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Origami Folded Surfaces:

kinetic systems behind the folding

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Abstract. "*Today's intensification of social and urban change, coupled with the responsibility of issues of sustainability, amplifies the demand for interactive architectural solutions. In the context of architectural need, the attribute of being able to adapt to changing needs is paramount in contemporary society.*" (Fox and Kemp, 2009)

Since the 1960's that Architecture is progressively more merged with several other fields. Fields like biology, robotics, mechanics, electronics, parametric design, digital fabrication and so many others get to be together through Architecture. It is getting easier and more feasible for the designer to create buildings that are kinetic, interactive and/or responsive in order to communicate with users, enhance the building's performance in response to changing atmospheric conditions and even transform its own geometry to reconfigure spaces as a functional answer to changing demands.

The use of kinetic buildings, or kinetic elements in a building is becoming a natural response to concrete architecture solutions in order to make buildings "intelligent" and "alive" so they can meet the actual demands of users and use the technological means that are currently available. On this sense this paper focuses specifically on kinetic architectural systems through the use of Rigid Origami Surfaces. Their geometry gives them elastic capacities and is versatile enough to be used in a wide set of systems..

Keywords. *Transformable Architecture; Kinetic Systems; Origami Geometry; Operable Roofs.*

Introduction

If one thinks about deployable/portable buildings as a kind of kinetics it is possible to say that kinetics has been present in Architecture since the nomad man started to construct tents and tipis that could be closed for transportation and opened when a good place for settling presented itself. Also the use of elements like doors, windows, shutters, movable walls, etc., have always been used as kinetic elements in buildings. (Kronenburg, 2003)

Buildings were also thought about, from centuries ago, in a manner that would allow them to be cooler in summer and hooter in winter or to have windows and solar shadings with a configuration that could take the best advantage of the solar trajectory depending on the time of year or day, even if only in a passive way.

Today the architect has at his reach the tools that make possible the design of buildings that can adapt, by transforming themselves, in order to meet the requirements of thermic comfort, insulation and space configuration, among others. Now the architect does not have to design static buildings thinking in the "worst case scenario" which often results in over dimensioned and over equipped buildings wasting resources and money for a situation that might not happen. With the new technologies and kinetic elements buildings may gain the ability to adapt to situations when they actually occur. (Fox and Kemp, 2009)

The present research is placed on this line of thought and focuses on the architectural kinetic systems particularly on the ones relevant to operable/retractable roofs. As a materialization of these roofs we propose the use of foldable surfaces based on Rigid Origami rules due to their properties of elasticity, self-support and, most importantly, their geometric versatility that makes them able to assume planar, single curvature and double curvature configurations.

Retractable Roofs

The existing options for retractable roofs for spaces with big span can be characterised in three main categories: Sliding Roofs, Pivoting Roofs, Foldable Roofs.

The most common retractable roofs are the Sliding Roofs. These are made with giant panels that cover part of the building´s top and that slide along linear or circular rails.

It is the case of the SkyDome in Rogers Centre, Toronto, Ontario, Canada designed by Rod Robbie and Michael Allen, 1989. This opening roof is composed by two massive steel panels that slide on top of each other on linear rails and a third part of the roof that slides circularly under the other panels allowing the stadium to be almost completely open. (Figures 1 and 2)

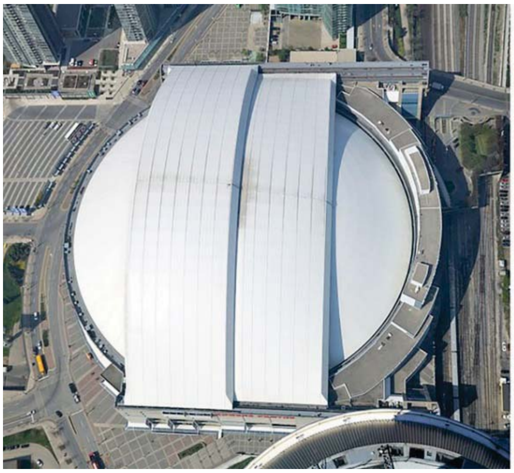

Figure 1. Rogers Centre - Roof closed

Figure 2. Rogers Centre - Roof open

Also the Wembley Stadium in London, designed by Foster and Partners, Populous and the Mott Stadium Consortium, 2007, as a retractable roof. The roof and its structure are made of steel and weight 7,000 tonne that are partially supported by the arch, identity of the stadium.

The central part of the roof is divided in 5 panels that slide linearly on top of each other and onto the static part of the roof. (Figures 3 and 4)

Figure 3. Wembley Stadium - Roof closed

Figure 4. Wembley Stadium - Roof open

The Pivoting Roofs are usually divided radially from the centre of the roof in pieces that rotate around a point or an edge, opening like a camera's diaphragm or a flower.
It is the case of the Qizhong Forest Sports City Arena in Shanghai, designed by Mitsuru Senda and finished in 2005. The roof is made with eight petals, each with 2 tonnes,that rotate about themselves on a point at the edge of the stadium allowing the centre to be open. (Figure 5)
Similarly the Bengt Sjostrom Starlight Theater, 2003, in Rockford, Illinois, designed by Studio Gang O'Donnell has an hexagonal opening area on the roof that opens through the rotation of six triangular modules. (Figure 6)

Figure 5. Qizhong Forest Sports City Arena - Roof open

Figure 6. Bengt Sjostrom Starlight Theater

The category of Foldable Roofs is the one where the Rigid Origami Foldable Surfaces belong, nevertheless the most common are retractable textile like roofs. These ones have very good points on their side. They are much lighter than the examples we have seen before, because it is mainly the structure, that makes the roof fold and unfold, that weights the most. They can collapse into a relatively small space when the roof is open and allow the entrance of light even when the roof is closed.
The BC Place Stadium in Vancouver, British Columbia in Canada had is roof collapsed so, in 2011, it was renovated by Stantec Architecture and Hightex that designed and constructed a textile foldable roof. The fabric retracts to the centre of the roof were lies the scoreboard. (Figures 7 and 8)

Figure 7. BC Place Stadium – roof closed

Figure 8. BC Place Stadium – roof open

The roof of the Wimbledon Centre Court in London, was designed by Populous and Hightex and inserted upon the renovation of 2009. Its structure slides on parallel linear rails that are hydraulically operated. The steel trusses make the translucent fabric skin fold and unfold. (Figure 9)

Figure 9. Wimbledon Centre Court – View from the inside, roof closed

The existing solutions are very interesting and each one responds to certain problems but all of them leave important issues without solution. The sliding and pivoting roofs are usually very heavy, costly, do not let any light inside the building when they are closed and even when the roof is open the panels occupy a big area. The textile foldable roofs are much lighter, let the light pass and can be compressed into a small space but have no supporting ability nor the capacity to assume a range of geometric configurations.

Although there are no Rigid Origami Foldable Surfaces in use on roofs of constructed buildings we believe that they have the most to offer when compared to the existing solutions, they can be low-weight structures, translucent, assume a wide range of geometric configurations and be collapsed into a very small area.

Rigid Origami Folded Surfaces

Origami and its geometric possibilities have been used for thousands of years but it was only in the 80’s that it began to be deeply studied and only then were defined the 7 axioms that summarize Origami's geometric potential.

These are the Huzita-Hatori Axioms very similar to the Euclidean axioms for constructions with straightedge and compass. The first 6 were defined by Huzita, the seventh was defined by Hatori in 2002, although it had already been formulated by Justin in 1996, these axioms are usually known as Huzita-Hatori or Huzita-Justin. Combining these axioms with operations to divide the paper in n parts and with the methods to construct any angle it is possible to reach an infinity of possible folding patterns. (Lang, 2010)

The Rigid Origami folded surfaces are of great interest in the fields of architecture and engineering, not only because of the aesthetic possibilities they bring but especially for their geometric, structural and elastic qualities. The possibility of transforming a flat element, without any structural ability, into a self-supporting element through folds in the material opens doors to a multitude of uses.

On a surface folded according to the rules of Rigid Origami it is mandatory that the faces remain flat at all times and that the folds act as hinges between the various faces. It is possible to make the same surface acquire different configurations by applying forces at strategic points which will oblige to larger or smaller angles between the faces. Therefore, despite the material used is rigid and does not have elastic properties, such a surface has the power to grow, shrink and adapt to several configurations. (Demaine et al, 2011)

These are the reasons that make the folded surfaces particularly suited to meet the requirements of kinetic surfaces that one wants to be light, with self-supporting abilities and able to assume different forms in a kinetic way. Adding to these qualities the Origami Surfaces have the ability to be used as an entire piece that can let a big portion of a building be open or closed, with the impact that brings. With these surfaces the architecture is changing every time because they have several different geometric states that are able to change spaces and the impact they have on users. Each state creates different ambiances through the refraction of light and sound that change as the day goes by or the number of people using the space. Finally, pondering on the matter of scale, these surfaces can achieve more or less resolution depending on the size of the faces, if bigger they act more as solid masses and if smaller the surfaces gain a fluid like expression.

Despite all this kinetic potential Origami has been more commonly used in Architecture in a "frozen" way, i.e., one state of the surface is selected and then statically reproduced with heavy materials.

Taking full advantage of the elastic properties of Rigid Origami we can find its use in temporary, mountable and demountable structures, such as the Recover Shelter by Mathew Malone or the Corogami Folding Hut by David Penner. The way these designers use the origami structures allows the structures to be deployed into a flat form so they can be transported or stored, and when they are in use they are self-supported and do not require any additional structural element, however when being used they remain static.

It is possible to find some examples, very few, that use Origami surfaces in kinetic facades or roofs, such as the Al Bahr Towers by AHR Architects or in solar panels and sails used in space satellites.

More easily we can find the use of Origami in a kinetic context in academic investigations or in temporary constructions or installations that use it in a kinetic and responsive way. It is the case of Auxetic Origami of Christopher Connock and Amir Shahrokhi from Yale University or the Lotus Dome by Roosegaard Studio. Unfortunately these examples do not use surfaces, they use modules with a small number of faces arranged around a central point, each module functions in synchrony with the ones surrounding it, like they were a surface, but geometrically speaking they are separate units.

Kinetics

Fox and Kemp (2009) make the distinction of Ways and Means in Kinetic Architecture. For these authors the Ways are the geometric transformations that occur in the kinetic element like folding, sliding, expanding, shrinking and transforming. The Means refer to the mechanics or chemical transformations in the materials that are behind the movement.

Moloney (2011) does not make the same distinction and defends that there are four building blocks for kinetics. For this author there are only three geometric transformations, translation, rotation and scaling and a fourth building block that is movement via material deformation.

We agree with points on both perspectives for what concerns Rigid Origami Foldable Surfaces. There is definitely a distinction between Ways and Means, and the chemical transformations that occur on a material should be placed under the Means category instead of the category for geometric transformations. For the geometric transformations that may occur on a foldable surface the folding one does not have to exist as a category, it is inherent to Origami Surfaces, also expanding and shrinking may be put together as a scaling transformation, which is mandatory on such surfaces. Therefore, for the specific case of Rigid Origami surfaces we consider that the related Ways would be sliding and rotation with a very important distinction, if the surface transformations happen only in one plane or out of the plane assuming single or double curvature.

For the Means we consider the mechanical systems rather than the Material's deformation for we assume there is no material deformation on the surface during the kinetic action. The faces must remain planar and with the same area at all times, the only material deformation is at the creases and is done during the creasing step, so they are irrelevant to the kinetic action.

We define that the most relevant kinetic and structural systems for the opening and closing of Rigid Origami Surfaces are those that can sustain the surface at the same time that they work with the surface's own structural component. These kinetic systems also have to move specific vertices or edges in order to achieve the desired geometries.

Amongst all the "Means" available we believe that the most suited to put Origami Surfaces in motion are Scissor systems, Sliding bars, rails and tensioned cables that work with pulleys. Systems with tensioned cables and pulleys can push and pull specific vertices of the surface. Rails can drive precise vertices in predefined trajectories. Trusses or bars can slide or rotate carrying with them an entire line of vertices or edges. Scissor systems can work linearly as the well-known "Lazy Tongue" or configure curved surfaces that open from the top to the perimeter as the domes invented by Hoberman.

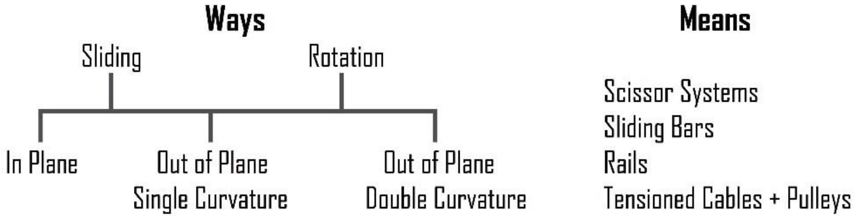

Figure 10. Ways and Means for Rigid Origami Surfaces

Below is presented a table with one Rigid Origami folded surface example of each one of the "Ways" categorized. The table shows the crease pattern and three folding states, from the unfolded to the completely folded state.

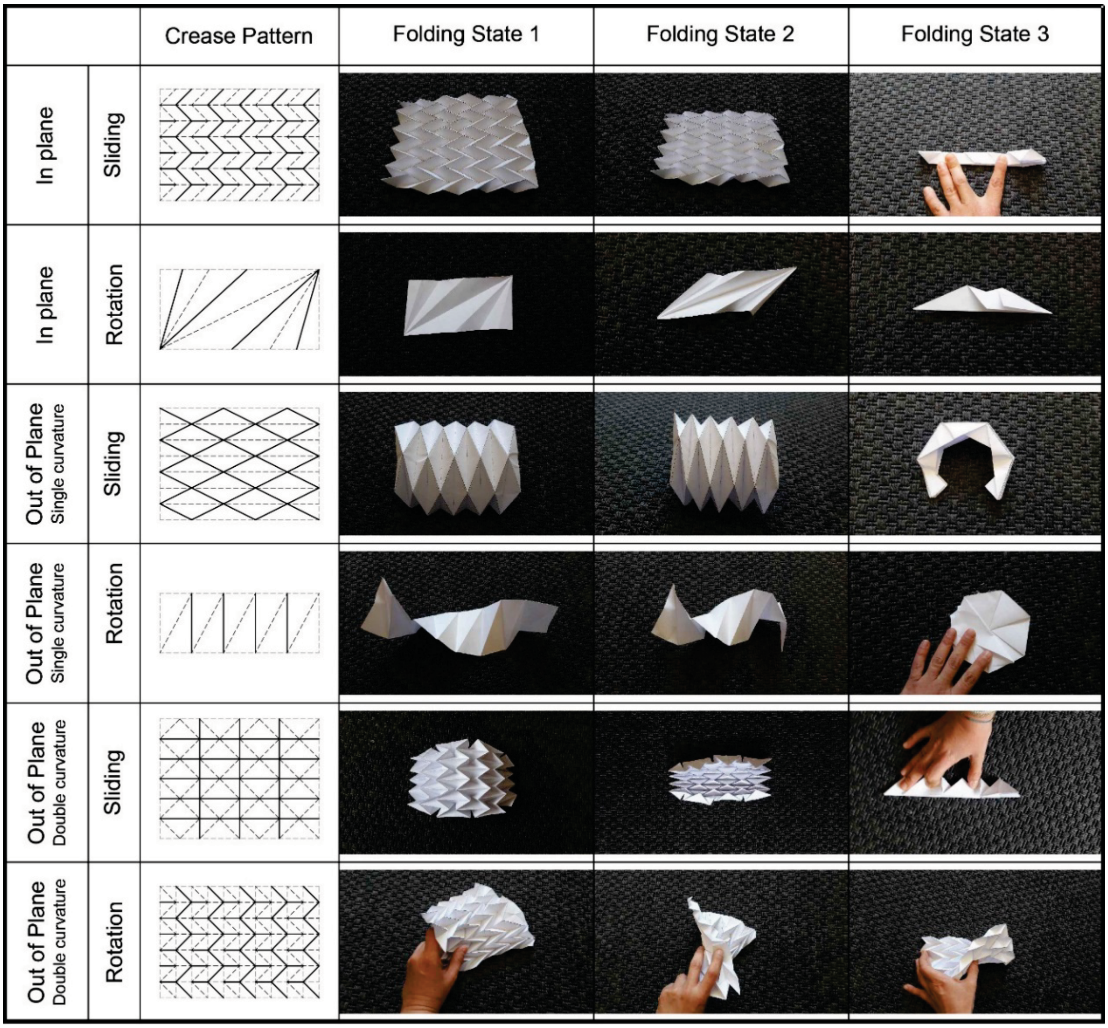

Figure 11. Examples of Rigid Origami Surfaces for each "Ways"

The kinetic systems can be put in action in an automated way, either with hydraulic, pneumatic or electrical motors that work linearly or rotationally depending on each specific surface and the chosen "Means" for action.

The automation can be a response to diverse stimuli. It can obey a direct command to open, close or assume pre-set configurations or it can dynamically adjust its position in response to other stimulus, such as meteorological, thermic or lighting conditions, proximity of users or objects, or any other, as long as there is a sensor feedback system that can inform the kinetic system in order to put it in motion to achieve a determined geometric configuration.

For all this to occur, and to succeed, the designer must understand the possibilities and limitations of every field present in the definition and construction of a kinetic building or element in a building.

"The outcome of kinetic design is not a singular form, but a process from which a range of forms manifest over time. This requires designers to consider the design of control system and data input, as well as the design of the physical components." (Moloney 2011)

In the case of Rigid Origami Surfaces it is of particular importance the understanding of Origami geometry and the path that the vertices follow from one state to another. Is that path that will give the designer the guidelines to the best kinetic system to use for a particular crease pattern and intended geometric configurations.

Conclusions

The tools that the designer has today at his reach allow the creation of kinetic buildings, or kinetic elements in a building that can improve the building's performance and adaptability to changing conditions.

We believe that Rigid Origami Surfaces may be a vehicle with great potential to be used in Kinetic buildings due to their specific properties of lightness, elasticity, rigidity and self-supportability. Their rigid, planar faces that rotate around the edges shared with the neighbouring faces allow the same surface to assume different configurations. Such a surface can improve the ability of a building to adapt to different conditions at the same time that it gives the building the capacity of transforming its own geometry creating different ambiances for its users.

Rigid Origami has been utilized in several architectural situations but the use of this kind of geometry as a kinetic surface does not have many examples. It was not yet found a constructed solution that has a Rigid Origami Folded Surface as an operable roof despite their described potential.

In order to create a base for future solutions this paper establishes the Ways and Means for Kinetic Rigid Origami Folded Surfaces, through Fox, Kemp and Moloney´s definitions.

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