synthesis between form finding, structural beauvoir and spatial qualities.
he believes in shape as medium to obtain structural resistance so by geometry manipulation , he molds the structure in order to obtain structural efficiency and giveS significance to the architectural space.

For David Billington the work of Eladio Dieste is "structural art" combing the efficiency and structural expressivity [7].
Diest has a strong link to the construction process, which is in many cases the support of its innovations.
His constructive concept has largely supported by a systematic refusal to incorporate technology coming from the "developed world" he tried to solve problems bearing in mind the circumstances and their environment [8].
To contrast with European designers, he avoids the use of concrete, choosing brick as their construction method, this option was based on an indigenous and ancestral tradition in Uruguay.
He used the curved surface of vaults to resist buckling and to improve the structural efficiency he focuses its research on prestressed masonry.
His construction technic was based in low tech solutions, to prestress his structural shapes he overlap steel loops firmly anchored to the vaults, and then with an car jack introduce stress in the surface.

Figure 6. Presstress Stell loops. (*http://communedesign.tumblr.com/post/24644338149/eladio-dieste)*

E. *Discrete flexible formwork*

This process has several variations, but basically this system replaces the membrane of flexible formwork for insulating material tiles, which are linked with cables.
Waling and Greszczuk also developed at Purdue University, Indiana, USA a method used a sandwich of two layers of cables with a EPS tiles cast by concrete.
Geometry of buildings resold of an assembly of four hypars. This method was used in two works the Refining Gas Station and Carwash in Midland, Michigan, and the club-house at the Purdue Golf Course in West Lafayette, Indiana demolished in the mid-1990s.

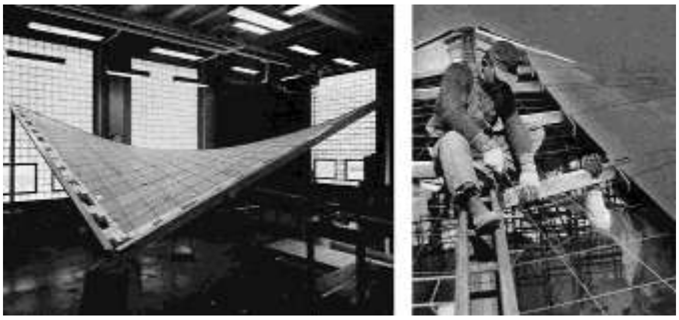


Figure 7. Hibrid structure made by cable net with EPS tiles. (*http://www. design-process-for-prototype-concrete-shells)*

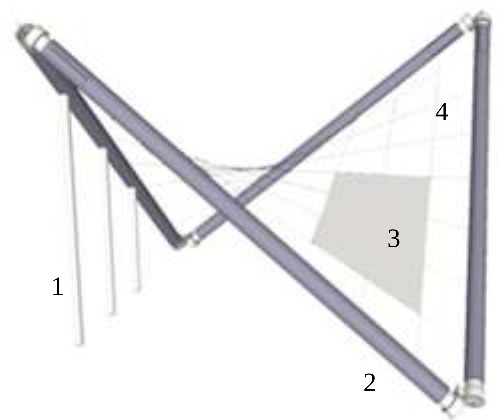
This shell had two layers of 3.4 mm wires 1.8 m offset from the straight line generators.
The bottom wires were spaced 30 cm apart, the top layer 60 cm apart. The shell used 3 in. thick EPS foam, a 0.5 in. stiffening mortar, a 3 in. concrete cover and traditional rebar, 16.5 cm in total [9].

F. *Standart vaults*

Figure 8. Standart vaults construction. (*http://formfindinglab.princeton.edu/news/realisation-pre-cast-segmented-form-found-shell/attachment/serguei-bagrianski-princeton-concrete-shell/)*

Serguei Bagrianski Student at Princeton University, developed as part of his master's thesis in 2012 a standard vaults.
He belives in the potentiality of the double curvature, for him the answer to build this structural shape is the standardization so he built a prototype in a large scale, made with ultra-high performance fiber reinforced concrete.
To produce its modular pieces he divides the vault surface in triangles, using 256 parts.
He also created an algorithm that allows to manage vaults divisions.
The shape is built only with 16 modules adjustable with 15x15 feet and a thickness of ½ Inch.
With this modules he can replicate this shape easily minimize the time of construction and labor cuts.[10].

V. Kirucrete system



1-Articulated falsework
2- Articulated frame
3-Rigid adaptable Formwork
4-Cable net

Figure 9. Kirucrete system components.

A. *Suport frame*

The construction process is based on a reusable and prefabricated frame, this element is constituted by two pairs of telescopic bars, stabilized by telescopic truss.
These articulated joints that form the frame allow to stabilized and manage the size and curvature of the surface.
This support has predefined a set of attachment points for the cables which form the cable net that defines the surface.

B. *Kirucrete formwork*

The formwork is decisive for the final cost of the system as well as the build final form.
The research now started takes advantage of the experiences previously made with flexible formwork associated with cable net.
This process proves to be very effective because it does not need falsework however is very easy to occur deformations.
Aiming to solve this problem we adopted a rigid adoptable system based on a cutting pattern turning flexible the material which naturally form a double curvature, these technics are inspired in old techniques used by carpenters.
This technique has similarities in terms of cutting principles to Eastern technique called Kirigami.
This word results junction Kiru meaning in Japanese cut with Kami word meaning paper.
The cuts produced are never face to face, leave a part of material connecting the other parts of the original piece.
The original plate keeps its original dimensions but the cuts allow the piece to acquire other configurations.

Figure 10. Cutting pattern results , transforming a alinear bord in to curved surfaces.

C. *Materials*

This cutting process originally used in wood boards, could be used in other materials.
Experiences made in International Seminar CorkWorkshop at Lisbon Faculty of Architecture, revealed cork as a good material to use this technic.
These materials prove to be more stable that fabrics used with flexible formwork, so the final form will be more faithful to the project.
Wood and cork have also a more favorable thermal behavior that the screens used in flexible systems

D. *Cutting patterns*

Cutting patterns are important because they are essential to produce the curvature in the boards.
The cutting process resizes the cross section making it smaller so more deformable.
The need to bend the board in both directions introduces new requirement that traditional patterns are not able to respond, because the traditional patterns use a unidirectional cutting scheme.
To answer this need we created a new pattern, the cuts are made in two directions.
This logic can generate several patterns influencing the deformability of the board.
The patterns can be arranged on one side of the board or both sides, these options influence not only the board´s deformability but also determine the constructive process.
Both side cutting patterns allows the passaging of materials with higher fluidity, this situation may affect the liquidity of concrete applied in formwork.

E. *Prodution formwork*

The cutting scheme is produced by a circular saw, this tool has low costs, high efficiency and ease of use.
The production process is faster compared with the milling machine, also does not require skilled labor or sophisticated and expensive tools and reveals a great spread potential.
This production process proves to be reliable, economical and simple, making it a very competitive system.
Making the production of surfaces of double curvature easier and viable and competitive.

F. *Concrete*

The concreting process is crucial to the success of this construction system.
This system needs flexibility and control in the application of the concrete, therefore shotcrete system is the more appropriate concreting system, is possible to improve the concrete resistance using bar chip fiber and a hexagonal mesh .
The steel frames can be minimized or even avoided with the utilization of fibers in concrete.
Bar chip show us an excellent structural beauvoir for the re-enforcement of shotcrete for the use on the freeform.

Figure 11. Shotcrete custing process. (*http://www.tudelft.nl/fileadmin/UD/MenC/Support/Internet/TU_Website/TU_Delft_portal/Onderzoek/Wetenschapsprojecten/Speerpunt_Bouw/Projecten/Lopende_Projecten/doc/3.1.16_Me.pdf*)

G. *System*

The system is based on cable net support by an adjustable articulated frame, turning possible any kind of anticlastic shape.
The rigid adaptable formwork boards are fixed to the cable net, the process is finished by a concrete slab made by shotcrete with bar ships.
The system involves the tension control applied to the mesh this management is of great importance for the accuracy of the final form.
Concreting process increased the load supported by the cables and the consequent deformation.
This new construction process by using an adaptive rigid formwork minimizes deformation.

VI. Conclusions

This system is basically a design set for double curvature sinclastic and anticlastic surfaces.

The rigid adaptable formwork compared with flexible formwork revels a higher accuracy whit out deformations.

The construction frame is based on articulated bars and adjustable falsework, all of then reusable, turning the system less expensive.

The flexibility of the system turns possible the construction of any kind of surfaces with all kinds of curvatures.

These solutions allows to build double curvature surfaces in a fast way with lower costs, unskilled labor, and without massive construction infrastructure.

This multilayer system has also a high production ratio because is based on an adaptable mass production formwork.

The entire system presents several innovations turning the difficult and expensive process of building double curvature shape into a standard and fast construction process.

The system revels to be more accurate than others, specially the flexible formwork.

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