Design of a Shading Screen Inspired by Persian Geometric Patterns: An Integrated Structural and Daylighting Performance Evaluation

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Abstract

Shading screens have been used as daylight control systems, which also play a role as design elements of transparent facades. A façade's configuration can be an explicit representation of its functions. There are multiple functions within a building and sometimes a dominant function imposes one configuration to the whole system; in this case, a replicated geometry that is used for the shading screen. In contrast, by grading the screen's geometry, there is a response to each individual programmatic function according to the interior space of the building [1].We propose a functionally graded shading system that responses to different programmatic building functions. In this study, some geometric patterns, widely used in Persian historical ornamentations, have been chosen as the underlying geometry for shading screens.

Geometric ornamental patterns are based on mathematical concepts, which are implemented on regular shapes of a certain arrangement. In general, such configurations have three geometric characteristics that have raised the tendency of employing the geometric patterns in ornaments of shading screens, facades, floor finishing and windows of both historical and contemporary architecture. First, these patterns can be fitted on different surfaces through geometrical concepts such as propagation, curtailment and scaling. Second, most of these types of patterns are self-similar configurations that are roughly similar to one part of themselves. This characteristic assists in making use of the properties of fractal geometry in parametric design of the patterns and further modification of an arrangement and density of a typical configuration. Third, some different patterns are generally based upon the same underlying rules and can be generated using almost the same geometrical processing techniques. Considering the self-similarity characteristic of the patterns, some shading screens are designed in this study with some Persian geometric patterns and then they are evaluated regarding their daylighting and structural performance.

In the daylighting performance evaluation phase, we look at the year around daylighting levels and light distribution of a regular office space, while the specified shading screen is installed in front of a transparent full floor to ceiling glass facade. It is assumed that by using the shading screen, the required lighting levels are being maintained, while the heat gain is being reduced. In addition, the designed patterns play a role as an architectural feature of the building.

In the structural performance evaluation phase, the shading screens which are considered as exterior self-supporting systems are analyzed under their self-weight and wind loads. The goal is to reach a minimum weight for the screens that are performing structurally.

Ultimately, the presented shading screens are based on Persian geometric ornamental patterns and arranged according to the lighting and structural requirements. Results are indicating a multi-disciplinary approach in the design of the shading screens, which can be employed in creating similar prototypes with different climatic and loading requirements.

Keywords: Shading screens, Persian ornamentation patterns, Performance-based design, Daylighting performance, Structural performance

1. Introduction

This study looks at the design of shading screens that are inspired by Persian geometric ornamentation patterns. Shading screens are defined as external perforated panels that are fixed in front of windows. We define shading screen as a self-supporting wall system that is located in front of a full floor to ceiling window. The goal of the study is to look at the interaction of variables and effect of the geometrical parameters of the perforated screen wall on the day-lighting performance of the space as well as the structural performance of the wall itself. The relation between form and structure has been well researched in the literature and realized projects. Also, the effect of form on daylighting performance has been researched in the environmental technology area. In a study carried out by Sherif et al., he studied different perforation percentages of screen walls and simulated the daylighting levels of the residential space. [2] The aim of this interdisciplinary, multi-objective research is to study the interrelated aspects structural and daylighting performance with geometry in order to aid the designer to understand the effects of decision making on various performance aspects of the design.

This research consists of two main phases, and each phase is divided in to daylighting and structural performance evaluation. In the first phase of this study, four possible configurations have been opted for based on a parametric design, and their performance has been individually evaluated; then the results are compared. The second phase adopts an evolutionary method, Genetic Algorithms (GA), which is a population-based optimization method. In this stage, pallets of possible design alternatives coupled with their relative performances are generated. The criteria for evaluating different designs can be set according to the indices like minimum weight, maximum daylighting levels, least deformation, etc.

2. Persian patterns

Persian art during the Islamic era set out deliberately to shun anthropomorphic forms regarding religious sentences. It led to geometric exploration, an enterprise that resulted in an extraordinary, large, complex and elegant collection of periodic patterns. If one asks the question as to how the Persian patterns, or indeed patterns of any culture, originated, then it would seem most logical to start with the practical experience of tiling and covering with simple naturally occurring shapes.[3] The shapes would then be worked on giving rise to triangles, rectangles, hexagons and circles. This has been noticed both in art and architecture of Persia. The Jame Mosque of Isfahan, renovated from the 8th to 20th century, Iran, or the Jame Mosque of Yazd, 12th century, Iran, inhibit great collections of geometrical patterns (Fig. 1, 2).

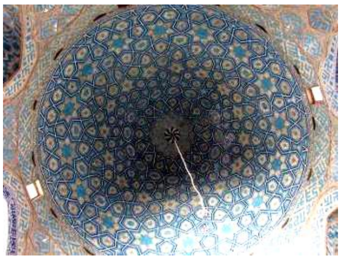


Figure 1: Jamé Mosque of Yazd

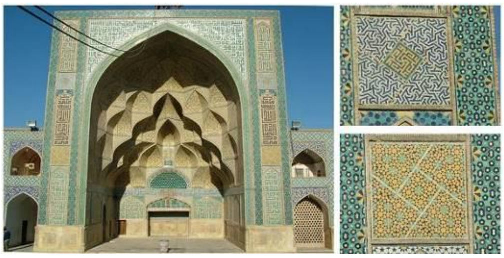


Figure 2: Jamé Mosque of Isfahan, Ostad Ivan

According to S.J. Abas, patterns are divided into four different categories [2]. The first category encompasses the patterns based on single-shaped tiles. In this case, just one single tile is used and through varying the orientation of neighboring pieces, or through removing pieces, related design emerges. Fig. 3b illustrates arising forms from different placing of hexagonal tiles compared to that used in Fig. 3a (Fig. 3).

The second category includes the patterns with overlapping tiles which are created by storing and stacking simple tiles. Fig. 4a shows how a square tile when rotated by 45 degrees and placed on top of an identical tile gives rise to an eight pointed star shape. If we refer to this shape as S1, an array of S1 is shown in the right diagram of the top row. By joining the vertices in S1, an octagonal tile S2 is obtained (Fig. 4).

The third category indicates patterns from geometrical constructions on familiar shapes. It is in this stage that some geometrical construction is added to familiar shapes. In Fig. 5, the base shape is obtained by overlapping placement of eight squares. This gives rise to octagonal holes, which can be filled in by extending the sides of the squares from vertices of the octagon (Fig. 5).

The last category refers to patterns based on concealed grids which require considerable geometrical ingenuity. In this case, a grid of some sort is drawn and then polygons/circles are placed in some regular fashion. Then the circumferences of figures are also divided, marked with points and joined together. After the pattern emerges, the construction lines are removed. The lines in the pattern are often replaced with interlacing lines (Fig. 6) [3].

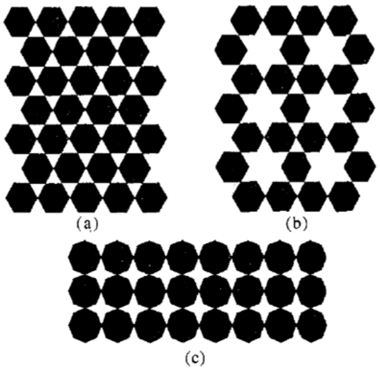


Figure 3: First category of patterns bases on single shaped tiles [3].

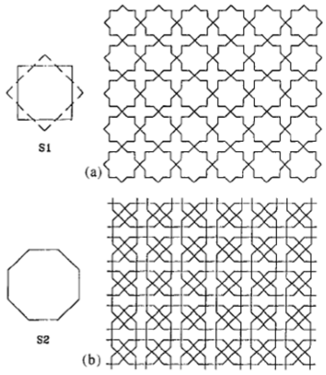


Figure 4: Second Category of patterns with overlapping tiles [3].

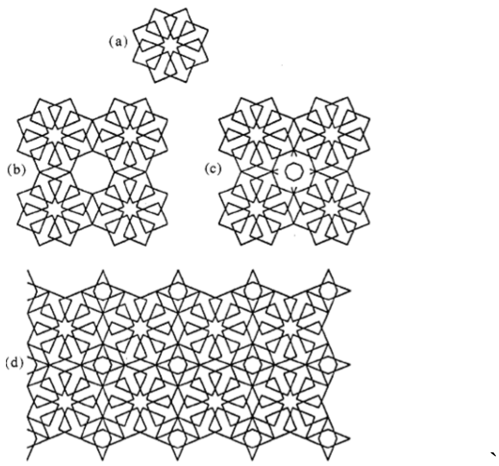


Figure 5: Third Category of patterns bases on geometric construction [3].

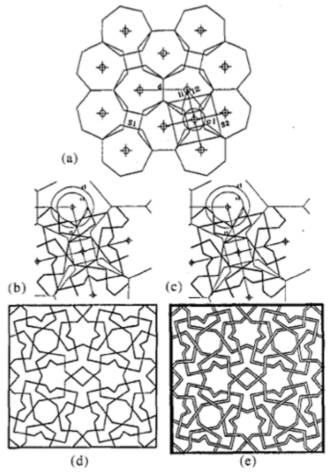


Figure 6: Fourth Category of patterns bases on concealed grids [3].

From another point of view, Eric Broug categorizes the geometric ornamentation patterns into three main families which include most (but not all) of the patterns. The geometric families are categorized according to the number of sections into which a circle has been divided in order to create the pattern [4]. Patterns based on the division of a circle into four equal parts, five equal parts and six equal parts are called *four-fold*, *five-fold* and *six-fold* designs respectively (Fig. 7). Broug categorizes twelve-fold design in the family of six fold designs. In addition, there are patterns that are not part of any of the categories represented in the geometric family tree, such as seven-pointed or eleven-pointed stars [4] which rarely may be seen in Persian ornamentation patterns. Besides Broug's categorization, usually grids are suggested to be considered which provide hidden structures for arranging the patterns. Its purpose is to provide a structure of polygons that can contain design elements (Fig. 8).

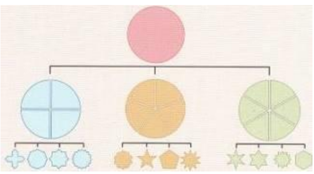


Figure 7: Family of geometric patterns divides [4].

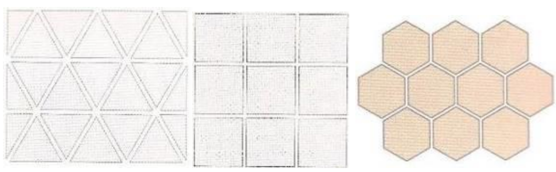


Figure 8: Grids as the invisible structure of patterns [4].

This brief introduction to geometric patterns leads to the next section, which looks at the design of shading screens inspired by these patterns.

3. Shading screens

Natural daylighting is desired in building envelopes, however thermal discomfort and the incidence of glare is unwanted. One type of shading system that is used to permit daylight while controlling solar penetration is "shading screens". These are external perforated panels that are fixed in front of windows [2]. There is a close connection between the geometric patterns and the design of shading screens, as the two dimensional patterns that were recognized by color and material in tiling of the buildings, evolve as three dimensional screens which play a role as daylight control systems. (Fig. 9).

Within the Middle East, historical examples of shading screens are wooden balconies, known as "Shanāsheel", and blinding unglazed latticeworks called "Shobāk" that both control view and daylight (Fig. 9). An additional advantage of these screens lies in their provision of privacy, which is a social-cultural need in its original region [2]. In tropical regions of Iran especially in Bushehr city, Shanāsheel played a role in providing view and light as well as natural ventilation for the buildings (Fig. 10).

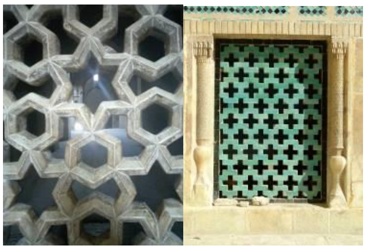


Figure 9: The shading screens, "Shobāk", in Jame Moque of Isfahan

Figure 10: Shanāsheel, Taheri House (left) and Deyri House (middle) in Bushehr, Iran. A house in Basreh, Iraq (right), [5]

During the past decade the traditional patterns of shading screens has been transformed to new patterns, by varying some of the basic mathematical rules like symmetry of the patterns or equal dimension of a replicated geometry. Furthermore, some active solar screens with such patterns has been developed.

A notable example in Middle East region is Masdar City, designed by Foster and Partners. The city is designed to encourage walking, while its shaded streets and courtyards offer an attractive pedestrian environment, sheltered from climatic extremes [5]. The undulating residential building facades have an external screen with a pattern that is inspired by traditional latticework providing shade (Fig. 11)[6].

Figure 11: Residential buildings of Masdar City, [6]

Another example is The New Headquarters of the Abu Dhabi Investment with a diaphanous screen that is in the form of a dynamic latticework, for the Al Bahr Towers. This is opened and closed in response to the sun's path (Fig. 12) and reduces the solar heat gain significantly to provide a more comfortable internal environment. The facade is computer controlled and is made of more than two thousand translucent, parasol-like units that are opened and closed as the sun moves over their surface [7]. This active shading screen can be considered as a reinterpretation of the carved and perforated screens that traditionally provided shade and privacy to Middle Eastern homes.

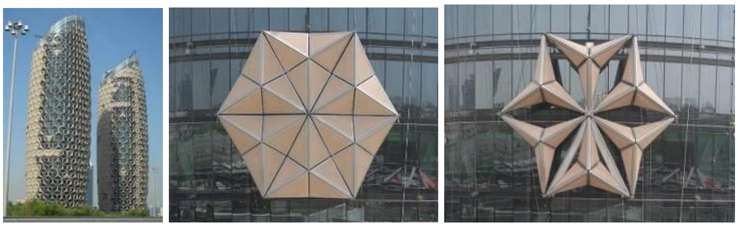


Figure 12: The dynamic shading of Al Bahr Towers, [7]

These examples indicate a re-interpretation of the traditional geometric patterns as shading screens that has led to design of new geometric patterns albeit based on the unchanged fundamental principles.

4. Configuration processing of a Persian geometric ornamentation pattern

To design the geometric patterns, Rhino has been opted as the modeling platform and Grasshopper, which is a parametric modeling plugin for Rhino, has been used. Grasshopper provides the opportunity to parametrically design and then alter the variables, in order to create various iterations of the design downstream. The constant and variable parameters and their acceptable intervals that are used for design are described in Fig. 13.

Figure 13: Geometric parameters on which the configuration processing of shading screens are based.

Parameter	*Symbol*	*Constant/ variable*	*Acceptable interval*
Width of the screen	W	Constant	500 cm
Height of the screen	H	Constant	500 cm
Depth of the screen	D	Variable	[5-35 centimeter] step 5cm
Hexagonal grid radius	Grid	Constant	35
Diamond diagonal dimensions	Diamond	Constant	35 * 61
Division Distance (the distance from attraction point is divided by this value)	Div. Dist.	Variable	[1-110] step 1
Radius of the wall's curvature	R	Constant	4819 cm
Center location of the subtracted curve	Center	Variable in y axis	[0- 36] step 1
		Variable in z axis	[0- 500] step 1

Based on the six-fold design, a basic pattern was designed and then replicated in the plane. A hexagonal grid with a radius of 35 cm was the underlying grid of the pattern. After the basic diamond pattern was designed, the diamonds were offset towards inside in order to create apertures. The offset value is dependent on the distance between hexagon's centers and a defined attraction point (Fig. 14).

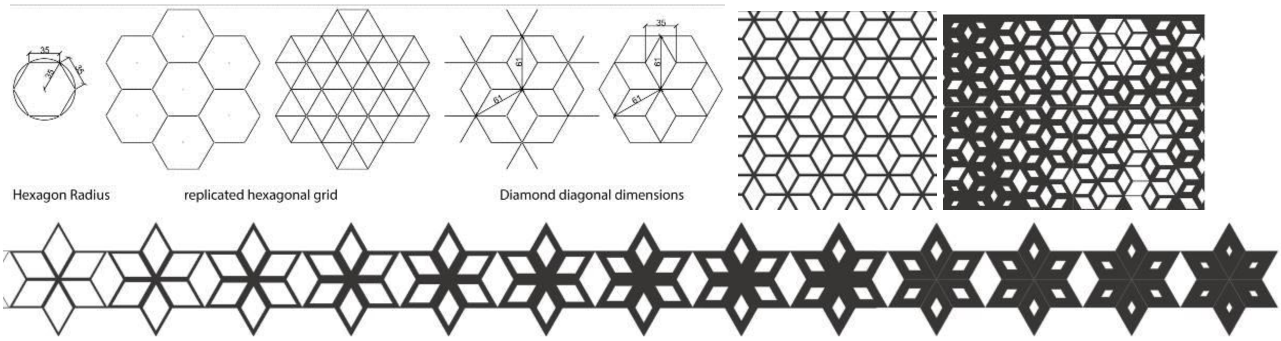


Figure 14: The basic pattern for the shading screen

From another point of view, the wall has a depth varying from 5 to 35 centimeters while a circle with a radius of 4819 cm is subtracted from the backside of the wall. The placement of the circle's center varies and can be shifted across the z-y plane. This creates a curved section on one side of the wall in case the circle intersects with the wall. There is also the possibility that the circle does not cross the wall which results a straight section with no curvature. The final step is subtracting the pattern from the wall (Fig. 15a) . It was initially assumed that the wall with maximum width at bottom and minimum width at top is the most efficient configuration structurally; and the wall with maximum width at top and minimum width at bottom is the most efficient configuration in terms of daylighting, since it will reflect light and act as a light shelve. The purpose was to look at the tradeoff among these two aspects. (Fig. 15b)

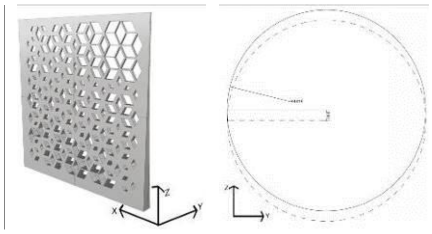


Figure 15a: The circle that moves along the z-y plane and is subtracted from the wall

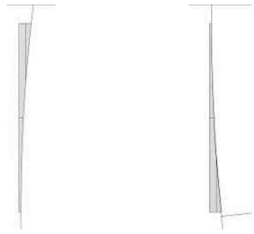


Figure 15b: the assumed efficient wall in terms of daylight (left), the assumed efficient wall in terms of structural performance (right)

This pattern provides the opportunity that the size and ratio of the apertures change, which leads to a change in the perforation ratio of the screen. This ultimately affects the daylight illumination. On the other hand, this affects the weight and the structural performance of the wall. The relation between daylighting performance and structural performance is defined in Fig. 16.

Figure 16: The effects of different parameters on daylighting and structural performance

Parameter	*Effect on daylighting performance*	*Effect on structural performance*
Depth of the screen	Daylight illumination (lux)	Weight of the screen, deformation
Perforation ratio	Daylight illumination (lux)	Weight of the screen, local stresses
Sectional subtracted curve	Light shelf effect, overhang effect	Changes the centroid of the structure

4.1. Design of experiments

In the first phase of the study, four different configurations were generated and then the simulations were conducted. All configurations have a curved surface on the back side of the wall. In two configurations, the maximum thickness occurs in the base (31 cm) while it reaches the minimum thickness at the head (5 cm). In the other two configurations, this is mirrored. Then two different perforation ratios are applied to each case. (54% perforation ratio with Div. Dist. of 90 and 35% perforation ration with Div. Dist. of 44). The design of the experiments is graphically illustrated in Fig. 17.

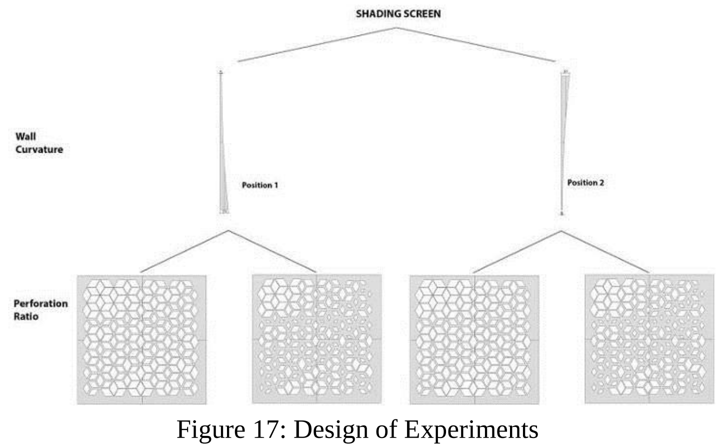


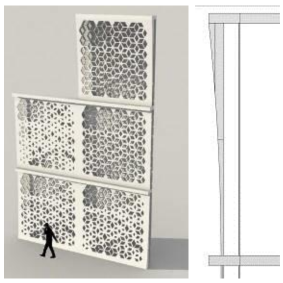
Figure 17: Design of Experiments

4.2. Architectural applications

These screen walls have the potential to be stacked on top of each other to create a perforated screen wall in front of a glass façade. This provides the opportunity to change the perforation ratio of each module depending on the specific program of the space and the required daylighting levels of that space.[1] In addition, the screen wall has the potential to be more integrated with the main structure of the building by connecting to the slabs from top and bottom, in order to transfer structural loads to the ground. (Fig. 18a) On top of this, the screen walls can change their role from shading screen to the main building facade, by placing the glass panes in the apertures instead of adding a layer to the glass envelope.

5. Daylighting performance

The designed shading screen is applied to a base case open-plan office space with minimum 500 lux illumination daylighting requirement [8]. The location has been defined as a cooling dominant location, Phoenix, AZ (33.45°N and 111.98°E). The buildings in this area receive extensive sunlight which requires to be mediated in order to reduce the heat gains. Maximum sun altitude at solar noon on the first day of summer equals to 80.05 (90 -33.45 +23.5) and maximum sun altitude at solar noon on the first day of winter equals to 33.05 (90 -33.45 - 23.5). This office measures 5 m wide, 5 m high and 7.5 m deep, and the only window of this space is a full floor to ceiling south oriented window. The reference plane on which daylighting performance was simulated is a grid at a working plane of 90cm height. (Fig. 18b)



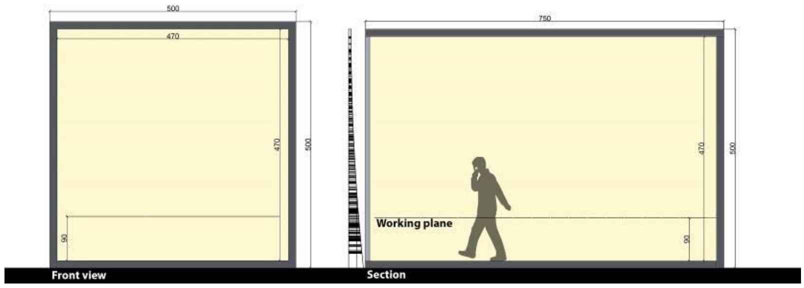


Figure 18a: Stacked panels connected to slabs   Figure 18b: Assumed design parameters of the office space

5.1. DIVA-for-Rhino

Since Rhinoceros has been chosen as the modeling platform, DIVA-for-Rhino, which is a highly optimized daylighting and energy modeling plug-in for Rhino, has been chosen for daylighting simulations. This also avoids geometry transfer between different software. The simulations in DIVA are based on powerful environmental performance engines such as Radiance, Daysim and Energy Plus.[9] The settings for the Diva analysis are shown in Fig. 19. The material assigned to the shading wall in DIVA is "outside façade" which is white material with 35% reflectance.

Figure 19: DIVA settings

Location	*Date*	*Time*	*Materials*	*Sky-types*	*Setting parameters*
Phoenix, AZ	September 21st 2014 (used for point in time visualization)	solar noon (12:21 pm)	Generic Floor (20) Generic interior walls (50) High reflectance ceiling (90) Outside ground (20) Glazing single pane (88) Outside Facade (35)	Clear sky with sun	ab 2,ad 1000, as 20, ar 300

Year round performance is addressed by using a Dynamic Daylight Performance Metrics (DDPMs). [2] Climate-Based Metrics use recorded data in the form of *.epw files to simulate the sun and sky conditions for various simulations including "Daylight Autonomy". The important aspect of Climate-Based Metrics is that they are annual calculations which mean they take the entire year into account. [9] The "Daylight Autonomy" index (DA) is defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone.[2] Therefore if a space with 500 lux requirement had a DA of 80%, it means that the required lighting level would be met by daylight alone, in 80% of the year; and the artificial lighting must be used for the remaining percentage. It is assumed that this space will be occupied weekdays from 9 am until 5 pm with the total annual hours of occupancy of 1827 hours per year. There is no active lighting control or dynamic shading system in the scene.

All four configurations have been simulated and the results have been compared with a base case model with no shading screen. The aim of this stage is to evaluate the effect of changing the Shading Screen perforation percentage and wall curvature on annual performance, in order to conclude the best coupled curvature and perforation percentage.

5.2. Daylighting Discussion

The simulations results and their year-round performance grid maps is illustrated in Fig. 20. Point in time visualizations are included in the table for September 21st 2014 at noon, to better understand the shading effect of each configuration. Case 1 which is the window with no shading screen is included in order to have a base case for comparison. It was expected that as the perforation ratio gets lower, the daylighting performance becomes lower too. Therefore, the decreasing trend in mean daylight autonomy of case 2 and case 3 (54% perforation) compared to case 4 and case 5 (35% perforation), can be clearly explained. (Fig. 21)

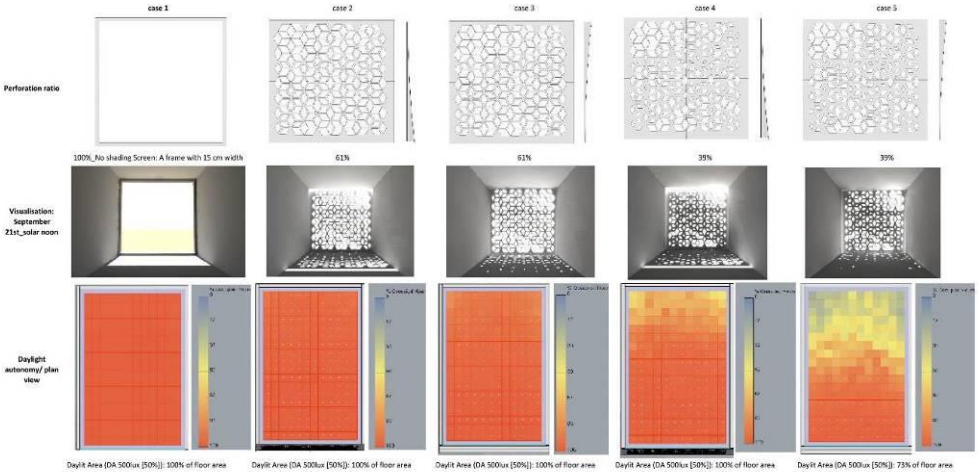


Figure 20: Visual daylighting simulation results

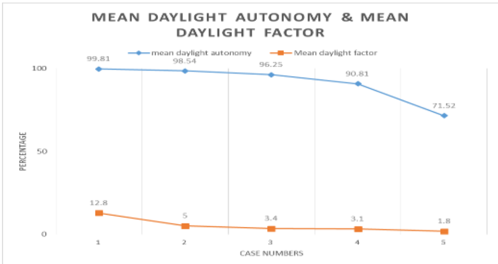


Figure 21: plotted values of daylight autonomy and mean daylight factor

However, looking at the plot, it is noticeable that the performance of case 2 and case 3 (with the same perforation ratio) differs, since the curvature is different in these cases. This can be explained by assuming that the case 3 with wider width at top and narrower width at base acts as an overhang and blocks the direct sunlight more, which results in lower daylighting levels in the space. When case 4 and 5 with lower perforation ratio (35%) are being compared, the difference in performance becomes even more when the curvature varies. In these cases, changing the curvature of the wall has a more dramatic effect on the mean daylight autonomy and drops the value from 90.81% to about 71%.

Indoor light distribution can be characterized through the measurement of illuminance on all useful surfaces. However, since the intensity of natural light varies, it is necessary to consider the ratio of the local illuminance to the simultaneous outdoor horizontal illuminance due to an unobscured sky, and this ratio is called the daylight factor (DF) %. [10] This metric is mostly useful for locations with overcast skies, and sunny skies are not well represented. However, the decreasing trend in daylight factor from case 1 (no screen) to case 5 (least perforation percentage) is consistent with the decreasing trend in mean daylight autonomy.

5.3. Daylighting Remarks

Daylight autonomy is an index to evaluate the overall daylighting levels of a space. However, there are other indices like the "vertical to horizontal" illuminance ratio, which can be used to assess a more comprehensive performance of the screen.[11] In addition, the comfort level of the space including glare and sun patches can be subject of further studies. From another point of view, the openings in the view band might have larger apertures based on a new placement of the attraction point, to create various other patterns for the façade.

6. Structural performance

In the structural evaluation phase, the screen wall has been simulated as a self-supporting structural system. It is assumed that the wall is constructed from reinforced high strength concrete and is subject to self-weight as well as lateral wind load of 355.75 Newton/m^2 (7.43 psf). This value is calculated according to ASCE-7 code for a windward wall.

The structural performance of the wall is simulated in "ANSYS" which is an FEM (Finite Element Method) software. After the wall is subject to loads, deformation and safety factor outputs are measured. The criteria for evaluating the structural performance of the wall is its maximum deformation and safety factor. The maximum allowed deformation is 50mm and the safety factor needs to be at least 1. In this phase, the objective is to identify the light weight wall which is performing structurally.

It is worth mentioning that looking at the maximum stress levels there is the potential to evaluate the structural performance. However, due to the existence of local stresses in the edges of the apertures (which are a result of the sharp-edged geometry), this option was not regarded.

6.1. Structural discussion

The simulation result which includes the deformation and safety factor, is illustrated in Fig. 22 and 23 for cases 2, 3, 4 and 5. The deformation and safety factor in case 3 and case 5 is about 200 mm and 0.02 respectively. This implies that these are not "appropriate" configurations to choose as a self-standing wall, even though their daylighting performance is acceptable. Different structural systems need to be designed to use these configurations. Looking at case 2 and case 4 with wider bases and narrower tops, the deformation is about 13 mm and 10 mm respectively which is quite small. The safety factor images show more yellow areas with an overall safety factor of 5. (Fig. 22) Nonetheless, there are some red areas at the corners of the apertures and sides of the wall with the minimum safety factor of 0.2. The unsafe areas in the apertures can be resolved by filleting the edges instead of having sharp edged corners. Case 2 has more unsafe areas in the sides of the wall as compared to case 4. This can be resolved by having more solid parts at the base and more apertures at the middle to top section of the wall.

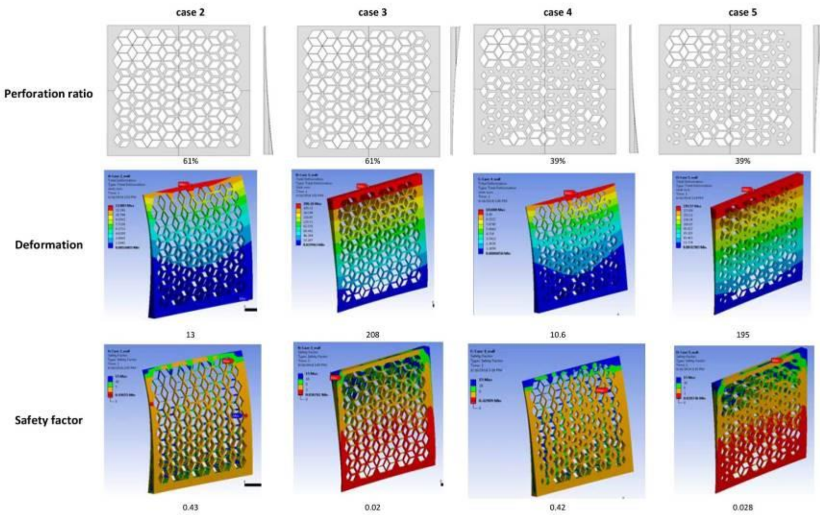


Figure 22: Visual structural simulation results

Figure 23: plotted values of deformation, safety factor and weight

Case 2 has the least weight (its perforation ratio is higher and the material that is used is lower) while case 4 has the least deformation and stress levels. However in general, the weight of these cases does not have a significant difference with each other. If we eliminate case 3 and 5 due to their large deflections, then case 2 and 4 are left and among these two cases, case 4 has a higher safety factor both in terms of minimum number and in general shape.

7. ParaGen

A more comprehensive search of screen forms and the interaction of both structural and environmental criteria is made using the ParaGen method [12]. In this approach, a Non-Destructive Dynamic Population GA (NDDP GA) is used to fill a database with solutions generated and analyzed using in this instance the Rhino-Grasshopper-DIVA-ANSYS software combination. ParaGen combines form generation and analysis steps which run in parallel on PC clients, with a web server that builds a searchable database and guides the search process with the NDDP GA. The ParaGen GA can be set to either generate random solutions or to breed solutions based on any combination of geometric or performance parameters. Fig. 24 shows a selection of randomly generated solutions used to initiate the search and optimization cycles. After the creation of an initial set of about 100 solutions, a fitness function was set to focus breeding on better performing solutions. Fig. 25 shows a graph of resulting solutions plotted as perforation ratio versus mean Daylight Autonomy (MDA).

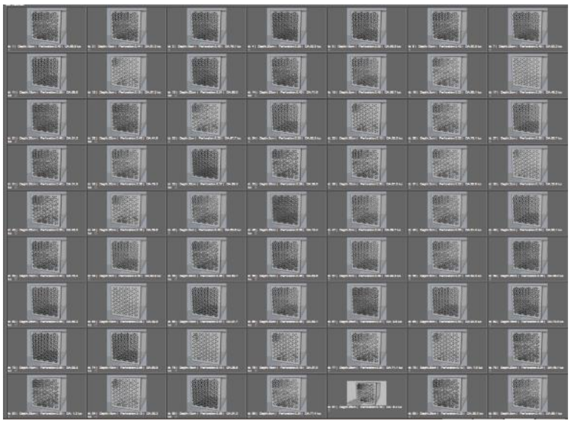


Figure 24: A selection of randomly generated solutions used to initiate the search

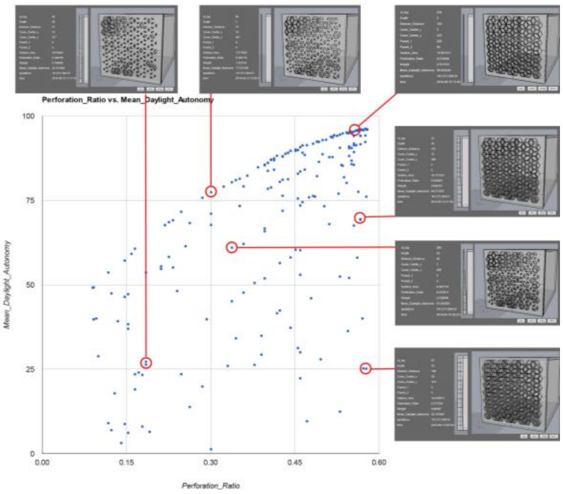


Figure 25: Mean Daylight Autonomy versus perforation ratio

The plotted values indicate that as perforation ratio increase, the MDA increases. There are multiple curves that follow this trend which represent different depths of the walls. The thinnest wall (5cm) has the forefront curve with the highest MDA. From another point of view, with the same perforation ratio (about 60%), the MDA varies noticeably among walls. The MDA of a 35 cm deep wall with perforation ratio of 60% is as low as 25, which is about the same as the performance of a 20 cm deep wall with perforation ratio of about 18%. This shows the effect of increasing the depth of the wall and how it acts as an overhang and reduces the daylight penetration.

In another analysis, the MDA was plotted against weight; not to mention that the weight is affected by both perforation ratio and depth of the wall. A forefront curve can be noticed which has the highest MDA and the least weight. This curve represents the 5 cm straight walls with various perforation ratios and is in line with the results of the previous section. (Fig 26) However, there can be seen a second trend that represents another group of high performance walls with a wider base (up to 25cm) and narrower tops (5 cm). Since these walls have thicker bases, their structural performance would outweigh the straight walls, in terms of both deformation and buckling; and would compensate their higher weight. In this case, these will have the potential to be integrated as structural elements in buildings. In addition, the curvature provides the opportunity for designers to bring variety to the performative screen walls, not only with varying geometrical perforations, but also with altering the form.

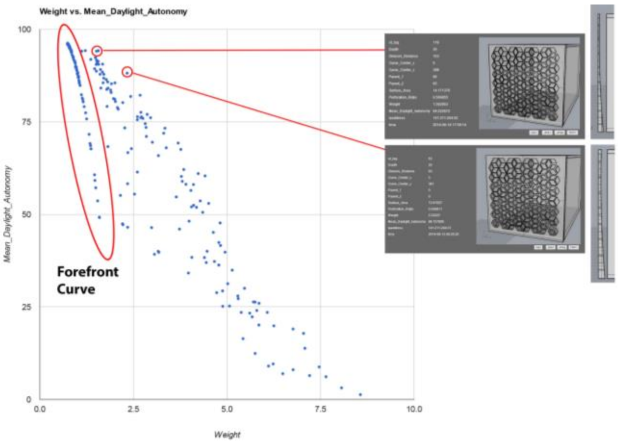


Figure 26: Mean Daylight Autonomy versus Weight

8. Conclusion

This research looks at a multi-objective performance evaluation of a screen wall, inspired by Persian geometric patterns. The study contributes to the design of screen walls, in order to control daylighting and to provide shading for the buildings. The loadbearing capacity of the wall provides the opportunity to be used as a self-standing building envelope. The modules of the screen wall can be stacked on top of each other to shield a multi-story building, which expands the boundaries of its application. In this case, the screen wall is no longer self-standing and needs to be integrated with the structure of the building. The perforation ratio of each module can differ to accommodate the unique daylighting needs of a specific space. The depth and curvature of the wall can vary depending on the required structural behavior, which ultimately affects the weight of the wall. From the construction point of view, since the screen wall is constructed from concrete, a minimum width of 2.5 cm (1 inch) must be considered for the apertures divider. Designers can bring variety to the design of screen walls, not only with varying geometrical perforations, but also with altering the curvature.

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