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Balancing the Energy Savings and Daylighting Performance of External Perforated Solar Screens

Evaluation of Screen Opening Proportions

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ABSTRACT: This paper aims at developing new types of external perforated solar screens by balancing between energy efficiency and daylighting. Three objectives were targeted: First, evaluating the energy saving potential of using solar screens in different geographic locations. Second: Examining the influence of screen opening proportions on illuminance values. Third, investigating recommended screen opening proportions for daylighting and their effect on energy efficiency. The usefulness of utilizing external perforated solar screens in front of windows was demonstrated. The screens reduced energy consumption by 25% to 35% in a number of cities that lie between 14˚N and 40˚N. Their effectiveness was less obvious in cities that were further north. An in-depth investigation of the daylighting performance suggested that changing the screen opening proportion (horizontal:vertical) from 1:1 to 18:1 would efficiently enhanced daylighting. Changing the proportion to 18:1 was recommended as it improved the deficient daylighting behaviour of the North direction, while resulting in a marginal effect on energy consumption. The 1:1 proportion was recommended for the Sothern orientation. As for the East and West orientations, it is up to the designer whether the improvement of daylighting due to change in opening proportion is worth the compromise in energy consumption.

Keywords: Energy efficiency, Daylighting performance, Solar Screen, Desert Environment, Egypt.

1. INTRODUCTION

In hot desert environments, solar radiation passing through windows contributes significantly to cooling loads and energy consumption of buildings. Shading of windows reduces such loads. However, this might compromise the availability of natural light. One of the shading systems used to diffuse daylight and reduce solar radiation indoors is a Solar Screen, which is an external perforated panel that is fixed in front of a window. It resembles a traditional solution named “Mashrabeya”, which is described as a wooden lattice of cylinders connected with spherical joints (Fig.1). The thickness of these screens provides selective shading properties, similar to egg-crate sun breakers.

Figure 1: Exterior detail, Mashrabeya bay window by e-moonstone – 2007.

The paper builds on previous publications by the authors that addressed the energy and daylighting performance of perforated wooden solar screens. In a previous publication [1], the authors demonstrated that perforated solar screens were effective in achieving significant energy savings in hot desert climates. The energy performance of the screens was investigated by modelling a typical residential space in desert environment using Energy Plus simulation software. The highest saving potential was found in Solar Screens with 80 to 90% perforation. This research continued through investigating different screen depths. Highest energy savings reached 30, 30, 25 and 7% in comparison with windows without screens for West, South, East and North orientations respectively. Depth to perforation ratio 0.75 / 0.75 achieved the highest and most significant savings with 80% perforation in West and North orientations and 90% perforation in East and South orientations.

In other publications [2 and 3], the authors addressed the daylighting performance of the perforated wooden solar screens. Minimum and maximum perforation percentages were recommended for daylighting purposes. A tool that could be used by architects for design of solar screens that effectively achieve functional needs, while maintaining visual comfort was provided. This was accomplished by performing a series of experiments using Radiance simulation software, where different screen perforation percentages were applied, and daylighting performance was analyzed. This was studied in terms of adequacy through illuminance levels and comfort through glare analysis for a designed living room.

A number of related publications also addressed the performance of solar screens in regards to daylighting and energy performance. A publication by Aljofi examined the potentiality of reflected sunlight through “Rawshan” screens [4]. Lee and Selkowitz evaluated the performance of two daylighting control systems installed in separate areas of an open plan office, where automated roller shades were installed and controlled to block direct sun [5]. Irregular screen types, such as thermal louvers and vine screens, were previously investigated. Cool or warm water was circulated through the louvers, absorbing or radiating sensible heat. It was suggested that it would be used as a multi function tool that reduces overall annual energy consumption [6]. A vertical vine sunscreen and its passive cooling effect as a solar control technique by plants was also examined. A comparative experiment was conducted on verandas with and without the vine screens [7]. Other research work addressed issues of control [8], user’s response [9], and geometry and tilt angle of venetian blinds [10].

Reviewed literature demonstrates that solar screens investigations did not address the balance between energy performance in different geographic locations and its relationship to daylighting. Configuring Solar Screen parameters that provide acceptable daylighting levels, while controlling thermal comfort and achieving energy efficiency, could pave the way for their utilization in an effective manner that does not only build on historical precedents, but also achieves performance goals of today’s modern buildings.

2. OBJECTIVES AND METHODOLOGY

This paper aims at the development of modern external perforated solar screens. The objectives of this paper and their investigation methodology are represented in following three phases:

2.1. Research phases

a) **Phase I:** Evaluating the energy saving potential of using solar screens in different geographic locations, and identifying locations that receive highest savings due to their shading effect. A computer model was created by the use of two computer simulation programs, Design Builder and Energy Plus 3.1.
b) **Phase II:** Examining the influence of screen opening proportions as one of the parameters that aid in the effective utilization of solar screens in daylighting. Experimentation was conducted using simulation software Radiance.
c) **Phase III:** Integrating results of Phase I and Phase II. This results in a solar screen design that balances between energy efficiency and visual comfort.

2.2. Base case parameters

A typical indoor space with a number of assumed fixed parameters was used as a base case for experimentation. The architectural parameters were chosen to represent the principal features of a typical residential living room (Table 1).

Table 1: Architectural parameters for the tested space.

Indoor Space Parameters	
Floor level	Zero level
Dimensions	4.20 m * 5.40 m * 3.30 m
Wall Thickness	0.35 m
Window Parameters	
Dimensions	2.30 m * 1.20 m
Visual Lighting Transmission	85%

3. PHASE I: ENERGY SAVINGS IN DIFFERENT GEOGRAPHIC LOCATIONS

The focus of the simulation process of this phase was to evaluate the energy demand resulting from the cooling, heating and artificial lighting loads of the modelled space. A “dwelling lounge” with a direct-expansion, split-type, air-conditioning system was modelled. The base case was opening-tuned to focus on the thermal effect of using the tested screens. The floor, roof and three of the room walls were assumed adiabatic. The fourth wall had a double glazed window at its centre where the solar screen was attached. This wall was modelled as a brick cavity wall covered with plaster on both sides. Different cases of external perforated solar screens were applied in front of the window of the base case. Tested screen perforation percentages were 80% and 90%. The screen openings were square shaped and their depth ratios (opening height / opening depth) ranged from 0.25 to 2 in different window orientations during all seasons (Fig. 2). Monthly and annual simulation runs were conducted for the main four orientations using the weather files of a number of cities located in the latitude range of 14˚N - 60˚N. Simulation results of each of the simulated cases were compared with those of their “no screen” base cases (zero depth ratio).

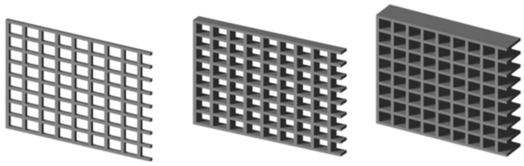

Figure 2: Geometrical Effect of Changing Solar Screen Depth Ratio.

3.1. Energy performance results

The following is a summary of the annual energy loads resulting from changing the screen depth for the screen case having 80% perforation percentage. Results were analyzed for two geographic location types: high and low temperature locations.

In the high temperature locations, such as the city of Jeddah 21˚N-39˚E (Fig. 3), the energy consumption is generally inversely proportional to the increase of screen depth. The lowest energy consumption was found in the range of depths between 0.75 and 1.25. As depth increased, window transmitted solar energy decreased with considerable rates till it reached the 0.5 depth ratio, where it decreased with lower rates afterwards. However, the lighting electricity is almost constant till depth 1.5, where it slightly increased. Cooling loads significantly decreased with the increase of depth till a depth of 0.5. It slightly increased after depth 1.5 till depth 2 due to the increase in lighting loads.

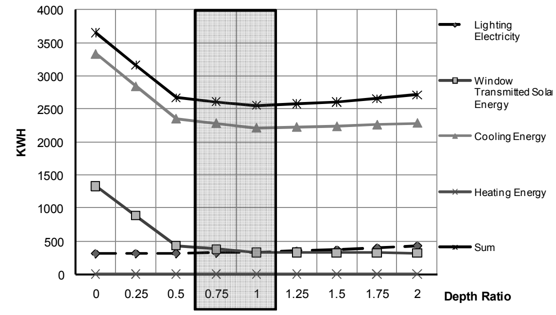

Figure 3: Annual Energy Loads for a South Oriented Solar Screen with an 80% Perforation, Jeddah (21˚N-39˚E).

In low temperature climates, such as the city of Paris 48°N - 2°E (Fig. 4), the lowest energy consumption was found in depths ranging from 0.5 to 1.25. Lighting electricity was directly proportional to depth, especially after depth 0.5. Cooling loads decreased with the increase in depth till it reached depth 0.5, and then it became constant. Conversely, heating loads increased significantly with the increase in depth till depth 0.5, and then it stabilized. This is due to the increase in lighting loads, which generated heating loads that led to a decrease in the need for heating energy.

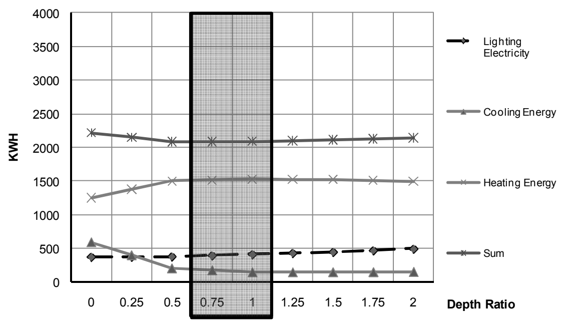

Figure 4: Annual Energy Loads for a South Oriented Solar Screen with an 80% Perforation, Paris (48°N - 2°E).

The energy savings resulting from using the screens in front of windows at different geographic locations was examined. Fig. 5 illustrates the energy savings due to utilizing an 80% perforated Solar Screen in the South orientation at different geographic locations. Different depth ratios were examined in search for the most promising energy savings.

In the South orientation, savings reached 32, 34, 30, 26, 27 and 27% of total energy consumption in the cities of Dakar (14˚N), Jeddah (21˚N), Kharga (25˚N), Taiwan (25˚N), Kuwait (29˚N) and Damascus (33˚N) respectively. The use of screens reduced the energy consumption by 28% in the city of Barcelona (41˚N). On the other hand, limited savings were accomplished in Paris (49˚N) where it became almost 8%. Also, savings diminished to 3% in Oslo (60˚N).

In the West orientation, the highest savings were found. These reached 38, 33, 30, 26, 27, 27 and 34 % of the total energy consumption in the cities of Dakar (14˚N), Jeddah (21˚N), Kharga (25˚N), Taiwan (25˚N), Kuwait (29˚N), Damascus (33˚N) and Cairo (30˚N) respectively. In the cooling dominated climates, the use of screens reduced energy consumption by 29% in Barcelona (41˚N), 7% in Paris (49˚N) and 3% in Oslo (60˚N) (Fig. 6).

In the North orientation, the savings could barely be recognized due to limited direct solar penetration.

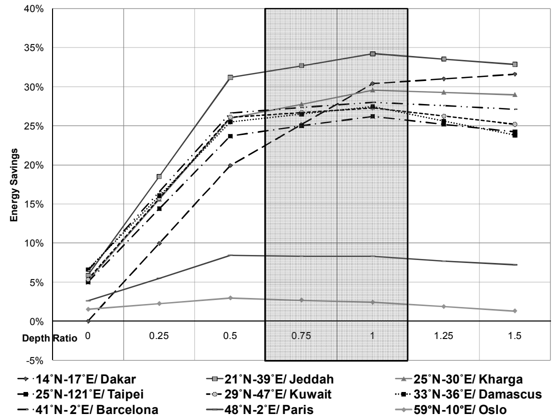

Figure 5: Energy Savings of a South Oriented Screen with an 80% Perforation at Different Geographical Locations

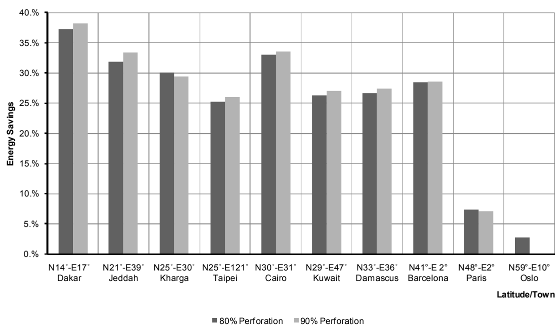

Figure6: Maximum Energy Savings of a West Oriented Screen Having an 80% - 90% Perforation at Different Geographical Locations

3.2. Energy performance discussion

Depth to perforation ratio 1/1 and 0.75/0.75 achieved considerable savings in most locations with 80% and 90% perforation percentages in the West and South orientations. In addition, the effect of depth/perforation configuration on energy consumption proved to be an important factor. It was found that while certain configurations drastically reduced energy consumption; other configurations increase the energy consumption in some of the locations.

4. PHASE II: SCREEN OPENING PROPORTION AND DAYLIGHTING PERFORMANCE

In this phase, the impact of the solar screen opening proportions on the daylighting performance was evaluated. The purpose was to explore their potential for performance enhancement, as daylighting has dynamic unique features that create visual richness and a productive atmosphere. Moreover, the utilization of solar screens diffuses natural light. This is important in the clear sky conditions of the desert environments. Consequently, an example clear sky condition location was chosen for daylighting simulation (El Sadat City, 30.2˚N - 30.2˚E),

Certain parameters of the base case were adjusted due to their contribution to daylighting performance. They include increase of wall and ceiling reflectance to 85.7% (white colour paint) and addition of a solar screen with a perforated top sun-breaker. The solar screen dimensions and depth ratio were based on results of Phase I to be equal to 0.75/0.75 with perforation percentage 90%. Simulation results were tabulated according to different orientations of the window on which the solar screen was fixed (N, E, S, W) and different seasons (spring, summer, autumn and winter) with different times (9:00, 12:00, and 15:00).

Research methodology was twofold; the base case was evaluated according to illuminance adequacy (≥200Lux) and daylighting performance was enhanced through change of the screen's opening proportion (Fig. 7).

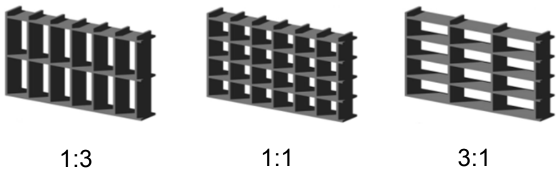

Figure7: Geometric Effect of Changing Screen Proportions: "Horizontal : Vertical" Dimension Ratio

Three zones were analyzed in the base case. The first zone is located near the window: the "near zone", second zone at mid length of the indoor space: the "mid-length zone" and third zone is near the rear wall: "the far zone". Each zone contained 84 measuring points in a grid of 0.3m *0.3m at a working plane of height 1 m (Fig. 8). The average of each zone was calculated, excluding the values of direct sun penetration points that were having illuminance levels higher than 5000 Lux.

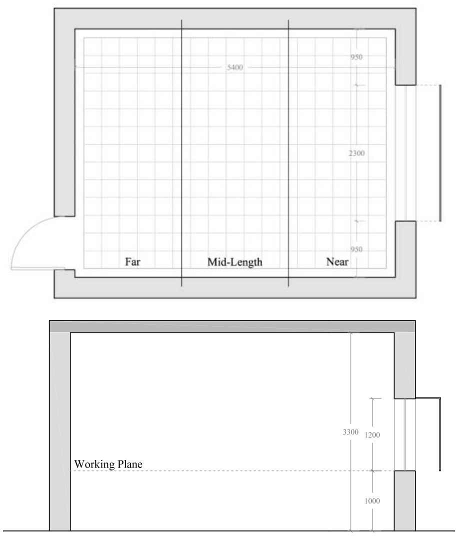

Figure 8: Phase II base case parameters.

Depending on the time of day and the season, each orientation had a different daylighting performance (Fig. 9). In the south orientation, daylighting performance was found adequate in almost all seasons and at all three tested zones, except for summer at the mid and far zone at 9:00 and 15:00. However, in the North orientation, there was a significant decrease in illuminance values. Consequently, daylighting performance was found inadequate in almost all seasons in the mid-length and far zones. Conversely, the near zone was adequate in all the tests except for the winter season, On the other hand, in the East and West orientations, change in daylighting performance was considerably affected by the time of the day. For screens oriented towards East at 9:00 and West at 15:00, illuminance values were found adequate in most cases. However, at 12:00 only the near zone met minimum illuminance requirements in all seasons. All other cases were found inadequate. As a general result, the mid-length and far zones were defined as problematic. Further research, thus, focused on their enhancement.

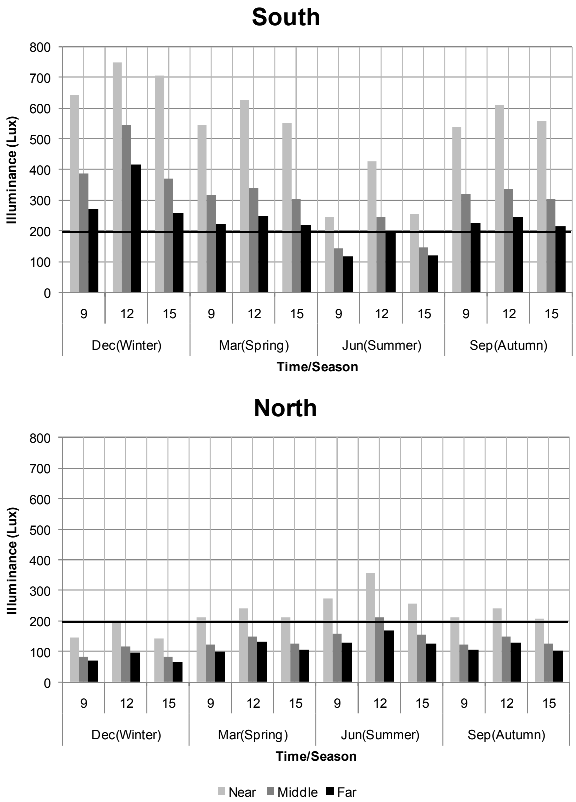

Figure 9: Base case evaluation at the three tested zones in different seasons and time (≤200 Lux = Inadequacy)

4.1. Daylighting performance simulation results

The base case solar screen dimensions, perforation percentage and depth ratio were kept constant. Opening proportions were increased in the horizontal and vertical directions to be 1:3, 1:6, 1:12, and 1:18. A comparative analytical study was drawn in reference to the base case. The aim was to test the usefulness of changing the proportion in either direction on illuminance levels.

As a general observation, the illuminance levels were directly proportional to the increase of opening proportion in both directions. For example, when the opening proportions were tripled in the horizontal and vertical directions, the daylighting performance increased in all tested zones of all orientations, seasons and times. In the near and mid-length zones, all illuminance values increased by at an average rate of 23.5% in reference to the base case, while the far zone increased by 18% (Fig. 10).

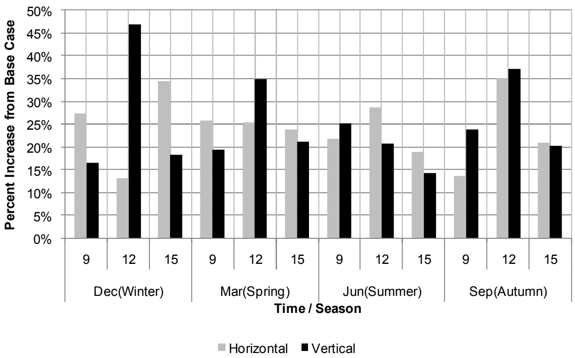

Figure 10: Effect of Changing Opening Proportion to 1:3 on the Illuminance Levels of the Far Zone in South Orientation.

A comparative analysis of daylighting performance in terms of adequacy was undertaken for all tested cases. Analysis of improvement was based on the percentage of cases that became adequate after applying a change in opening proportion. Special attention was given to the mid-length and far zones due to their identification as inadequate in most of the base cases (Fig. 11 & 12).

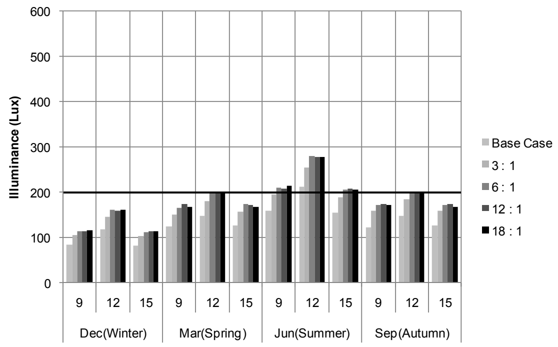

Figure 11: Effect of Changing Opening Proportion on the Illuminance Levels of Mid-Length Zone in North Orientation.

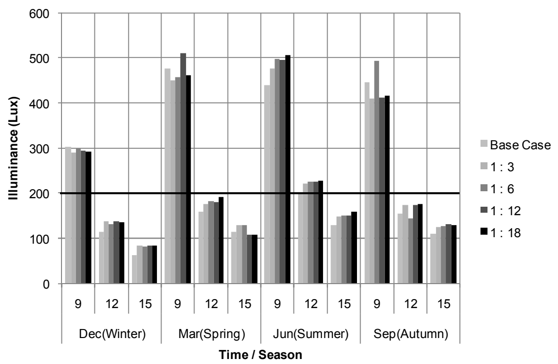

Figure 12: Effect of Changing Opening Proportion on the Illuminance Levels of Far Zone in East Orientation.

An increasing trend in performance was observed until the 1:12 ratio was reached. However in the 1:18 ratio, performance increased, decreased or remained constant as compared to 1:12. To verify if the observed reduction forms a trend, an extreme case of 1:32 ratio was tested. Results showed that performance either decreased or remained constant in comparison with the 1:18 ratio (Fig. 13 & 14).

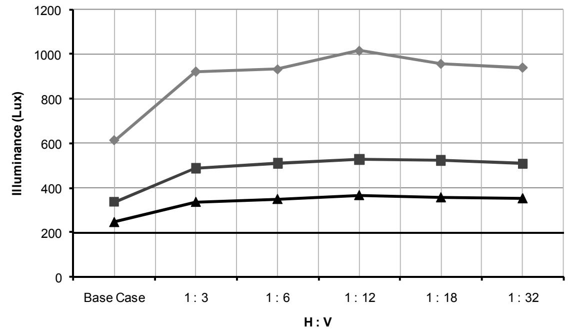

Figure 13: Illuminance Levels Resulting from Changing Opening Proportion at 12:00 Noon in Autumn at South.

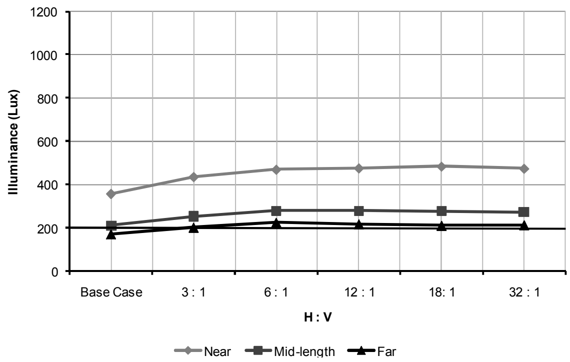

Figure 14: Illuminance Levels Resulting from Changing Opening Proportion at 12:00 Noon in Summer at North.

4.2. Daylighting performance discussion

In all orientations, the different opening proportions achieved comparable improvements in daylighting performance. However, it was found that the 1:18 ratio in the horizontal direction had the most positive impact in terms of adequacy and relative illuminance values. Table 2 compares improvement percentages of each orientation in all tested zones.

Table 2: Percent Improvement Due to Changing Screen Opening Proportions.

Orientations	Zones	Base Case	H:V 18:1	Total Improvement
North	Near	75%	100%	22%
	Mid	8%	42%	
	Far	0%	8%	
East / West	Near	83%	100%	14%
	Mid	42%	58%	
	Far	33%	42%	
South	Near	100%	100%	6%
	Mid	83%	92%	
	Far	75%	83%	

The percentage of adequate cases increased in the mid-length and far zone when the square proportions of the opening were changed in ratio to become rectangle-like. This is because the screen openings started to resemble light louvers that reflect daylight deep into the space. This effect was exploited till the ratio increased more than 1:18.

5. PHASE III: POTENTIAL OF ENERGY SAVINGS THROUGH RECOMMENDED SCREEN OPENING PROPORTION

In this phase, the overall energy performance of the screen proportion that resulted from phase II analysis (18:1) was tested. Cases with 1:1 and 18:1 opening ratio screens were compared with a no screen window. The same architectural parameters of the base case of Phase II were used.

Energy savings through use of 1:1 solar screen reached 17, 15, 14 and 4% in West, East, South and North orientations respectively in comparison with the window without screen. However, savings through utilization of 18:1 solar screen configuration were only 8, 7, 9 and 1% respectively in comparison with the window without screen (Fig. 15).

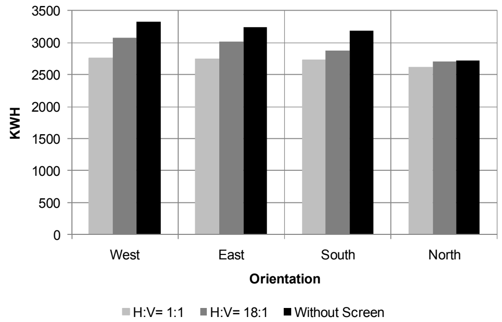

Figure 15: Comparison of Energy Consumption.

6. DISCUSSION AND CONCLUSION

The usefulness of utilizing external perforated solar screens in front of windows was demonstrated. The screens reduced energy consumption by 25% to 35% in a number of cities that lie between 14˚N and 40˚N. Their impact was less obvious in cities that were further north. The depth to perforation ratios of 1/1 and 0.75/0.75 achieved considerable savings in most locations with 80% and 90% perforation percentages in the West and South orientations.

An in-depth investigation of the above configurations' daylighting performance suggested that changing screen opening proportions (horizontal : vertical) from 1:1 to 18:1 would effectively improve daylighting.

The energy behaviour of the suggested screen opening proportion was tested. Changing the opening proportion to 18:1 improved the deficient daylighting behaviour of the North direction, while resulting in a marginal effect on energy consumption. It is, then, recommended. On the other hand, the 1:1 proportion is recommended in the Sothern orientation, since use of the 18:1 proportion increased the energy consumption by 5.6%. This was not justified especially that the daylighting performance was almost satisfactory in the 1:1 proportion. As for the East and West orientations, it is up to the designer whether the improvement of daylighting due to change in opening proportion is worth the compromise in energy consumption, which ranges between 9-10%.

A satisfactory balance between achieving efficient energy savings and daylighting performance within an indoor space constitutes the real challenge when selecting and designing solar screens. Further research is directed towards exploring other screen configurations and their efficient combinations.

7. ACKNOWLEDGEMENTS

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