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## Shaping an Origami shading device through visual and thermal simulations

Marco Pesenti<sup>a\*</sup>, Gabriele Masera<sup>a</sup>, Francesco Fiorito<sup>b</sup><sup>a</sup>*Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, 20133 Milano, Italy*<sup>b</sup>*Faculty of Architecture, Design and Planning, the university of Sydney, NSW 2006 Sydney, Australia*

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### Abstract

This paper presents the first results of a research work aimed at the optimisation of a shading system through parameters of visual comfort – Useful Daylight Illuminance (UDI), Daylight autonomy (DA) and Daylight Glare Probability (DGP) – and Total Energy (TE) consumption (cooling, heating and lighting per year). The goal is to define a shading system for office buildings that delivers visual comfort for users whilst reducing energy consumption for indoor climate control and artificial lighting.

As the design of the shading system considers the use of shape memory alloys (SMA) as micro-actuators to accomplish solar adaptation, Origami pattern has been adopted to guarantee a relatively large displacement of the shading system with a small deformation of the SMA wires actuators. Thanks to this shape change, generating overlapped pleats and angle variation and using different materials, it has been possible to provide alterations of the direct light transmission inside the building while maintaining a certain degree of diffuse light component.

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**Keywords:** shading device; thermal control; visual comfort; Origami; Shape Memory Alloy

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### 1. Introduction

The growing interest for adaptive systems that reconfigure themselves to meet climatic conditions and users' needs leads to envisioning an envelope that is multifunctional, responsive and dynamic [1]. As a response to the expected reduction of building energy consumption, the studies about kinetic shading devices to perform adaptation show

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\* Corresponding author. Tel.: +39 3463952051

E-mail address: [marco.pesenti@polimi.it](mailto:marco.pesenti@polimi.it)

possibilities to enhance the environmental performance allowing better users' comfort and better integration between envelope and building. Bringing natural light into the building is one of the key strategies to save energy and to satisfy user's comfort requirements. In fact, as the literature suggests, light provides better environmental quality by influencing physiological and psychological responses, such as the human biological rhythm [2][3][4]. However, if the amount of light coming through the windows is too high, other issues like the rise of internal loads and the glare discomfort can happen [5][6].

In order to increase the responsiveness of the shading systems and to reduce the occurrence of failures typical of traditional, mechanically-operated devices, the use of Shape Memory Alloy (SMA) micro-actuators electrically activated has been considered. Since several studies are investigating the use of shape memory materials as actuators to accomplish solar adaptation [7][8], the information available in literature and studies by the authors including physical models with SMA wires [9] showed some restrictions in terms of deformation and material handling. With these regards, through the shape change generated by Origami patterns coupled with SMA micro-actuators, the research computes in which measure the deployment of the pattern and its angle variation resolve the light transmission inside the building while maintaining a certain degree of diffuse light component. Choosing materials with different light transmission properties, it has been possible to highlight how the shades operate as dynamic elements able to filter the solar radiation throughout the year.

The importance of natural light as a way to reduce the energy consumption and to reach a better level of satisfaction for the users has been evaluated through the consideration of the Useful Daylight Illuminance (UDI), Daylight Autonomy (DA) and Daylight Glare Probability (DGP) parameters. Then, the evaluation of the Total Energy (TE) needed for cooling, heating and lighting based on the type of shading has been assessed so as to find optimised configurations. A single office room has been evaluated through the variation of several parameters of the shading device. The impact of these changes has been studied through computer annual simulations of thermal and daylight distribution by using 3D software tools.

The initial analyses presented in this paper, carried out with a 3D parametric model, investigate how the combination of different parameters (e.g. reduction of total energy demand and increase of visual comfort) can influence the performance of the analysed room. In each configuration, the light transmission properties of the materials are set in accordance with the desired amount of shading. Reproducing that for three diverse rates of shading device deployment, different materials have been combined to define a variety of possible mixed solutions able to cope with the deployment percentage limits while meeting the expected values of UDI, DA, DGP and TE.

## 2. Method

The process starts considering three configurations to reproduce the behaviour of the Origami shadings for a medium-sized office room throughout the whole year. The Ron Resch Origami pattern has been chosen because of its dynamic characteristics, which allow the shape to expand, contract, to be bent and twisted in many directions [10]. Furthermore, the application of SMA wires along the outer edges of each triangular module has shown the potential to deliver an interesting rate of contraction [9]. The focus is about the analysis of the main shading pattern using different materials and percentage of displacement. In this way, it has been possible to understand the potential of each configuration from the point of view of energy efficiency and visual comfort. Moreover, a comparison among the Origami configurations and the solutions with no shading and complete shading has been carried out.

Due to the parametric nature of the study, the Rhinoceros® plug-in Grasshopper® has been used to conduct the analyses. The generation and alteration of all modelled elements has been controlled with the software thanks to specific algorithms that define the rules. Thus, by changing parameters, the architectural elements can be easily controlled. While parametric software was used to combine different dimensions and proportions and to simulate shape kinetics, daylight and thermal analyses have been carried out considering the pattern variations as static during the year. To do that, the plug-in Honeybee® [11] has been adopted to run the environmental simulations. Honeybee allows the user to connect Grasshopper to EnergyPlus™ for thermal simulations, and Radiance® and Daysim® for daylight analyses.

The calculation has been developed in two steps: the first analysis considers UDI, DA and DGP as parameters to assess visual comfort conditions. According to [12] UDI has been defined as the annual percentage of illuminance values on the reference point within the comfortable range of 100 – 2000 lx while the DA threshold has been set to 500 lx [14]. A DGP maximum threshold of 0.35 has been considered [13]; it corresponds to the limit between

perceptible and disturbing glare. The second analysis investigates the potential energy impact of each shading configuration considering the overall TE.

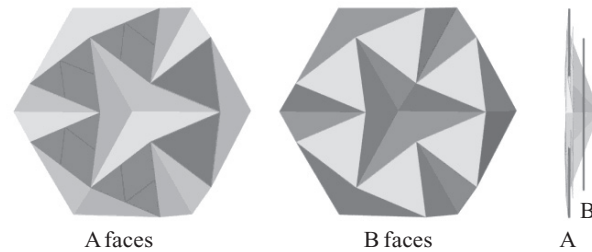


Fig 1. Simplification of the Origami pattern's geometry.

During the preliminary simulations the three-dimensional nature of the shading device proved difficult to compute properly. So, to avoid geometric issues with the ray-tracing algorithm and to obtain reliable data, a shape simplification of the geometric model has been introduced. As shown in Fig. 1, the 3D shading shape has been flattened maintaining the ratio of overlapping surfaces of the contracted Origami (10% and 25% configurations). Then, based on the 3D Ron Resch pattern depth, the gap between the two layers (A, B) has been calculated.

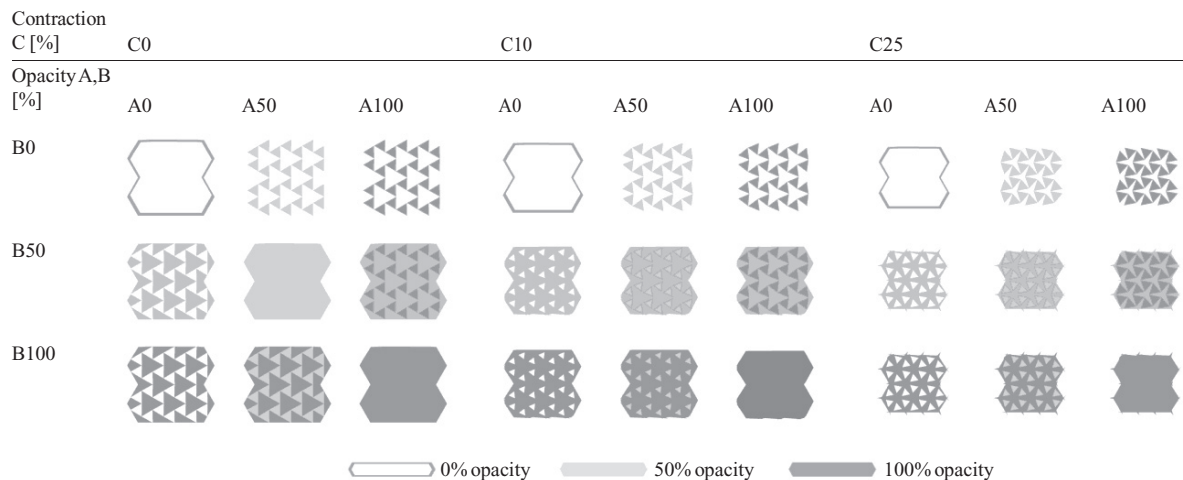


Fig.2. Twenty-seven configurations of shadings: no shadings (A0; B0), complete shading (A100; B100) and mixed combinations of opacity for the A and B faces, each for a specific rate of contraction.

To take into account the dynamic behaviour of the shading, the simplified pattern has been reproduced varying the rate of contraction and the materials' opacity for A and B faces. This variation generated twenty-seven configurations.

The proposed shading solutions have been then applied to the south-facing window of a typical office space. The office room is 3 m wide by 5 m deep, with a south-facing window 2.2 x 2.5 m wide (window-to-wall ratio of 60%). South facade has been modelled as fully exposed to outdoor, while all the other surfaces have been simulated as adiabatic. This assumption is realistic because the single office room is ideally part of a medium-size office building. A Double-Glazed Unit (3+13+3) has been adopted as window's transparent panel. Overall, the Visible Light Transmittance (VLT) of the window is 0.837, the Solar Heat Gain Coefficient (SHGC) is 0.75 and the central thermal transmittance of the window is 2.8 W/m<sup>2</sup>K. External shadings have been positioned at a distance of 100 mm from the outer window's panel. Milan (Italy) has been assumed as location and hourly weather data have been extrapolated from the International Weather for Energy Calculation (IWEC) database. Out of the entire year, only the simulation results in the period of time from 8.00 am to 6.00 pm for the working days have been considered.

## 2.1. Daylight Simulation: UDI, DA and DGP

In order to evaluate the trend of the selected daylight parameters, annual simulations for each configuration have been performed. To create a realistic scene, all the inner surfaces have been assigned with a material. According to the European standards [14], reflectance values of the surfaces have been set to 20% for the floor, 50% for the walls and 80% for the ceiling. The surface specularities have been considered equal to zero, while a smooth to medium-smooth roughness has been associated to opaque surfaces. This assumption has been made in order to consider a perfectly diffusing behaviour and the ability of indoor surfaces to reflect light equally in all directions. Two different materials have been associated to the shading devices with Ron Resch geometry pattern. The first one, opaque, has been identified as a metal with 68% reflectance, 1% roughness and 1% specularity. The second one, a translucent plastic material with 5% reflectance and 50% diffuse transmission, defines the shading material with 50% opacity.

UDI has been calculated as the average value over 8 reference points equally spread onto a 1 x 1.5 m work plane. The work plane has been assumed at 0.8 m above the floor and its reflectance has been considered as negligible.

In order to calculate surfaces' luminance values, and therefore to define the glare probability, the viewpoint has been located at 2.5 m of distance from the window and at 2.5 m of distance from the west wall. It simulates a seated user (eyes at 1.35 m above the floor) looking the south-west corner (45 degrees to the south window). This position has been assumed so as to evaluate the worst condition without considering a computer screen on the work plane. Radiance simulated parameters have been defined according to previous researches carried out in similar conditions [15][16]. In particular an ambient bounces (-ab) of 6, an ambient division (-ad) of 2000, and an ambient super-sample (-as) of 16 have been assumed.

## 2.2. Thermal simulation: the total energy needed for cooling, heating and lighting (TE)

The thermal model was built with EnergyPlus 8.1™, a thermal dynamic simulation program widely used and validated in several researches performed in similar cases. Internal loads have been considered following Italian codes and standards. Infiltration rate of 1.5 ACH and ventilation rate per person of 0.88 ACH have been set [17]. The assumed occupancy is 0.067 p/m<sup>2</sup> (1 seated person per room), while artificial lighting load is 9 W/m<sup>2</sup> and equipment load is 10 W/m<sup>2</sup>. These are average values typically needed for single-occupancy offices. Artificial lighting has been assumed as linearly dimmable and controlled through natural light sensors; the total amount of light (natural and artificial) has been assumed to provide the room with a minimum level of illuminance on the work plane of at least 500 lx [14]. Thus, the thermal model used the output of the daylight simulation to create lighting schedules that varies based on the calculated illuminance values on the work plane.

As for the internal loads, an ideal air system has been considered active during the occupancy period, with heating set point temperature of 20°C and cooling set point temperature of 24°C. Ideal Coefficients of Performance (COP) of respectively 3.5 and 2.5 have been assumed for cooling and heating.

In order to properly compute the Origami shading geometry in the energy simulation, rather than using the restricted design components for shading devices provided by Honeybee, it has been necessary to consider it as an outer element of obstruction of the window. Thus, through the Context Surfaces component, the geometry has been linked to the office zone. Moreover, the use of the EnergyPlus solar distribution parameter "*Full Interior and Exterior with Reflection*" has been considered [18], so as to take into account the effect of the shading device. Furthermore, while Radiance allows assigning materials to the objects, EnergyPlus simulations through Honeybee allow doing so only if a thermal zone is involved. Therefore, to consider the rate of opacity of the shading device, a transparency schedule has been defined.

## 3. Results and discussion

The simulation outputs are shown in Tab. 1. For each pattern, the amount of TE is included, together with the annual percentages of UDI (below, within, or above the comfortable range of 100-2000 lx) and the annual percentage of hours with a daylight autonomy over 500 lx and non disturbing glare (DGP < 0.35).

If the first block of data is considered, which is the situation with transparent B faces, the behaviour of the shading device does not show a significant increment of the UDI rate when the shading moves from the open position to the closed position while the DA percentage drops down under the 50%. Instead, DGP percentage increases,

highlighting a reduction of glare probability with opaque A faces (A100). Furthermore, analysing the TE values, it is noticeable how the deployment of the shading takes to better energy performance thanks to the increase of the shaded area (C25; A100; B0).

Tab.1. TE, UDI, DA and DGP data subdivided by contraction (C) and opacity rate (A, B).

Contraction C [%]		C0			C10			C25		
Opacity A, B [%]		A0	A50	A100	A0	A50	A100	A0	A50	A100
B0	TE [kWh/m <sup>2</sup> y]	109.7	96.2	91.6	109.7	93.5	88.6	109.7	91.5	79.1
	UDI < 100 [%]	8.2	9.4	10.7	8.2	9.7	11.0	8.2	10.3	13.1
	UDI 100-2000 [%]	67.2	70.1	74.2	67.2	70.0	73.4	67.2	70.5	74.0
	UDI > 2000 [%]	24.6	20.5	15.1	24.6	20.3	15.6	24.6	19.2	13.0
	DA > 500 [%]	78.3	74.5	67.3	78.3	73.6	65.2	78.3	69.6	45.2
	DGP < 0.35 [%]	73.0	74.9	84.9	73.0	76.7	86.4	73.0	76.2	90.1
B50	TE [kWh/m <sup>2</sup> y]	91.2	86.7	89.1	97.0	83.0	88.9	64.0	69.8	84.5
	UDI < 100 [%]	10.5	12.7	15.5	11.8	12.9	14.7	11.3	13.4	16.3
	UDI 100-2000 [%]	70.2	76.5	84.5	74.1	81.6	85.3	70.6	82.2	79.1
	UDI > 2000 [%]	19.3	11.3	0.0	14.1	5.6	0.0	18.1	4.4	4.5
	DA > 500 [%]	68.9	62.3	49.9	64.3	59.6	51.8	65.9	57.4	42.9
	DGP < 0.35 [%]	79.2	85.2	99.6	81.5	91.0	99.6	79.9	94.1	97.9
B100	TE [kWh/m <sup>2</sup> y]	95.2	100.3	144.1	133.3	148.2	144.1	85.1	112.7	144.1
	UDI < 100 [%]	14.2	24.1	100.0*	46.0	59.6	100.0*	20.6	36.1	100.0*
	UDI 100-2000 [%]	75.0	75.9	0.0*	53.5	40.3	0.0*	71.7	63.9	0.0*
	UDI > 2000 [%]	10.8	0.0	0.0*	0.6	0.0	0.0*	7.7	0.0	0.0*
	DA > 500 [%]	39.0	29.8	0.0*	6.7	0.0	0.0*	21.0	3.7	0.0*
	DGP < 0.35 [%]	97.2	100.0	100.0*	99.2	100.0	100.0*	97.4	100.0	100*

\* shading completely opaque, therefore no natural light passes through the façade system

Except from DA, better results are visible in the second stack of data, where the mixed shading materials highlight the best values out of the other parameters accounted. The most promising configuration is the one with opaque A faces and translucent B faces in their contraction at 10% (C10; A100; B50), which displays 20.8% TE saving, 18.1% increment of UDI percentage and 26.6% DGP values under the threshold in comparison to the configuration without shading (C0; A0; B0). Moreover, comparing that with the same configuration with transparent B faces (C10; A100; B0), the potential benefit of using a translucent shading material is clear. While TE remains the same and DA slightly decreases, the UDI and DGP percentages improve thanks to the addition of the translucent layer, which maintain daylight and heat transfer in winter while limit overheating in summer. The same happens when the contraction is equal to 0% (C0; A100; B50), where the parameters are mediated by the translucent shading, showing 84.5% of UDI and the 99.6% of the time under the DGP limit of glare. On the opposite, the last block appears to be the worst out of the three, displaying lower performance when opaque B faces and variable A faces are considered. While in the open position the values of the first column can be compared with the other lines (C0; A0; B100), when the shading device starts to close the amount of total energy dramatically increases and the rate of UDI and DA decrease considerably (C10; A0; B100) (C10; A50; B100). When a contraction of 25% is applied, the values fairly improve because of geometric reasons (C25; A0; B100) (C25; A50; B100). In fact, being the Ron Resch pattern a 3D geometry, the opaque B faces collapse into a sort of pyramid. Thus, this type of movement reduces the opaque areas through contraction and so, the ratio between the two face types (A, B) substantially changes. That's why the values highlighted in the last third of the last line show better performances than the second line.

The preliminary analyses show the overall behaviour of each pattern during the whole year, allowing to discard

those configurations that do not show promising result throughout the year. Instead, the annual data coming from each simulation describe the amount of contraction the SMAs have to perform, hour-by-hour, in order to achieve the fixed thresholds. Thus, through dynamic simulations delivered over static configurations, it is possible to know the required adaptation of the shading device.

#### 4. Conclusions

Envisioning an adaptive envelope means to optimize the relationship between interior and exterior continuously and so to assess the correct visual and thermal conditions inside the building. In this paper, simulations have shown how the control of several parameters can deliver energy saving and users comfort goals. The combinations of different materials to cope with the imposed thresholds highlighted the intrinsic potential to have a dynamic shading device instead of a static one. Mixed combinations show the most promising behaviour, highlighted by their ability to contribute during the whole year to a reduction of the energy consumption, an increment of the daylight autonomy and a more uniform daylight distribution in the office room. Starting from the idea of activating the adaptive shading device with shape memory alloys (SMA) micro-actuators, the research will continue to investigate how these materials work, testing their capabilities when applied to Origami shapes. More refined analyses are required to consider a variety of shading schedules that take into account the continuous adaptation of the shading device, with their own specific light-transmittance properties that will be considered in the optimisation process. Moreover, a complete definition of the three-dimensional shading geometry – simplified for this first step of the research – will be assessed, in a way to increase the accuracy of the model and thus to predict the pattern's behaviour more reliably.

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