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Kinetic solar skin: a responsive folding technique

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Abstract

The paper focuses on optimized movements analysed by means of Origami, the Japanese traditional art of paper folding. The study is a way to achieve different deployable shading systems categorized by a series of parameters that describe the strengths and weaknesses of each tessellation.
Through the kinetic behaviour of Origami geometries the research compares simple folding diagrams with the purpose to understand the deployment at global scale and thus the potential of kinetic patterns' morphology for application in adaptive facades. The possibilities of using a responsive folding technique to develop a kinetic surface that can change its configuration are here examined through the variation of parameters that influence kinematics' form. Moreover, in order to perform the shape change without any external mechanical devices, the use of Shape Memory Alloy (SMA) actuators has been tested.

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Keywords: solar skin, shading device, responsive architecture, Origami patterns, kinetics, adaptive, SMA, Smart actuators, actuation

1. Introduction

Nowadays façades are made up of many layers and materials that allow the envelope to perform many different functions. The increasing interest for adaptive architecture that reconfigures itself to meet environmental mutations and user's needs drives the concept of a new building skin that is multifunctional, responsive and dynamic. Multiple features could be incorporated into façades in order to optimize their response to climate changes [1]. Responsive façades are thus becoming an innovative research topic, due to the necessity of reducing building energy

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consumption and improve architectural integration [2]. Given that, a kinetic shading device can be useful to regulate windows' gains.

The paper brings the attention to the kinematics potential of Origami creased patterns, investigating how those geometries can be modelled so as to optimize the surface displacements. In these terms, the kinetics exploration is developed through the achievement of different ways to fold the surface, exploiting the type of crease pattern and the use of active materials as actuators. Since the latter typically present limited deformation capacity, the hypothesis is that their combination with the Origami technique would deliver a system whose displacements are compatible with façade applications. The use of Origami at different levels fits Origami patterns into several engineered applications; as deployable and reconfigurable structures, folding geometries have been used in biomedical devices [3] and in space and aircraft applications [4]. However, in architecture the use of self-folding Origami is mainly experimental, especially regarding shading devices and façade applications. At building scale, responsive surfaces have different typologies of movement like translation, rotation and scaling. To do so, external forces are required. Current trends in shading device research aim to replace traditional mechanical systems with multifunctional and smart actuators [5]. The use of Shape Memory Alloy (SMA) wires to switch Origami patterns can produce a responsive system with low activation energy. Currently there are no diffused applications of SMA actuators in the building industry; on the other hand, their intrinsic ability to sense and directly respond to the changing conditions with a range of movements makes these materials attractive for application in kinetic solar shading devices.

1.1. Responsive architectures: a bioinspired deployment

Contemporary architecture has adopted kinetic motion as a process of self-adaptation and responsiveness. Responsive façades are expanding and improving thanks to technological enhancement and the use of clever geometries. Coined by Nicholas Negroponte and then revised by Tristan d'Estree Sterk, the term responsive architecture is defined as "a class of architecture or building with the objective of physically reconfiguring themselves to meet changing needs with variable mobility, location or geometry" [6]. Currently, this type of response is used in architecture to regulate solar gains, ventilation and to solve energy saving issues, especially when a massive use of Heating, Ventilation and Air Conditioning (HVAC) systems is needed.

Dynamic systems have already been investigated since 1987, when French Architect Jean Nouvel envisioned what is deemed the first and most famous built kinetic façade. The responsive robotic shading screen of the "Institut du Monde Arabe" represents a particular type of scaling kinetics [7]. The façade is composed of several independent modules individually controlled. The movement performed by each module can be described as a planar rotation of flat elements overlapping with each other. Therefore, the resulting multiple contractions and expansions control the incoming solar radiation. More recently, two other important examples of kinetic shading devices have been developed. Foster and Partners and Hoberman Associated have proposed a dynamic sun-shading system for the new "City of Justice" of Madrid [8]. The adaptive shadings on top are constructed around a triangular grid, where hexagonal sunscreens contract and rotate independently. In the "Showroom Kiefer Technic" designed by Ernst Giselbrecht and partners, kinetics is instead performed by vertical translations with a scaling effect resulting from a folding joint [9]. The solar screens arranged along the curved façade are controlled by a computer system. When actuated, the shading devices show a composite pattern of translating and scaling object that follow the solar path [10]. Kinetic façade systems use a large number of moving components connected to each other to perform movement. This makes the system complicated and, above all, consumes a lot of energy to work. On the opposite, mechanisms in nature are much simpler, as they move changing one of their intrinsic properties. Several plants have developed a variety of mechanisms able to sense and directly actuate the movement to execute vital functions. Sensors and actuators, through controlled geometry changes like turgor pressure, cell growth, swelling and shrinking, are able to solve physiological issues. Spatial reorientation, seed dispersal, ingestion and fixation are some of the natural processes activated to preserve the organism and to protect it from environmental changes. Venus flytrap leaf folding and Mimosa plant [11] highlight a rapid response to external stimuli. Other natural systems, like tree branches, perform very slow movement to adjust organs' orientation.

To find strategies for deploying surfaces, nature is a good place to look. In some leaves and flowers, a folding technique is used efficiently so as to optimize their shapes continuously. Thanks to corrugations, Hornbeam leaves have been taken as inspiration for engineering structures [12]. Hornbeam, Beech and Maple leaves exhibit a deployment mechanism; the pleats are disposed like V-shaped patterns in a way to allow young leaves to fit into the buds. Plants movements are relevant when approaching a design concept of moving components starting from a bio-inspired approach. Active materials can be easily related to plants multifunctionality characteristic, in which sensors and actuators are integrated into their structure. Reversible movements are the ones most interested for deployable structures. Leaves motion, like Oxalis Triangularis, has to be considered as nastic movements [13], where active structures respond to an external stimulus independently of direction, inducing a reversible movement – folding/unfolding of the leaf. So, learning from nature may be particularly useful for a biomimetic translation into the design of a kinetic shading device [14].

1.2. Actuation: shape memory alloy (SMA) wires

While the creased sheets' kinematics is at the basis of the geometric issue, kinetics implies the use of micro actuators able to activate self-folding [15]. The adaptive Mashrabiya solar screen, which is the main stand out feature of the Abu Dhabi Al-Bahar Towers, well represents a type of Origami-based shading device [16]. As the sun moves around the two buildings, over 1049 units deploy dynamically into their unfolded configuration, thanks to the mechanical actuators settled. Instead, the paper considers actuation systems that entail low energy demand to activate the sunshade, so as to support sustainability concepts. The adoption of lightweight and elastic materials, as a way to perform movement suitable for sun control purposes, has excluded all those mechanical systems that cannot be used: for example, pneumatic and hydraulic systems because of their dimensions; the ones that need electronic control to work, as the Dielectric Electro Active Polymers (DEAP); those that display durability issues, as the shape memory polymers (SMP); and the hybrid ones (SMH), that can be affected by external weather conditions. For these reasons, the research has taken advantage of the particular characteristics that mark SMA from the other types of actuators.

Since 1960s SMAs have been extensively used for aircraft and biomedical applications. However, in architecture the use of SMAs is still experimental and more related to design concept. Commonly used in a wire or spring form, SMAs can be embedded into other materials and behave like an organ plant, producing deformations when an external stimulus is provided. The dynamic nature of SMA results, when actuated, in a contraction of matter, due to the reconfiguration of the alloy molecules. When the SMA crystalline structure is below the transformation temperature, the material maintains its original shape. If the temperature exceeds its transformation temperature, the material changes its initial shape and reaches a pre-set temporary new shape [17]. This process can be used to activate kinetic shading devices and substitute mechanical actuators. Within the micro actuators category, the power-to-weight ratio highlighted by SMAs is the highest among the others similar technologies. Furthermore, SMA actuators have some advantages as like as the simplicity of mechanism, the silent actuation and most of all the low driving voltage [18].

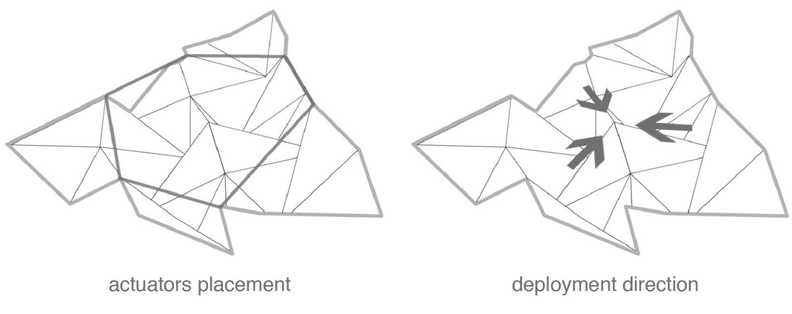

Fig. 1. The embedded SMA wires define the direction of deployment

As a way to increase the feasibility of SMA micro actuators, and in particular to obtain a sufficient deployment of the shading system with their comparatively limited expansions and contractions, the paper links the Origami

creased patterns with SMA wires performing displacement analyses out of three folding paper mechanisms. The surfaces are presented through a collection of flat-folding models with their corresponding kinematic actuation. The embedded SMA wires activate the Origami patterns based on their location on the surface, as well as following the natural direction of pattern deployment. The linear transformation performed by SMA wires should be combined with geometry constraints given by the flat surface lines. According to the type of pattern explored, the transformation allows the actuation to take place on the three-axis resulting in different configurations.
Thermally, SMAs are designed to change their shape when the temperature rises to 50-70°C (depending on the alloy) [17]. Recent researches have shown the importance to evaluate the daily temperature range at which the sunshade is exposed and how this can deliver the expected shading performance [19]. As the shading system should be guaranteed over the entire year, the SMA actuation would be more likely to be activated by an electricity source. Moreover, the use of electricity allows users' interaction thanks to the override of the shades.

2. Method

The kinematics performed by folding geometries has been studied to overcome the limitation of traditional louvers, especially to improve their efficiency thanks to the dynamic nature of these patterns. The variety of angles coming from the folding/unfolding rates offers a louver-like behaviour capable to manage the incoming radiation in the whole year.

Another reason for choosing Origami as a process to develop shading screens is represented by the spontaneous self-organization of these particular geometries, considered as an intuitive way to perform adaptation. In fact, thanks to tessellation's creases, the Origami folding patterns enable the system to deform easily into a preset deformation direction, while remaining stiff in the other directions. This anisotropy in deformation can be applied in morphing structures. In fact, these systems are capable of changing their shape to accommodate new requirements while maintaining a continuous external surface [20]. The other advantage of Origami technique is its ability to change the curvature without producing material's stretch. Folding techniques have also many advantages over traditional constructing methods, like the reduced consumption of material and therefore an implicit structural lightness [21]. By using Origami as a developable surface it is possible to create a desired shape from a number of folded parts. The resulting 3D shape is defined by its 2D crease pattern, following the folding lines. Two types of folds describe flat patterns: the valley folds, which develop a negative angle when deployed, and the mountain folds, which happen into a positive angle when folded. In Fig. 1 V-pleat pattern has been taken as an example to show how the flat surface is defined and the consequent position of the lines when the pattern is folded.

The research starts considering simple folding techniques, in terms of number of folding lines and intersection of valley and mountain folds. The output is defined by different patterns that result in different forms, volumes and directions of deployability. The purpose is to understand the behaviour of the geometry pattern at the global scale, rather than formulate an alternative method to describe the origami surface. Thus, the study of pattern geometries followed the Origami technique as a generative process has been studied in order to comprehend the kinematics behind this type of movements. Furthermore, the influence of cuts and folds in generating different types of folding has been demonstrated through the construction of some basic origami patterns with digital and physical models.

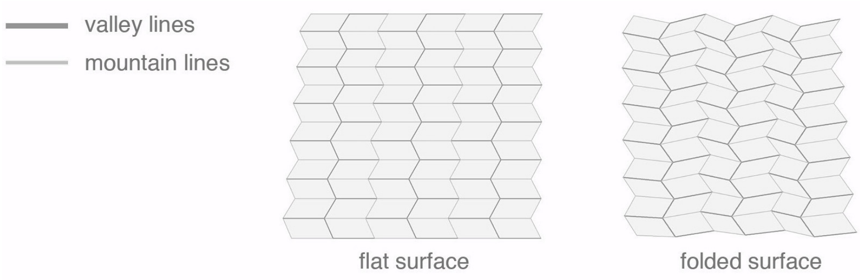

Fig. 2. Two types of folding lines describe Origami surfaces: valley lines and mountain lines

2.1. Types of Origami: explored pattern families

Engineered origami-inspired design focuses on testing and developing folding patterns that result in a set of geometric deployments. There are various methods and approaches to design Origami diagrams. Many types of tessellations and geometric patterns can be described by regular triangles, squares or hexagons regularly arranged into a matrix. In order to understand the potential kinematic mechanism of Origami, the paper presents patterns that belong to three of the most famous Origami families.

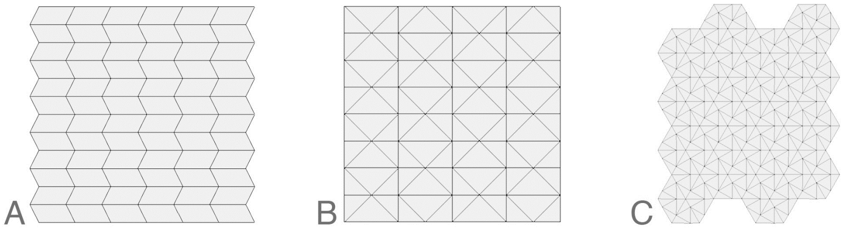

Fig. 3. Different pattern families: V-pleats (A), Glide Reflection (B), Ron Resch pattern (C)

V pleats, represented in Fig 2 (A), are characterized by a repetition of V shape elements, in which three mountain folds and one valley fold –or vice versa- meet a node. Almost all V pleats are dynamic: they have the ability to make a surface expand or contract along the two orthogonal axes, and can be bent and twisted in many directions. In the case of Miura-Ori pattern, all folds can be manipulated so that the pattern can be compacted into a small, flat shape. Variation of this type of pattern is achievable by modifying module proportion. Glide Reflection Fig 2 (B) represents the most complex form of symmetry, as described by the combination of a reflection around a line and the consequent translation along the same line. The complexity of this pattern is due to module displacement; infact, the unit disposition doesn't follow a straight line. Once folded, the surface is very flexible and can be bent and twisted as the V pleats pattern does. Modular pleats, like Ron Resch pattern Fig 2 (C), are usually asymmetric. However, the patterns of this family are constituted of a repetition of honeycomb-like modules. Unlike the previous families that remain in a plan when folded, modular pleats can be deployed to various shapes thanks to the intrinsic deformation along the three main axes.

2.2. Digital model: the use of Grasshopper and Kangaroo

The relationship between modules, folds and cuts creates infinite shape alternatives that can be modelled and then selected accordingly to the actuator material characteristics. Geometric patterns can be studied with the help of generative algorithms, setting up rules to generate the modules and then apply these rules to the object. Therefore, in order to increase the number of combinations given by folding and shape changes, the Origami approach has been constructed with the help of 3d parametric models. Digital software have been used to control variables through a parametric design that can be updated step-by-step defining dimensions, deformation strength and degrees of control. Relying on geometry, the digital model includes a study of movements following actuators placement. Through pattern experimentation, kinetic activation is set by the parameter variations included in digital configuration, allowing the description of a range of possible space configurations depending on movement.

As predicted, the outcome shows multiple optimal solutions that fit the issues. To accomplish the aim of the research, digital algorithms have been used: while the geometric parameters have been set with Grasshopper [22], the actuation of SMA wires is simulated using the plug-in Kangaroo [23]. Grasshopper uses pre-defined scripts in a way that allows to manipulate and to modify data when needed. The first step in constructing the algorithmic design is to provide data through the use of scripts grouped in components.

In order to set up the algorithms, the components must be connected in the desired order so as to obtain the desired shape. Basically, the pattern is originated by the main module, digitally defined by a series of points connected by lines. To create the whole surface a rectangular grid component has been used, which is able to replicate the single module along the X and Y-axes. Moreover, since the module shows displacements along X-axis, the use of Boolean functions –True/False- to cull the elements has been implemented. Then, Item list has been used to select the lines in two sets of lines, respectively mountain lines and valley lines. To start running a simulation, the main Kangaroo component must be included into the definition.

Kangaroo uses "Force Objects" that can come from various parameters, like user input and geometric constraints. Before adding the actuators, the designed surface has been tested using the origami component. In order to start the simulation, the origami component needs inputs like a flat single mesh, pre-assigned curves, target angles and folding percentage.

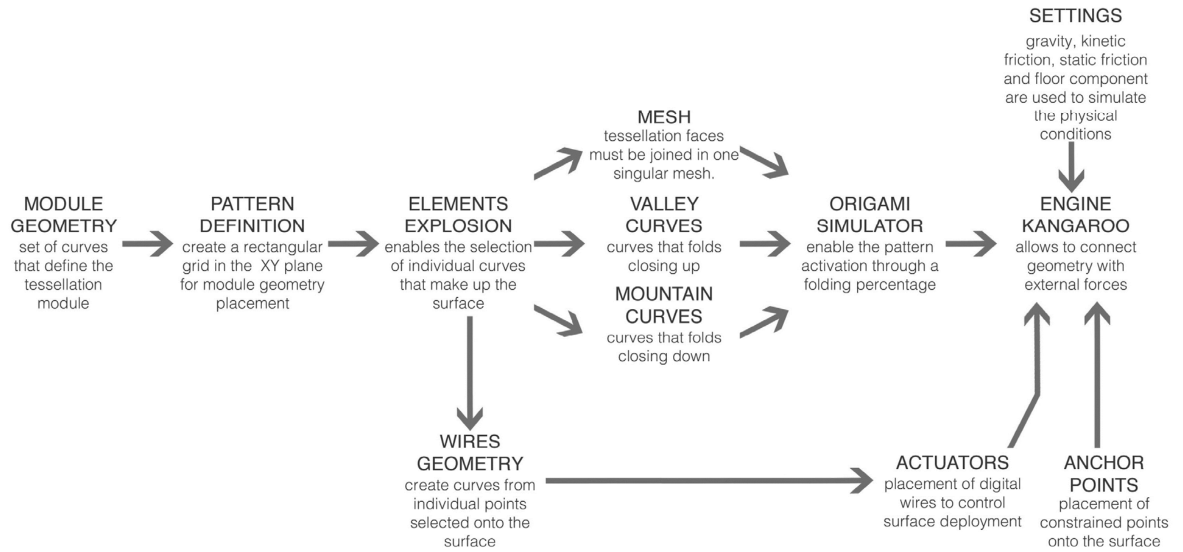

Fig. 4. Schematic representation of digital model actions

Subsequently, surface activation due to digital wires has been implemented. Without considering the folding percentage highlighted by the origami component, the Kangaroo engine has been combined with spring components as "Force Objects". To insert wire actuators on the surface, the same has been exported into Rhino Environment [24]. Through the obtained surface, points have been extracted to arrange the actuators on the pre-folded geometry. Digital wires have been modelled as linear springs with variable original length, which is adjusted through global settings applied to the main engine component. Furthermore, in order to consider the surface connected to a substructure, the use of anchor points has been considered. No matter the intensity of the applied forces, Kangaroo will not be able to move these points. The Grasshopper experimentation allows envisioning a worthy pool of patterns through a better understanding of the physical behaviour of the surface. Digital design tools can be seen as a form-finding guide and as a valuable assistant for physical experiments.

3. Results and discussion

3.1. Geometrical exploration: design parameters

The generated geometry is defined by parametric inputs that cause variations from the initial shape.

To set up the algorithm, components must be connected to each other to generate a collaborative task. Each component performs a task based on the data provided by inputs; the result is used as input for the next step. The design algorithm takes shape little by little, as a result of the order of connection of components. The digital model is able to fix which geometric properties can be modified and which one remains constrained. Thus, the design parameters variation becomes a design driver for finding solution strategies on the investigation of the optimal crease pattern behaviour. Transformations are made possible by using numerical values slides to modify proportions and by using vectors and planes to set the shapes. To make the system adaptable to an adjusted condition, surface divisions, anchor points and different actuator placements have been considered.

3.1.1. Surface divisions

By connecting points in a desired order, it is possible to generate base lines of Origami pattern. This method extracts geometrical rules for points, lines and surfaces and thus uses those rules to force the design. Since the module is defined by adjustable base lines, changing the numerical values associated with each line can result in different shape proportions. The same concept is applied to the grid. In fact, the generated module is used as input for the rectangular grid component. This action allows a repetition onto the grid by module geometry, cells dimensions and number of cells along the X and Y-axes inputs. Regulating parameter values gets various geometric surfaces out of the same process. As a result, when the simulation runs the system reacts differently.

In Fig 5 are shown three V-pleats patterns obtained by manipulating the vertical and horizontal proportion values of the module. While pattern (A1) has a square proportion, the other two shapes (A2) and (A3) have a rectangular proportion. Contrariwise to module (A1), the same folding percentage applied to pattern (A3) makes the surface unstable. Besides, if the same number of actuators is applied to pattern (A3), a smaller contraction is needed to reach the same deployment percentage. Thus a modification of module's parameters can get the surface unstable, but can also increase the actuation performances.

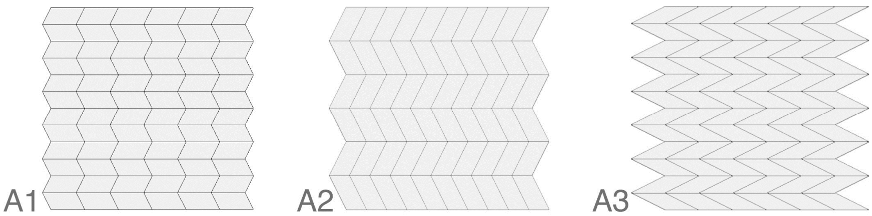

Fig 5. V-pleats patterns generated by different proportion using generative algorithms

3.1.2. Anchor Points

In order to consider the future development of physical prototypes, the digital experimentation has taken into account not only the surface without constraints, but also the application of anchor points. Fixed anchor points determine movement's constraints; these sometimes produce unexpected rotational or twisted displacements. The use of anchor points has been considered so as to define different shapes and thus to highlight the kinetics pattern behaviour. As shown in Fig 6, bonded vertex and edges change the actuated surface, in terms of percentage of closure and configuration.

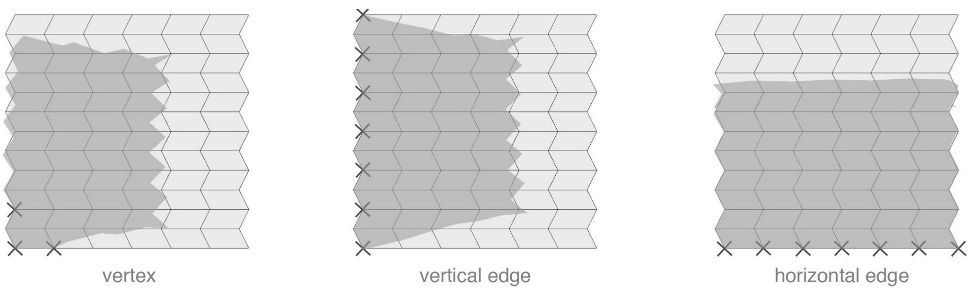

Fig. 6. Anchor points settings applied to pattern analysis

3.1.3. Actuators placement

In order to better understand how Origami surfaces can be updated inserting active materials allowing self-folding activation, a number of different actuators placement have been studied. The position of SMA wires controls in many ways the system's form. As shown in Fig 7, sets of actuators are located onto the surface following the folding direction and the main valley and mountain curves. Actuators have been connected to each vertex of the crease pattern in many ways, to obtain multiple transformations from the same surface. The experiment considers the activation of all the actuator as a net, in a way of increasing the total length of the wires and thus to increase contraction percentage.

In the case shown in Fig. 7, horizontal and vertical directions have been hypothesized because of the nature of the pleated pattern. Due to the inertia, for flat surfaces – folding percentage equal to 0 – it has been found difficult to activate pattern self-folding. On the opposite, once folding takes place, easier deployment rates have been found in order to reach the closed position. As an outcome of the digital exploration, it can be concluded that a pre-folded condition is necessary to actuate surfaces maintaining stable conditions during kinetics transformations.

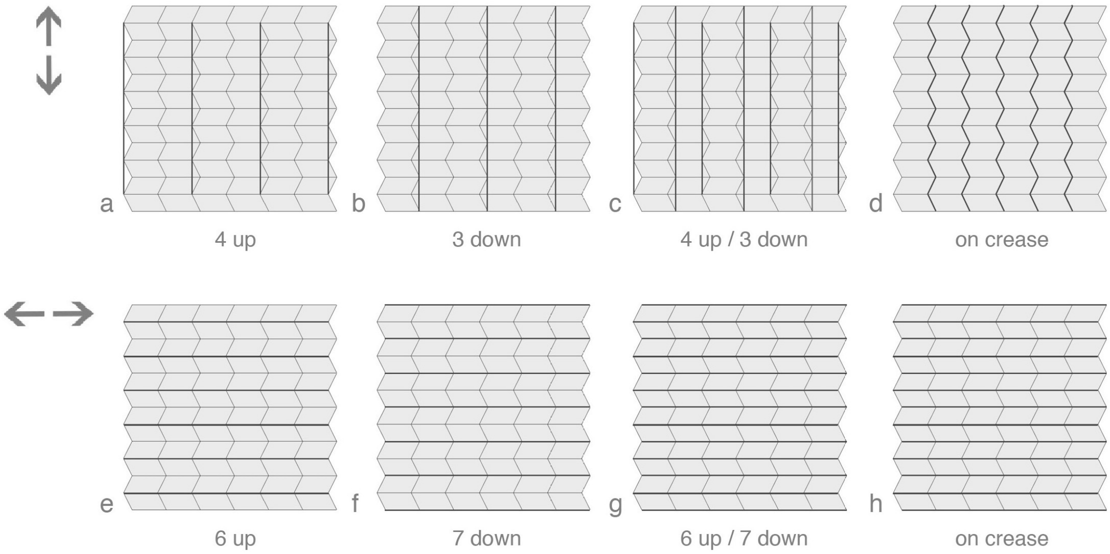

Fig 7. The arrangement of digital wires (black lines) on pattern affect folded shapes

3.2. Pattern comparison

The use of digital algorithm tools is not limited to a simple change of geometry values; they can also be used to apply external forces within the surface. Here, folding percentage is not directly related to real forces, but rather it indicates the degree of deployment due to the activation of the actuators. In this research the output data from digital softwares have been used to compare pattern geometry displacements based on the actuator locations, starting from the same boundary conditions.

The exploration investigates how the linear contraction executed by digital actuators has consequences on the two-dimensional or three-dimensional deployments of the creased patterns. The paper points out which wire configurations arise better folding percentages and thus can be used as a concept to develop a kinetic sunscreen that would be effective in a real situation. As a result, the method can be adapted to provide quick feedback for setting physical simulation.

Combining all the digital models together, Fig. 8 represents the outcome for the Origami diagrams investigated. The digital analysis focuses on the deployment optimization of each creased pattern according to wire distribution, constrained points and self-folding feature. For each pattern the extracted surfaces are presented by eight types of wire distribution – from a to h –, doubled to propose the same pattern without bonds and bonded. In order to activate self-folding, a fixed wires contraction of 25% has been set, so as to point out the amount of folding respect to the initial configuration. Without evaluating the wire length, at geometric level it must be noted that folding percentage and Kangaroo settings used to set up the simulation are the same for each pattern. So, it is possible to select through all the creased geometries, which one provides deployments eligible to optimize the movement. Once the first pattern has been activated, the contraction results in a surface reduction (A.a, B.a, C.a). The shape reduction of the other patterns has been defined by a percentage value compared with the first one. In this way it is possible to directly envision which patterns show the largest potential.

As shown in Fig. 8, V-pleats pattern (A) presents a deformation of about 24% (A.a). A better performance is achieved when SMA wires are inserted along the folding direction of the pattern, increased by 35% (A.b) respect to the previous pattern. Similar deployment values have been obtained also disposing wires "on crease", arranged orthogonally respect to folding direction (A.p). In this case the percentage grows to 40%. However, the latter wires organization generates bending that pushes the surface on Z-direction. This behaviour can be associated with the type of force applied, which reduces dimensions through a curvature in space. When one edge is fixed, in the case of actuators disposed "on crease" (A.r) the prevented deformation along Z-direction makes the surface unstable. Glide Reflection pattern (B) is described by an overall deformation if actuated by a grid of actuators horizontally and vertically organized. The most promising out of the sixteen patterns is the one defined by a regular wire net (B.f), with an increment of 18% respect to the 36% of the first pattern (B.a). This pattern (B.f) takes advantage of two actuator rows located along mountain and valley folds. The same result is displayed by the analogue fixed solution (B.h).

Differently from the previous geometries, due to its modular nature the Ron Resch pattern (C) works better with 60 degrees wires disposition. Advantageous deployment values have been found with wires inserted as hexagons around the module boundary points (C.p), able to reach a 20% growth respect to the 28% of the pattern with 9 wires arranged along the 60 degree angle (C.a). In addition, using wires to connect each boundary point with the central one allows to reach better deployment percentages. With 20% deployment respect to the first actuator positions (C.a), the pattern actuated by a triangular geometry wires arrangement repeated in each module (C.o) is the most interesting of the group with the previous one. Furthermore, if subjected to constraints, these two actuated patterns (C.r, C.q) are the only ones able to exhibit deformation along the Z-axis.

3.3. Preliminary exploration with physical SMA actuators

The geometric analyses conducted on both physical and digital models have shown some potentialities in the study of new deployable solar shading devices. To perform tests on a physical model, a Ron Resch pattern module has been chosen. The triangular sheet made of 300 g cardboard has been pleated without any cuts, so as to preserve self-folding characteristic. This pattern has been selected due to its triangulated elements, which assure structural integrity while maintaining all elements planar. Besides, using linear actuators placed on valley vertex allows achieving a better deployment level.

The preliminary tests have been carried out in an indoor laboratory, where the shape memory alloys wires have been joule-heated through electricity. In order to avoid the wire's overheating and thus losing the memory shape, a power supply feeder has been used to initiate Nitinol low temperature SMA wires. This type of alloy, which has a nearly equal amounts of nickel and titanium atoms, has a range of activation temperature that goes from 68 °C to 78 °C. Before inserting the wires on the Origami module, characterization tests have been conducted so as to verify the technical information provided by the producer. Even if the NiTi alloys could reach a contraction of about the 8% of their length, the cyclic memory strain was no more than 3.5-4%. Besides, according to the producer, if the materials are to be used extensively, it is recommended not to strain the wire over 5% of its length [25].

The first experiment has been made using 720 mm SMA wires with a 150 μm thickness stimulated by 16 V electricity input and 0.48 A. Test results of this module pattern highlighted how the self-folding properties of origami can be used to bring the wires at their initial position. Fig. 9 shows difficulties to insert the wire on pattern. Passing through the cardboard and returning to the centre compromises the actuation of the whole system. In fact, when actuated, the wires' contraction works against the direction of pattern folding.

Considering that, a second hypothesis of wires distribution has been made avoiding slipknot shape near vertexes.

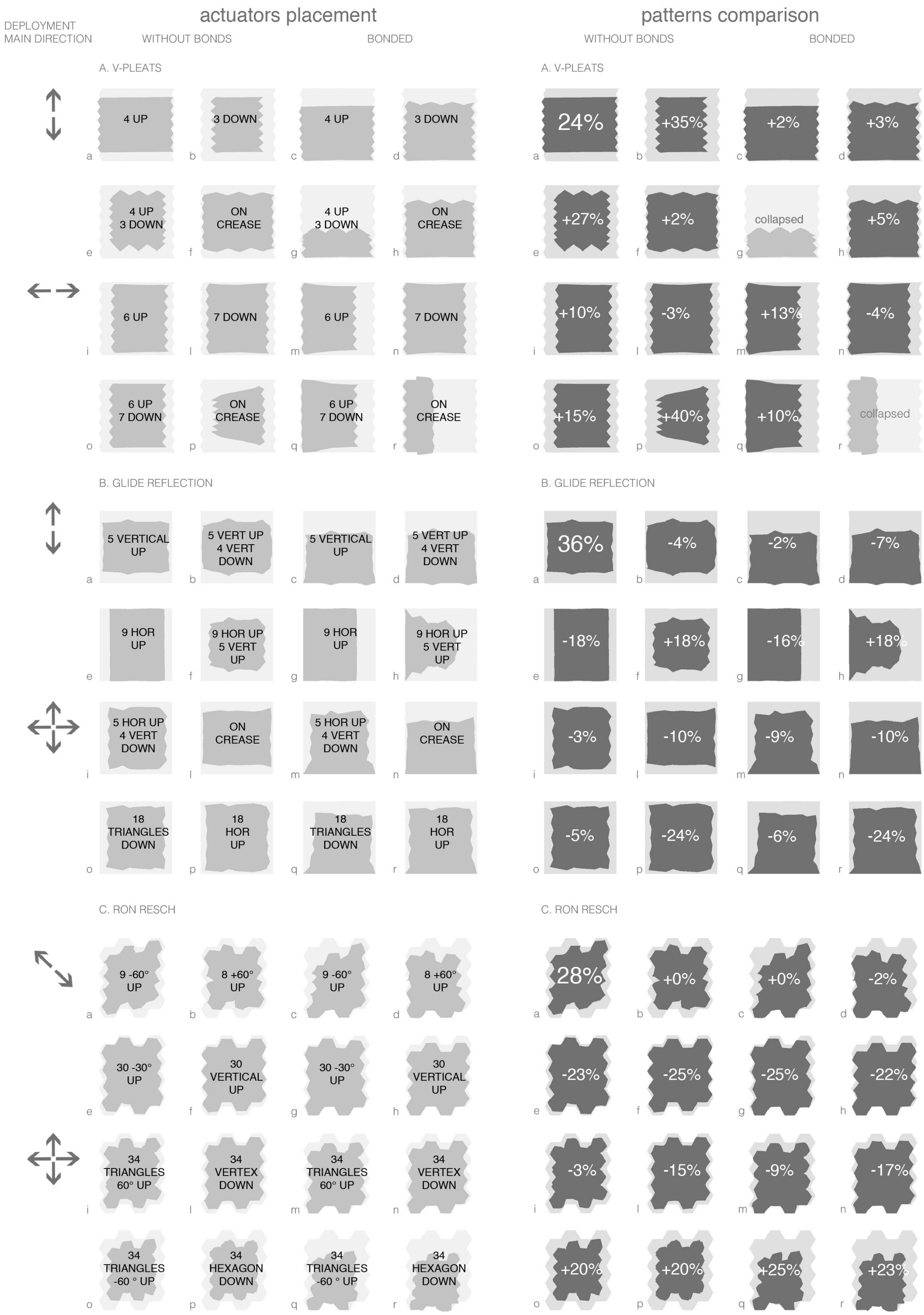

Fig 8. Pattern comparisons based on 25% actuators contraction: V-pleats (A), Glide Reflection (B) and Ron Resch pattern (C)

In this way it seems possible to prevent wire local deformation, which results in a pure linear deformation.

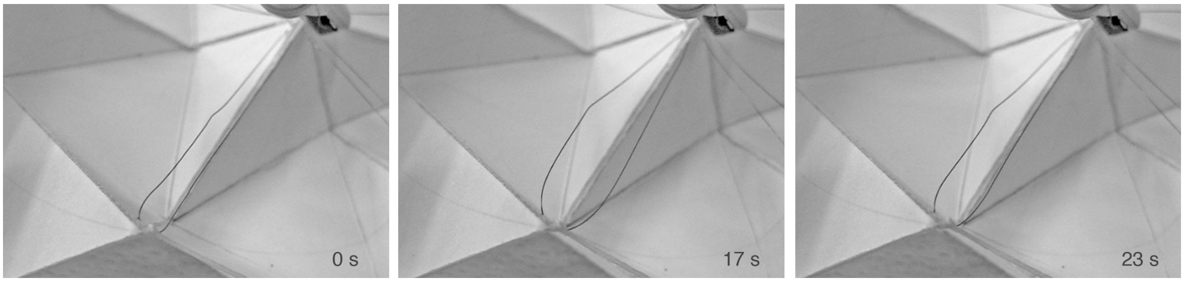

Fig. 9. Preliminary Origami patterns exploration and folding pattern with SMA wire application

The paper model in Fig 10 takes wires arrangement from pattern C.p (Fig. 8), based on hexagon wire displacement. This configuration used 360 mm out of the same type of SMA wire, here activated by 8 V electric current and 0.54 A. To prevent local deformation, the experiment did not take into account connection wires from the boundary vertexes to the central vertex. Even if this has underlined a physical contraction smaller than the corresponding digital one, the wires distribution here envisaged confirm what was found in the digital environment.

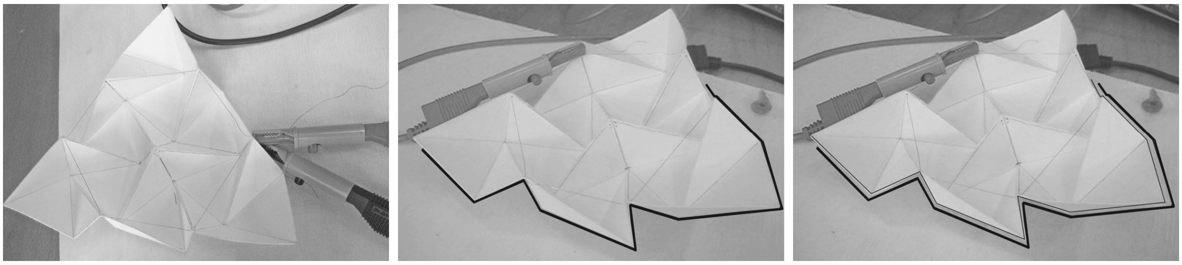

Fig. 10. The actuators placement allows envisioning the deployment direction

4. Conclusions

A folding technique used as a generative process promises, since early investigations, a new way to conceptualize a responsive kinetic façade. With this meaning, the principles behind the digital algorithms that generate the buildings' components geometry are here implemented by the mechanical motions of the digital wires. By integrating kinematics and kinetic constraints into one digital model, the research has been able to fully control geometry and wire linear deformation. Thanks to shape optimization, the use of smart actuators is becoming more feasible, leading to the development of further studies in order to test the real potentialities of the use of such materials. Hence, the flexible and lightweight characteristics of Origami geometries, combined with the use of active materials instead of mechanical devices can result in a reduction of actuation energy.

In recent years, an increasing number of researchers started to think about smart materials as a way to perform adaptation leading to an environmental responsive envelope. Although there are few examples of researches that have taken into account the use of smart materials as actuators [26], the growing interest for this topic continue to analyse the potentialities of those new kind of materials. Shape memory alloy wires, springs and plates have been extensively tested and studied in a variety of fields; therefore, on the base of their applications they currently remain within the most suitable materials for shading applications.

The preliminary physical experiments highlighted the necessity to somehow multiply the deformation of this new generation of engineered materials. At present, SMA wires have a non-sufficient deformation percentage for immediate use in adaptive shading devices. Furthermore, it is important to understand how to incorporate the wires into physical models without losing their capabilities. Geometric definition and SMA actuation must be deeply investigated in order to obtain their best performance.

The paper investigation has taken an initial small step toward the exploitation of new geometry potentialities in the field of shading devices. The approach of integrating form-changing parameters so as to think to SMAs as responsive actuators has shown a different angle of view about buildings' components conception. Far from suggesting an ultimate answer, the exploration wants to serve as a trajectory for future researches in the field of kinetic architecture.

For this reason, the research will continue moving from the early stage experiments presented here to new pattern comparisons and physical experiments. The future results will be addressed on conceiving a set of prototypes bridging the physical and the digital worlds.

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