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# Openwork Walls and Their Solar Applicability Range

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**Abstract:** The environmental potential of perforated surfaces in the tropics is noticeable. They allow obtaining higher attenuation and spatial dispersion of both direct and diffuse lighting in indoor spaces, whereas in outdoor areas, the openwork elements reduce surfaces temperature and mitigate the characteristic glare of smooth surfaces when exposed to sunlight. Openwork walls have an immense sustainability potential in modern tropical buildings: they limit the solar rays' admission, as well as provide an advantageous use of natural light and cross ventilation, but the research on their solar behavior is scarce. In order to obtain suitable levels of solar gain, relationships among shape, proportion, thickness and partitions composing openwork elements must be studied. This research evaluates solar gain in perforated surfaces by defining the "solar applicability range", a property useful to identify intervals of guidance where a perforated pattern shape will present a definite solar gain, giving valuable input in the geometric design of openwork elements and introducing shade performance in the design of openwork walls. Results give geometric guidelines that allow to widen the solar applicability range of a perforation pattern and to define two perforation features that have impact on the solar performance of perforated surfaces: focalization and solar performance shift.

**Key words:** Openwork bricks, openwork walls, solar performance, shadow, tropic architecture.

## 1. Introduction

Perforated surfaces are one of the cheapest methods for dealing with solar control needs without sacrificing natural air circulation. Sometimes, this type of surfaces is the only lighting and visual connection with the outside and, sometimes, it is an extra element to the projects' windows. Vernacular architecture of many places presents buildings' envelope with this type of solutions and many buildings from the last century show examples of openwork wall application, in particular, in the equatorial zone [1]. Since this type of solution is still valid, modern interpretations are numerous and the subject is far from being exhausted (Fig. 1).

Contemporary environmental needs require to integrate shadow into the architectural surrounding structure in a predominant way. What resulted in the esthetic delight of surfaces with visually attractive shadow patterns is now going back to the primary sense of openwork: a device favoring energy efficiency in buildings and improving environmental conditions inside them [2]. The inclusion of digital production and parameterization in architecture opens an immense field of exploration for openwork surfaces and allows environmental aspects to be taken into account when determining their different materials, textures, color and geometrical features.

The environmental benefits and the innovation possibilities offered by openwork surfaces are broad, but it is necessary to study this type of surfaces in depth. An openwork element produced by using the prefabricated technique should have a good solar performance in any orientation which it is used, but this is not always possible. That is the reason why this research widens the conceptual basis needed to understand and predict solar performance of openwork surfaces.

Solar gain in perforated surfaces is evaluated by defining the "solar applicability range", a property useful to identify intervals of guidance where a perforated pattern shape will present a previously established "desired solar gain level". Results give geometric guidelines that allow to widen the solar applicability range of a perforation pattern and to define

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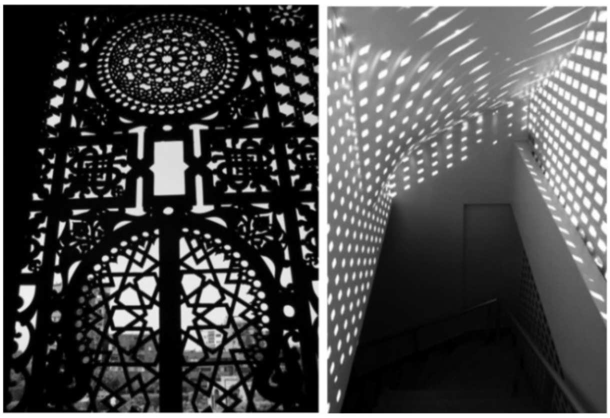

(a) (b)

**Fig. 1 Openwork elements are part of the architectural tradition of many places on the planet: (a) Cairo, 19th century or earlier; (b) Brasilia, 20th century.**

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two perforation features that have a strong impact on the solar performance of perforated surfaces.

## 2. Void-Surface Ratio and Its Benefits in Tropical Regions

An openwork surface is composed by empty and full shapes alternated according to some types of rhythm. Apparently, when studying this kind of surfaces, the relevant aspects are the empty spaces, which break the surface monotony, which otherwise would be continuous and homogeneous. Certainly, perforations' shape, size and direction strongly determine the solar performance of openwork surfaces, but that is not all. Alternation and separation between fullness and emptiness totally depend on the solid shapes, which define the proportion between both. There is no rhythm without the full shapes.

The relationship between the area occupied by the openwork surface and the total area of its empty shapes depends almost completely on its full shapes, and in particular, on the width and shape of the partitions separating a drilling from its neighbors. Even for reduced partition thicknesses, to package a 1.0 $m^2$ emptiness in 20 or more perforations will always cause a significant increase in the surface area to be intervened, regardless of the drilling method. Doubling partition thickness will always result in a sudden and non-linear increase of the area needed to reach an equivalent empty area. This situation becomes more evident as the full/empty proportion increases, either because perforations become smaller or because partitions become progressively thicker. In both cases, a much bigger surface will eventually be required to be able to place all the perforations needed in an orderly way.

Since the increase in the area needed for the distribution of modulated, regular and easy-to-pile-up openings depends mainly on the partitions' width and shape, using regular polygons does not affect more than 5% on the area required for the perforation distribution. The maximum value of compactness corresponds to a perforation pattern carried out with regular hexagons (Fig. 2). The impact of the shape factor becomes evident with rectangles having 2:1 and 3:1 proportions. This originates an increase of about 10% in the required area. The situation changes when the perforations' shape does not allow such a compact packaging: without the possibility of minimizing the surface intended for the partitions, the empty/full relationship begins to be determined by empty shapes rather than by full shapes.

The spatial dispersion of solar radiation entering through an openwork surface does not solely depend on the increase of the area needed for perforation distribution. Every opening made on a surface originates some solid partitions with a considerable perimeter area. Unless a wall has exceptional thickness, the surface provided by its perimeter planes close to the released area is in no window. It suffices to fragment an opening into a few perforations for the relationship between the perimeter planes surface and the released area to be reversed and becomes markedly unequal. This phenomenon is very prominent: for a 0.15 m thick wall, it is enough to have a 1.0 $m^2$ square opening divided into three for the perimeter planes to totalize an area equivalent to the void. If the opening is repeatedly subdivided until reaching 25 equal 0.20 m × 0.20 m perforations, then the perimeter area will triple the area

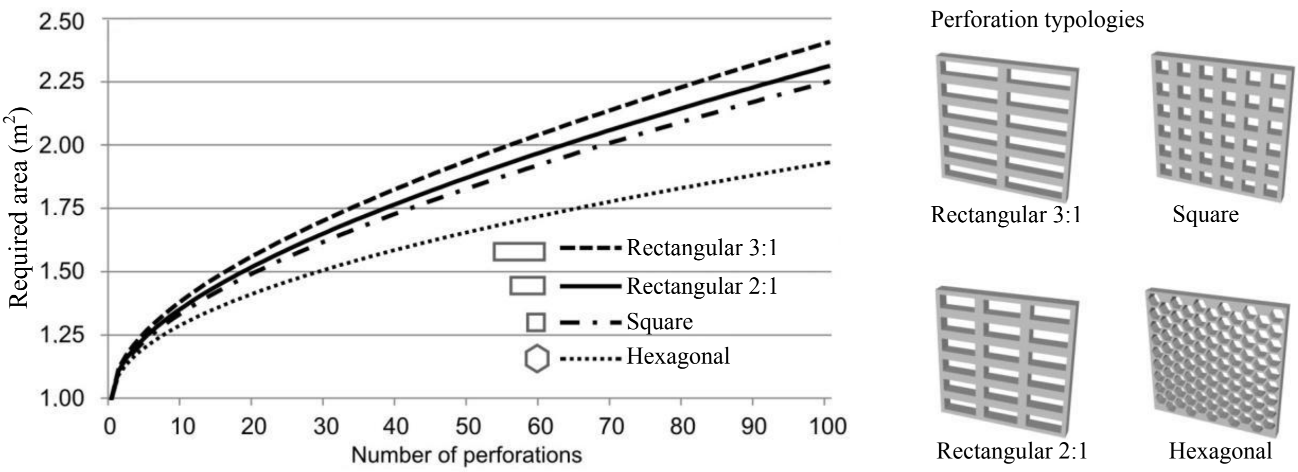


**Fig. 2 Required area for placing perforations totaling 1 m$^2$ with 5 cm width partition walls.**

of the void. This relationship becomes more dissimilar as the number of perforations, the thickness of the perforated surface and the angle of such perforation increase. A little geometry suffices to demonstrate that the relationship between both areas is exponential and that for square perforations over 150 subdivisions, this relationship becomes, in practical terms, almost linear, without this behavior substantially affecting the variation in the shape of the voids (Fig. 3).

The surface increase, when a wall is no longer solid and is replaced by several small and repeated perforations, has an important impact on the environmental performance of the enclosures that have openwork walls. An openwork surface never gathers environmental factors inside a space as much as a single opening does. When the interaction surface between the indoor and the outdoor environments increases, an evidently greater exchange area becomes available. Consequently, solar rays have a greater surface to become heat, light has more planes to spread on and air has more elements to exchange energy with. That is the reason why when a surface is perforated massively, there is always an expansion of its transition zone, favoring a higher energy dispersion compared to the one originated by a single opening of equivalent area.

When an opening in a wall allows the entry of solar rays, the enclosure will present a sun incursion region. The division of this opening into several openings creates a set of small sunny locations with a higher spatial dispersion (Fig. 4). Although the perforations sum up the same area of the original opening, the impact

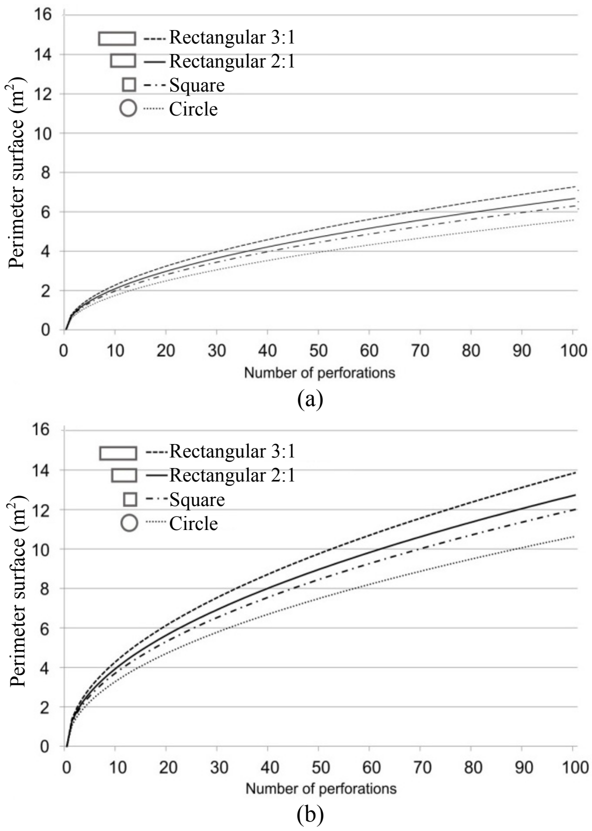


**Fig. 3 Openwork wall surface variation depending on the opening shape for a constant open area of 1 m$^2$: (a) perimeter surface depending on the number of perforations for four types of holes drilled on a 15 cm thickness wall; (b) same results for a 30 cm thickness wall.**

on the indoor environment is lower in terms of light and heat [3]. Additionally, as the perforations become smaller, the shadow contribution of the planes that define the compartments becomes proportionately larger, which is why, for a constant thickness, an openwork wall will always result in a lower solar income than a single opening of equivalent area (Fig. 5).

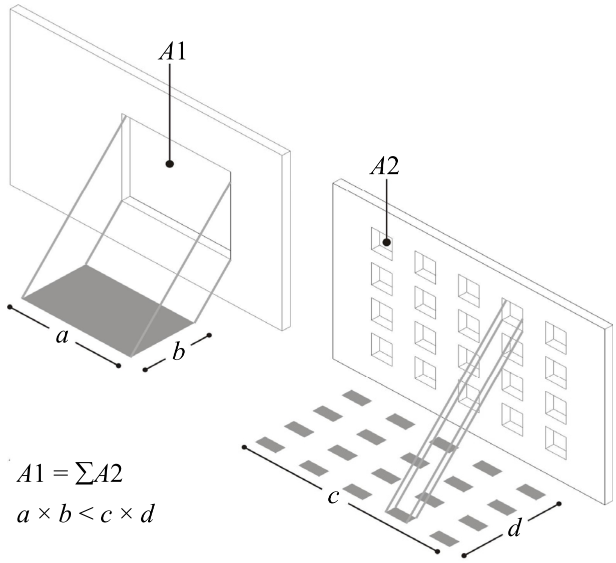


**Fig. 4 Sunlight spatial dispersion: the openwork area exposed to solar radiation can be equal to an equivalent area window, but distributed over a larger area. Its impact is lower in terms of light and heat.**

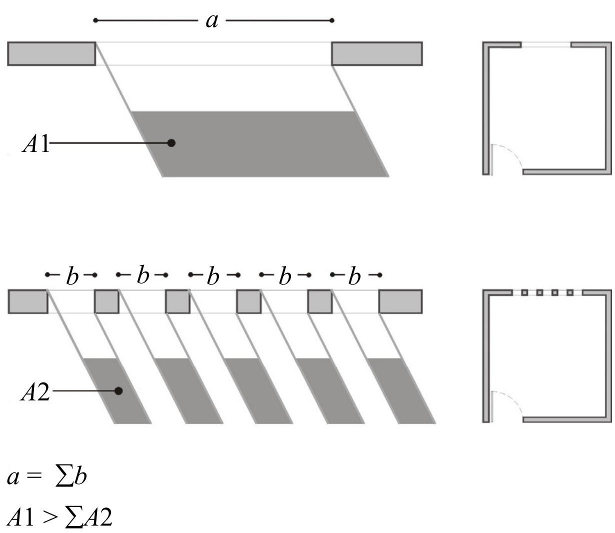


**Fig. 5 For a constant thickness, an openwork wall will give origin to a lower solar income than a single opening of equivalent area.**

Dispersing solar radiation has a beneficial effect in the tropics, where light intensity and solar power surpass by far the maximum bearable threshold. In temperate zones, openwork surfaces are not common since hermeticity, exchange surface minimization and transparency maximization are the norm for those places. On the contrary, in places with high temperatures located between the tropics or near one of them, perforated surfaces have been successful.

Architecture for the tropics shows great affinity with rugosity and penumbra because of their intense solar influence [4]. The environmental potential of perforated surfaces in this part of the planet is noticeable since increasing the perimeter surface widens the range of architectural options to respond to climatic agents [5]. Perforated surfaces allow to obtain a higher attenuation and spatial dispersion of both direct and diffuse lighting in indoor spaces, whereas external conditions are shaded in outdoor spaces. This reduces sunny surfaces temperature and mitigates the characteristic glare of smooth surfaces when exposed to sunlight.

## 3. Solar Radiation in Openwork Walls

In order to obtain suitable levels of solar gain, relationships among shape, proportion, thickness and angles of the partitions composing the openwork elements must be studied first, according to the sunshine conditions of the place. In any openwork wall, if both the desired maximum solar gain and the range of orientations advised for the use of openwork brick have been established, it is possible to derive the geometric configuration and proportions of the solid elements comprising the wall [3]. To further develop the previous work, in which the procedure allowing to carry out studies about sunshine on openwork walls was emphasized, here we define the geometric characteristics that define the solar performance properties of the openwork walls.

The solar geometry principles applied in the evaluation of openwork walls allowed to demonstrate that each perforation pattern has a different solar performance which depends on latitude, solar access allowance, geometry of the perforation and especially, orientation of the plane that contains them. In the past, previous works analyzed openwork elements with a diagnostic approach using shadow masks [6], but these studies have not been quantitative. Comparison of different openwork designs based on the amount of solar radiation that crosses the wall, as well as the calculated orientation ranges which would be inappropriate to apply, would help to obtain other results.

Knowing in advance the range of orientations for which an opening with a particular shape will have an adequate solar behavior is the first step for the environmental optimization of the openwork wall. The variety of openings and possible orientations is large and, therefore, a method has been developed to study the openwork walls to make their geometric enhancement possible, improving the shading level that can be achieved. The aim of this research was to define an openwork wall property called "solar applicability range" in order to establish orientation intervals for which a perforated wall will provide a certain level of shading and use this parameter to identify practical traits of the perforated elements, which allow to formulate strategies intended to improve their performance.

To study the effectiveness of solar control devices preventing sunlight entrance through an opening, it is necessary to calculate the shaded area for every solar position during the year, regularly assuming no cloud covering. The procedure that allows comparative studies of the solar performance for any shape is named "shading device evaluation method" [7, 8], but it has not been applied to the study of openwork bricks so far.

## 4. Methodology

The calculations by which we have studied the solar performance efficiency in various shading devices are based on orthogonal projections in the direction of the opening or the working plane. It is a methodology suitable for openings with significant size, but would require excessive computational power when applied without modification on an array of items. To overcome this difficulty, we decided to work with shadow masks and, therefore, in polar coordinates. The automation of such projections allowed the increment of the resolution of the analysis to the necessary degree to make quantitative assessments. The average time of sun exposure was obtained by superimposing a cloud of points outlining the solar paths over a set of shadow masks produced from the geometrical transformation of the studied element. The analysis procedure requires modelling the openwork element through 3D drawings representing, one by one, all its partitions. Using the 3D model and from a point located behind the element, numerous projections are made toward a hemisphere representing the sky dome.

Choosing the representative point for the geometric transformation to be carried out requires, first of all, identifying the distance in which maximum outward visibility conditions would happen. Trigonometric functions that relate distance, wall width and perforation size allowed to conclude that the optimal distance to carry out the analysis of a perforation varies, in a non linear way, according to the progressive increase in the surface thickness. For a 0.05 m thickness surface, the optimal assessment distance is 0.07 m, and for 0.20 m, this distance only increases to 0.10 m. A diagram calculated based on the perforation height allowed to generalize the results for square and rectangular perforations (Fig. 6).

By using this point as the center of a polar coordinates system, every flat polygon composing the openwork element representation was transformed into a spherical polygon, to finally have a spherical representation of the complete object (Fig. 7). On this spherical model, a cloud of points representing the paths of the sun for the latitude under consideration was plotted by 1,949 points calculated every 12 min, distributed throughout the solar trajectories every 5 days during half the course of a solar year. These parameters were enough for the level of resolution required for this study.

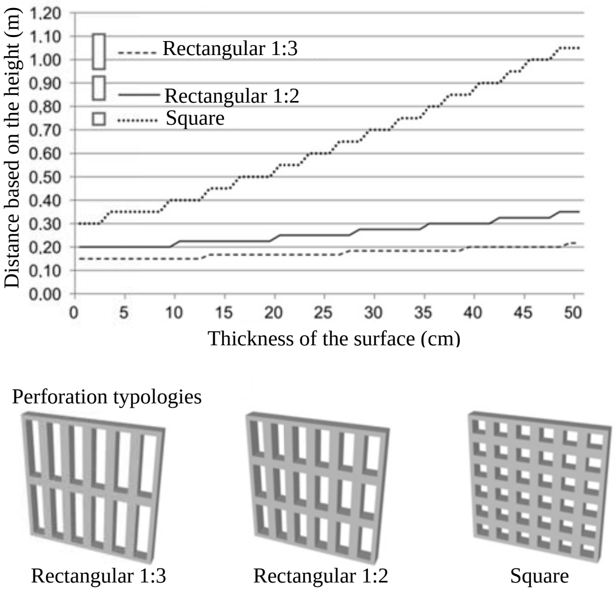


**Fig. 6 Distance based on the perforation height, for which maximum visibility conditions are present through perforations of different proportions as the perforated surface thickness increases.**

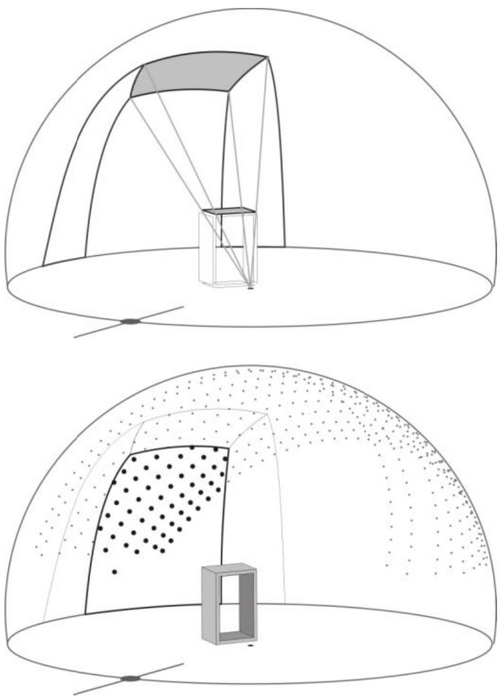

**Fig. 7 Each flat polygon composing the openwork element is transformed into a spherical polygon to create the shadow mask needed to totalize the solar positions not included in the shadow mask.**

To distinguish the intervals when the solar rays are entering through the opening under evaluation, it was necessary to make a polygon-recognizing process to totalize the solar positions not included in the shadow mask. The number of unshielded solar positions during the year is enough to calculate the sun exposure, giving a daily average in minutes of the sun rays reaching the analysis point. Counting unobstructed solar positions gives a value which is only valid for one orientation. The computer routines then store such result, rotate the spherical polygons 10° and repeat the count in order to complete one orbit around the point of analysis. The result is a list of 35 values of sun exposure that the openwork element would present in all the possible orientations. Thus, different comparisons between perforation patterns can be made with ease (Fig. 8).

Having calculated the solar performance of different openwork elements, the resulting database was processed with respect to a reference value called “solar entrance threshold”. This is the highest degree of sun exposure that can be considered as acceptable for the conditions of use and climatic characteristics of the place where the openwork wall will be built, for instance, 4.0 daily hours in public spaces, 2.5 daily hours in scholar buildings and 1.5 daily hours in office buildings, for the mild climate of Medellin, Colombia. This procedure helps to identify orientations which, for a given geometric solution, would result in values above or below the solar gain reference.

Grouping the results that fall within the threshold values determines the “solar applicability range”, i.e., orientations for which a pattern of perforations will present an acceptable level of sun exposure (Fig. 9). Broader ranges represent the possibility of a wider

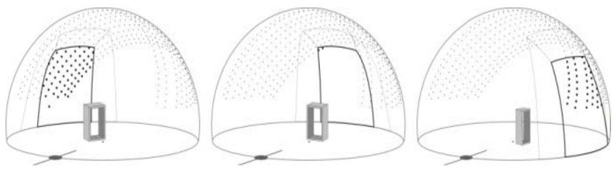

**Fig. 8 Counting unobstructed solar positions gives a value only valid for one orientation, so the result is stored, the spherical polygons are rotated and the counting is repeated until completing one orbit around the analysis point.**

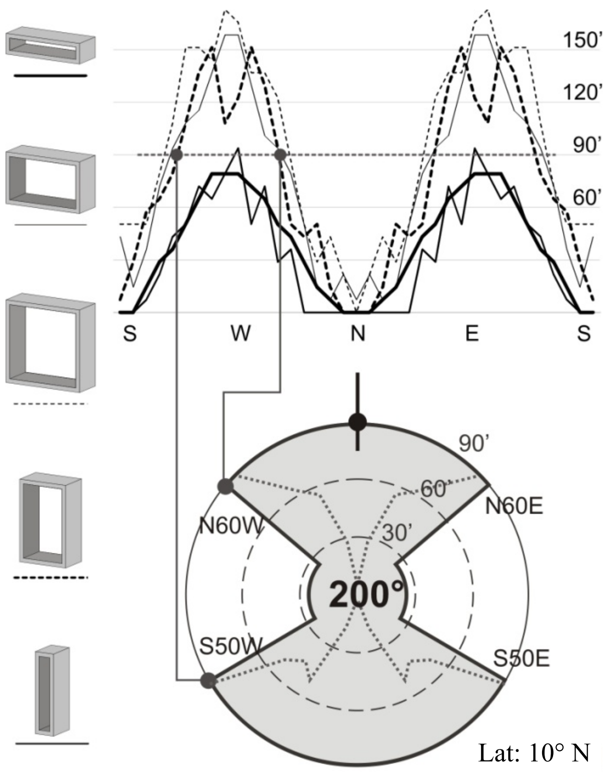


**Fig. 9 Average daily solar exposure caused by five openwork bricks in all the directions for latitude 10° N (above); solar applicability range of the fourth element of the series (below).**

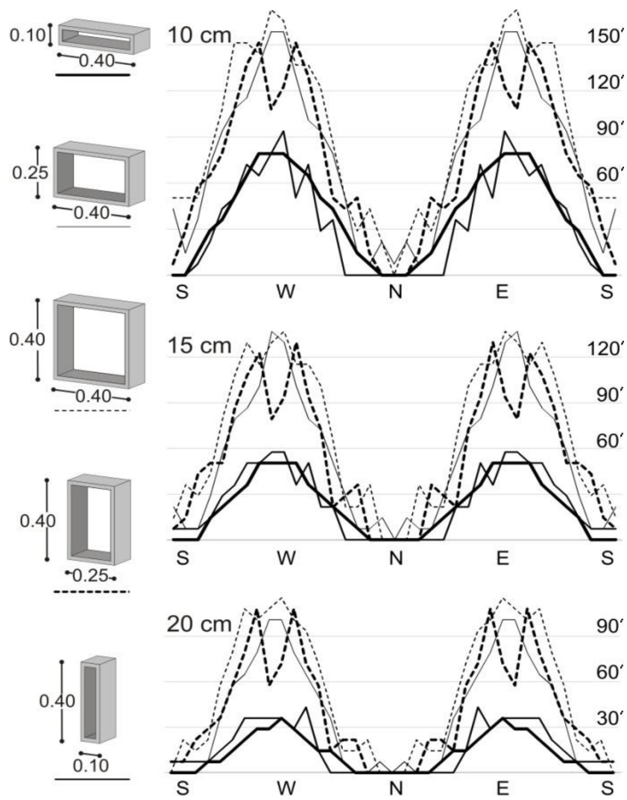


**Fig. 10 Average daily solar exposure caused by five openwork elements in all possible orientations in latitude 10° N: holes in a 10 cm thick wall (above); 15 cm (middle); 20 cm (below).**

assortment of orientations. Conversely, orientations exceeding the threshold limit should not use the studied openwork element, at least at the latitude under consideration.

## 5. Results

Three groups of simulations were produced which allowed to calculate the variation of the "solar applicability range" based on the thickness of the wall. Thicknesses of 0.10, 0.15 and 0.20 m were studied in 13 different rectangular openings with a width/height ratio between 4:1 and 1:4. All calculations were analyzed under the same geographic latitude of 10° N. After the studies of several horizontal openings, a square shape until reaching vertical slits, it was found that, regardless of the width/height ratio, every perforation shape efficiency increases when the thickness of the surface where it is applied increases (Fig. 10). However, the increments do not follow a linear proportionality. Hence, an extreme increase in the thickness of the wall does not necessarily lead to an increase in the "solar applicability range".

It was observed that increasing the wall thickness reduces the average daily solar exposure in a more noticeable way when the openings are elongated, whether they are vertical or horizontal. Doubling the thickness of the wall in openings with a ratio of 1:4 and 4:1 reduces the sun exposure by a factor of three, while for the remaining openings, changing from 0.10 m to 0.20 m thickness reduces the sun exposure to less than half.

It is important to note that the highest solar exposure observed with all thicknesses in almost all the orientations was obtained by the square openings. Nonetheless, the square shape has the most favorable shape factor of all rectangular openings, allowing to maximize light utilization while reducing natural ventilation loss by having less friction with the fins.

However, it is noteworthy that, precisely, this shape, having the worst solar performance, is applied more regularly.

The previous information was used to study the variation of the "solar applicability range" for constant thickness, changing the width/height ratio of rectangular perforations with their fins perpendicular to the plane of the wall (Fig. 11).

It was observed that, for a threshold gain of 90 min a day, an openwork element with a horizontal slit and ratio 1:4 (Fig. 11) can be used in building walls of any orientation. In latitude 10° N, it will always present a satisfactory solar performance. The curve towards the east and west still has a remaining margin of approximately 10 min of sun exposure and, therefore, element dimensions could even be adjusted, avoiding unnecessary sky obstruction.

Furthermore, a similar element vertically installed (Fig. 11) would only be recommended for a range of orientations of 240°. Whereas a square shape, which is the one with the lowest solar applicability range, would only be appropriate to build walls in a range of 180°, unequally distributed between north and south.

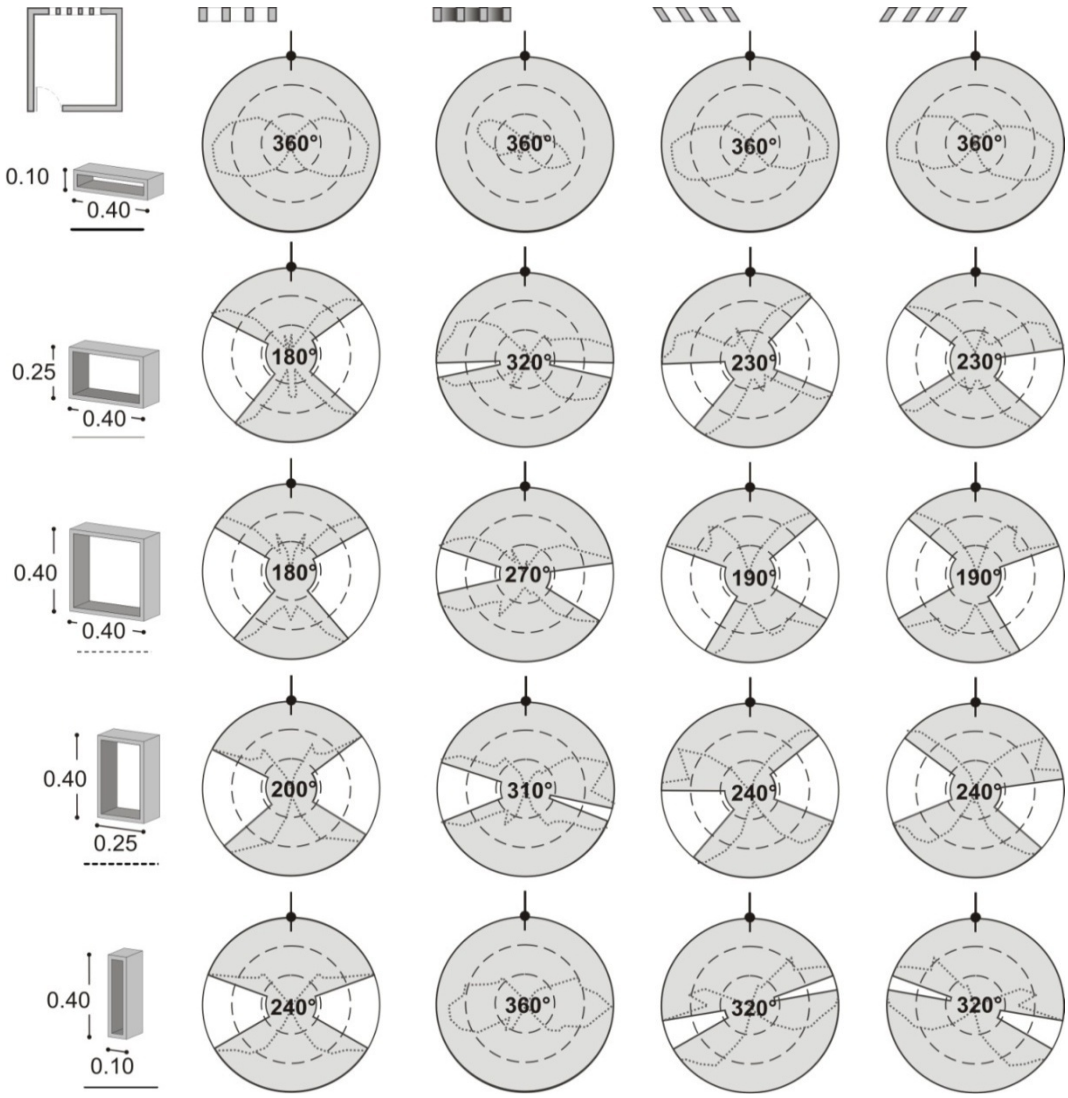


**Fig. 11 Variation in solar applicability range for 20 perforations on a 10 cm thick surface placed in 10° N latitude. In the columns, the four studied families are represented: perpendicular perforations, with an added diagonal partition wall, and oblique perforations with a 30° rotation in opposite directions. In the lines, prototypes in which perforation proportion changes from a 4:1 to a 1:4 relationship are represented.**

A second set of simulations, similar to the first set but with a diagonal partition, allowed to study the impact of adding an extra partition wall (Fig. 11, second column). A third and fourth sets of simulations allowed to estimate the variation resulting from the "solar applicability range" if the vertical fins of the openings were rotated 30° from the normal to the surface. There are two options for this rotation: clockwise and counter-clockwise (Fig. 11, third and fourth columns). It was noted that both spins resulted in double asymmetry in the solar behavior of the element. On the one hand, the worst performances do not occur on the east-west axis anymore, but are redirected northeast and southwest if the rotation was counter-clockwise. On the other hand, the clockwise rotation presented the worst performances located in the northwest and southeast quadrants. In both cases, the fins' rotation angle did not derive an equal solar applicability range rotation.

The second situation of asymmetry caused by the rotation of the fins consists of the differences between both sides of the orientation ranges initially discouraged, which were aligned with respect to the east-west axis and had originally the same values. It was observed that the rotation favored the performance of openwork walls facing the northern hemisphere while being inappropriate for the openwork walls facing south. However, counter-clockwise turns are more appropriate for eastern facades, while the clockwise rotation favors the performance of walls facing the sunset.

## 6. Discussions

All the simulations carried out correspond to 10° N latitude, covering much of the Caribbean Coast of the Americas. For solar symmetry reasons, numerical results obtained are valid for the opposite latitude, i.e., 10° S, corresponding to the northern coast of Peru. However, the recommended guidance ranges are totally different depending on the location, whether it is north or south of the equator line, including perpendicularly perforated openwork walls.

Due to the climatic stability of the equatorial zone, in this region, the "solar gain threshold" can be considered constant. For this reason, the processing database needed to consider the separation of data with respect to the horizontal line, i.e., data above or below a reference value. A similar technique could be used to evaluate openwork bricks in areas with significant seasonal variations: it will be sufficient to classify the data with respect to a wavy line, which would represent the variation of the desirability of solar gain throughout the year.

It can be seen that the "solar applicability range" is a sensitive magnitude, which changes with the orientation of the wall or the shape of the openings. As all values are relative to a single point located behind the openwork brick, this point must be positioned so that the results are representative. To achieve this, in all cases, the point was located on the bisectors of the perforations, where the maximum sun exposure is expected.

Significant differences in the solar performance of the studied elements were observed. In all cases, the highest solar incursion times were obtained by elements with width/height ratio close to 1. Proportions away from this shape resulted in reductions in the times of sun exposure, accompanied by increases in the "solar applicability range".

By making comparisons regarding the openings used as a comparison pattern, two characteristics of the perforated walls were identified: focalization and solar performance shift. Focalization lies in a variation of the slopes and oscillations of the curves, which shows a solar behavior significantly higher in a limited orientation range. Focalization possibilities are significant and allow to design openwork walls with a solar performance higher than those with similar perforations, provided that a geometrically detailed design is made. In compensation, a very focused opening will show a lower solar applicability range, so that it would be advisable to resort to it only when the orientation, which the openwork wall will have when built, is known in advance (Fig. 12).

Results also allowed to prove that making perforations obliquely or adding diagonal partition walls generates an important decrease in solar incursion times for some orientation ranges (Fig. 13). It can be easily noted that the results show a strong asymmetrical condition, but with characteristics that the focalization effect does not have. In the second case, a rotation of the obtained results was observed, with no noticeable changes in the slope or the curves shape. Therefore, it was concluded that this is a different phenomenon, and it was called solar performance shift.

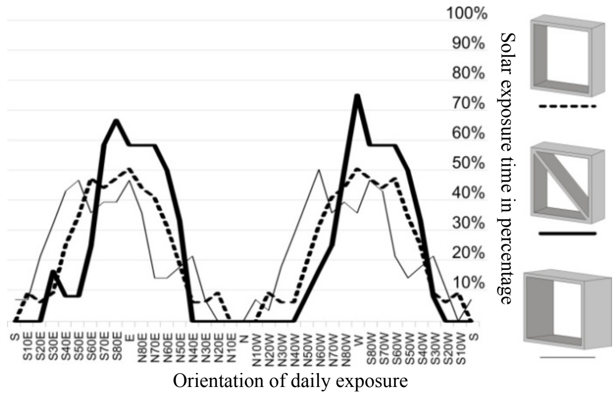


**Fig. 12 The focalization effect allows a significant reduction in solar contributions for a wide direction range. It is observed that this positive performance is carried out at the expense of worsening some other direction range.**

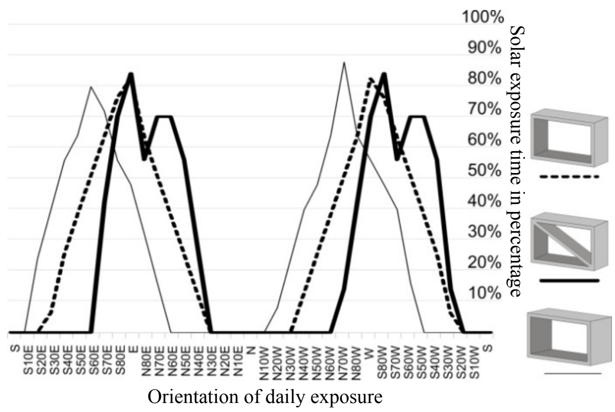


**Fig. 13 In predominantly horizontal perforations, the solar performance shift effect can be seen. Visibility masks derived from asymmetric shapes allow to obtain positive performances in a similar direction range but with a shift of several degrees with respect to the perpendicular perforation most similar to them.**

Due to this effect, an asymmetric perforation continues showing a performance similar to the one that characterizes a perforation with similar shape, but with a rotation of several grades. The angle of this shift does not match the angle the perforation was made with: it depends on the bisection angle instead, and thus varies according to the surface thickness.

The possibilities of improving the solar control of perforated surfaces through a suitable application of the solar performance shift effect are significant. For instance, it is enough to change the installation of an openwork brick for its solar performance to experience a noticeable increase. According to this principle, there are precise orientations from which it is advisable to reverse the openwork brick's position in order to be able to travel through the curve of minimum values for a particular geometry perforation.

## 7. Conclusions

The "solar applicability range" is a useful value to determine the orientation intervals for which an openwork wall will exceed a given solar incursion level. Variations in the test procedure in order to include the solar incursion tolerance based on schedules, calendars and rainy or cloudy seasons are still necessary. It would be helpful to continue improving the way of assessing indoor presence of sunlight in the tropics.

Two characteristics related to solar performance of openwork walls were identified. The first one, called focalization, appears with a higher intensity in predominantly vertical perforations. The second one, called solar performance shift, was observed only in asymmetric perforations.

Since doubling the thickness of an openwork wall depth requires the same amount of material as changing the ratio of the openings, the second choice will be the better design option from the standpoint of solar control. Changes in the openings shape, rather than in the thickness of the walls, are the way to reduce sun exposure times caused by the openwork walls in the tropics.

Rotating the vertical partitions of the openings by 30° to the normal of the wall has a significant effect only in predominantly vertical openings. In square openings, the benefit is not significant and therefore the rotation angle should be greater than this. In predominantly horizontal openings, the benefit of turning 30° is imperceptible.

Exception made of predominantly horizontal openings, improving the geometry of an openwork brick in order to provide its best performance in a particular orientation will generate a worsening in its performance in other directions.

The obtained differences in the "solar applicability range" for the two oblique opening families analyzed in this study have been rather drastic. Apparently, 10° was a moderate distance with respect to the equator line, but certainly the design criteria for openwork elements required in tropical areas should be totally different, regardless of the climatic similarities between both sites, as long as they are located north or south of the equator line.

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