Multi-objective optimization of Indian Jaali fenestration system for Visual, Thermal and Perceptual Performance using Computational methods

Afshan Rehman¹, Amulya Surapaneni¹
¹ Carnegie Mellon University, Pittsburgh, USA

Abstract

Jaali is a term used for perforated screens with floral or geometric patterns native to Indo-Islamic architecture. By changing the depth and the size of apertures of the Jaalis, one can reduce glare, solar insolation, achieve unobstructed views and cool breeze. Although individual studies on the impact of Jaalis on daylighting comfort (Batool, 2014) and thermal comfort (Sherif et. al, 2012) exist, no research currently examines how Jaali patterns affect both daylighting and thermal comfort simultaneously. This paper introduces an experimental study to evaluate these concepts by replacing a glass facade in a 3D-model with a Jaali screen. A qualitative sample study was conducted using six Jaali screens to ascertain the Jaali pattern that best improves the quality of light. The most preferred Jaali pattern from the survey was then studied to quantitatively assess its visual and thermal properties. To determine the optimum aperture size and depth of the Jaalis, daylight metrics such as ASE and SDI, and thermal metrics such as annual indoor solar radiation were used.

Key Innovations

- The effect of Jaali patterns on both daylighting and thermal comfort were assessed by using visual programming simulation environments for a quantitative study.
- Innovations in building simulations have paved a way for optimizing these intricate Jaali patterns for daylight and thermal comfort. The solid to void ratio and depth of Jaali screens were optimized parametrically to produce well-lit, thermally comfortable and glare-free indoor spaces.
- The paper highlights an important research methodology to generate an optimized innovative Jaali pattern that can be used by architects and building performance engineers to develop building screens that improve the lighting and thermal quality of indoor spaces.

Practical Implications

This paper generated a final Jaali screen of solid-void ratio of 70%-30% and a depth of 100mm using both qualitative and quantitative strategies. The result of the paper demonstrates that the solid-void ratio and depth of Jaali screens can be optimized to produce well-lit, thermally comfortable and glare-free indoor spaces.

Introduction

Jali or Jaali is a term used for partition or curtain walls with intricate geometric and ornamental perforations. Jaali was commonly used in India during the Mughal and Rajput architecture timeline and was mostly made out of sandstone, marble and clay (The Hindu, 2018). Initial Jaali work had geometric patterns carved into stone and the Mughals introduced more floral patterns [Figure 1].

Figure 1: Geometric and Floral Jaali patterns.

The characteristics of these patterns are such that each module is symmetrical and is repeated multiple times on a grid which gives the illusion of continuity. The patterns vary from simple six-point hexagons to 10-fold rosette [Figure 2].

Figure 2: Geometrical parameters for Jaalis (Abdullahi and Embi, 2013).

For the last several years, Jaali has been used as a screen that lets sunlight and air in while providing privacy and adequate views. Recently, Jaali has been adopted as a modern façade pattern because of the alluring shadows it creates. As Jaalis control the light entering in, by reflecting some light from the outer surface, they also...
reduce the heat associated with it (G Kamath et al., 2016). The aspect of Jaali that makes this happen is the aperture and thickness of its cross section. The height of the perforations in a Jaali should be smaller than or equal to the depth and each void forms a cube (Perforated screen designer, 2018).

The Mughal artisans devoted great attention to the proportions and patterns of these lattice walls. There is a lot of research on the evolution of geometric patterns of Jaalis (Reki and Selçuk, 2018) and solid to void ratio of these screens in terms of daylight performance (Gandhi, 2014). Although individual studies on the impact of Jaalis on daylighting comfort (Batool, 2014) and thermal comfort (Sherif et al., 2012) exist, no research currently examines how Jaali patterns affect both daylighting and thermal comfort at the same time. This paper introduces an experimental study that analyses the effect of shadows created by these Jaali patterns perceptually. An online poll was conducted to rank the patterns based on the quality of their shadows. Built on the results of the survey, a Jaali pattern was generated that achieves both thermal and daylighting comfort indoor through simulations.

Methods

Location and Building Selection

Given its history of invasions, the architecture of Delhi is juxtaposed with both Mughal and Rajput architecture. For this study, Delhi, India (28.7041° N, 77.1025° E) was selected due to the possibilities its climate creates for enhancement of indoor thermal quality using Jaalis. Heating Degree Day (HDD) and Cooling Degree Day (CDD) define the heating demand and cooling demand in a location based on its outdoor temperature. For Delhi, the balance point of outdoor temperature was set to 18.3°C and the CDD and HDD was 2639 and 305 respectively that was calculated using Ladybug plugin, a plug-in for rhino and Grasshopper that runs environmental simulations. Delhi is a cooling dominant climate with dry bulb temperatures soaring up to 44.3°C in peak summers. The New Delhi Gandhi Intl AP: 421810: TMY3 weather file from EnergyPlus weather data was used for the lighting and thermal simulations.

A library space was used for the study due to the importance of quality of daylight in reading, learning, and cogitating. A 3D digital model of a library hall, facing South, with an open plan was assumed as the test space and was modelled in Rhinoceros (version 6), a commercial 3D modelling computer aided drawing software (Robert McNeel & Associates, LLC). The test space measures 28m wide, 15 m deep by 4.5 m high. It was assumed that the test space has occupied hours from 8 AM to 6 PM.

Selection and Development of Jaali Patterns

The historical architecture timeline of Delhi provided the scope to select six unique Jaali patterns. The six unique patterns (6-point, 8-point, 6x8 point, 10-point, 12-point and 14-point Geometrical patterns) selected for the study were inspired by Abdullahi & Embi’s detailed study of the history and evolution of Islamic geometric patterns (Abdullahi et al. 2013).

The geometry and mathematical algorithm of the selected 6 Jaali patterns were observed and modelled parametrically in Grasshopper plug-in for Rhinoceros (Robert McNeel & Associates, LLC). Grasshopper is an algorithmic modelling tool that uses visual programming language. Because the South facade receives the most amount of sunlight in a day, four large openings were created on the South-facade of the library hall. The Jaali patterns that were created in Grasshopper were morphed onto each opening using a bounding box. The U and V values of the patterns were modified in order to get unique perforation ratios for each.

Survey and Participants

The test space with the Jaali screens created in Grasshopper were baked and internalized in Rhinoceros and were then rendered in Enscape (Enscape GmbH). Enscape is a real time rendering software with in-built options for environment and furniture. The scenes were used in an online poll to assess the perceptual performance of these patterns.

![Figure 3: Renders of 6 Jaali Patterns.](image1)

![Figure 4: Renders of interior view created for the online survey.](image2)
A total of 30 subjects participated in the study. Participants were unpaid volunteers over 18 years of age, who were graduate students from the School of Architecture at Carnegie Mellon University. A google form (Google LLC) was created and the participants were asked to select their most preferred pattern. The survey was divided into two questions; the first question had an exterior view of the front elevation of the Jaali walls [Figure 3] and the second question had interior views of the same Jaali walls [Figure 4]. The two disparate yet contrasting questions were asked in order to study if internal shadows, furniture and perspective views had an effect on the results.

Based on the results from the survey, a final pattern was chosen for the next phase involving daylight and thermal simulations. The overarching aim of this experimental research study was to conduct an integrative study that takes advantage of both lighting and thermal performance qualities of native Indian Jaalis to generate a single Jaali pattern that renders excellent quantitative and qualitative indoor daylighting and thermal comfort.

**Daylight Analysis**

From the survey results, the most preferred Jaali pattern was selected and further developed. The depth and perforation ratio of the Jaali screen was varied parametrically in Grasshopper to achieve an optimum thickness and depth to height ratio of a cross section which cuts out glare and distributes the daylight evenly indoors. To perform this daylight analysis, Climate Studio (Solemma LLC, 2020), a Rhinoceros plug-in for daylight and energy analyses was used.

For the daylight analyses, ‘New Delhi Gandhi Intl AP: 421810: TMY3’ was inputted for the location. A clay material with 13.8% Rvis properties was assigned for the Jaali layer on Climate Studio plug-in. To achieve optimal daylighting comfort inside the library hall, simulations were run to measure the Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). sDA is the percentage of floor area that exceeds 300 lux for a specified percentage time or 50% of occupied hours. The occupied hours are taken as 8am to 6pm. ASE is the percentage of the horizontal work plane that exceeds 1000 lux of sunlight illumination over 10% or 250 occupied hours per year over a specified daily schedule with all operable shading devices retracted (IESNA, NPO). The optimum values for these are adopted from LEED v4 (USGBC) which says that the sDA has to be more than 55% and ASE has to be less than 10%. The sensor spacing for simulating sDA and ASE was taken as 600mm and the ground plane offset was taken as 10mm. Through an iterative design and performance analyses process between daylighting and thermal simulations a final Jaali pattern was developed. The iterative design determined a Jaali pattern based on daylight and annual solar radiation that gives the optimum proportions in terms of depth and solid to void ratio that ultimately provides perceptual, daylighting and thermal comfort in the library hall in New Delhi, India.

**Results**

The first section presents the results of the two-question survey and the final Jaali pattern selected by the respondents. The subsequent sections show how the solid-void ratio and thickness of the selected Jaali pattern were changed parametrically to arrive at a final optimized pattern that gives the best possible results for daylight and thermal analysis.

**Survey Results**

Although the same six patterns were used for both the questions in the survey, the angle of view (AOV) was different. The exterior front camera angle for question one and interior perspective camera view for question two presented different opinions from the respondents. Figure 5 shows the tally of the number of votes received for each Jaali pattern. Jaali pattern-2 had the majority of the cumulative votes in both the questions. Figure 6 shows how the probability of selecting the same pattern for both the questions varies. The discrepancy in the respondents’ choices show how AOV plays a major role in the perceptual analysis of shadows and daylighting.

![Figure 5: Results for the 2-question survey.](image_url)

![Figure 6: Summary of results for the 2-question survey.](image_url)
Daylight Availability Results

From the survey results, Jaali pattern 2 was selected and further optimized for daylight analysis. The solid to void ratio of the selected pattern was varied parametrically in Grasshopper and baked on to Rhino workspace to run the daylight analysis on Climate Studio. Simulation of daylight availability (LEED® v4) was used to see how perforation rate affects the quantity of daylight.

Table 1: Daylight Availability for different perforation ratios.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Solid: Void Ratio, Depth</th>
<th>Results</th>
<th>LEED Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid: Void Ratio = 80% : 20%, Depth = 50 mm</td>
<td>sDA = 42.70%, ASE = 0.00%, LEED Credits = 0 credits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid: Void Ratio = 70% : 30%, Depth = 50 mm</td>
<td>sDA = 79.30%, ASE = 6.40%, LEED Credits = 4 credits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid: Void Ratio = 60% : 40%, Depth = 50 mm</td>
<td>sDA = 83.70%, ASE = 11.37%, LEED Credits = 0 credits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid: Void Ratio = 50% : 50%, Depth = 50 mm</td>
<td>sDA = 93.26%, ASE = 12.15%, LEED Credits = 0 credits</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. shows how a lower void ratio was not sufficient to provide enough spatial daylight. A greater void ratio though provides good amount of daylight, also receives a lot of annual sunlight exposure which causes visual disturbance and increase in thermal temperature. The thermal analysis simulations were run simultaneously to understand the impact of geometry on indoor thermal comfort. The solid to void ratio and the thickness of the Jaali pattern 2 was varied parametrically in Grasshopper and baked on to Rhino workspace to run the annual solar radiation simulations using Ladybug plugin. Annual Solar Energy Density (SED) decreased with the decrease in perforation ratio and the solid to void ratio of 80% to 20% performed the best in terms of indoor thermal quality. However, too much decrease in the perforation ratio contributed to poor daylighting quality of the library hall. Also, higher ASE leads to potential glare issues. Hence, the solid to void ratio of 70% to 30% (as chosen in the daylight analysis) was chosen and the thickness of the screens was varied to cut down the annual indoor solar radiation as shown in Table 3.

Since the overarching aim of this research was to create a Jaali screen that satisfies both daylighting and thermal comfort, the 100mm deep screen from Table 2 was selected. When the cross-section of the Jaali was made more than 100mm, the spatial daylight was reduced drastically.

Thermal Analysis Results

Thermal analysis simulations were run simultaneously to understand the impact of geometry on indoor thermal comfort. The solid to void ratio and the thickness of the Jaali pattern 2 was varied parametrically in Grasshopper and baked on to Rhino workspace to run the annual solar radiation simulations using Ladybug plugin. Annual Solar Energy Density (SED) decreased with the decrease in perforation ratio and the solid to void ratio of 80% to 20% performed the best in terms of indoor thermal quality. However, too much decrease in the perforation ratio contributed to poor daylighting quality of the library hall. Also, higher ASE leads to potential glare issues. Hence, the solid to void ratio of 70% to 30% (as chosen in the daylight analysis) was chosen and the thickness of the screens was varied to cut down the annual indoor solar radiation as shown in Table 3.
The results showed that a deeper Jaali screen provided better indoor thermal performance by reducing the annual indoor solar radiation. However, the overarching aim of this research was to create a Jaali screen that satisfies both daylighting and thermal comfort, the 100mm deep screen from Table 3, was selected as Jaali screens that are more than 100 mm deep were drastically reducing the spatial daylight.

**Table 3: Annual Solar radiation results for different Jaali depths.**

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Depth</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid : Void = 70:30</td>
<td>Depth = 50 mm</td>
<td>Total Indoor Solar radiation = 20231 kWh Avg indoor SED = 29.5 kWh/m2</td>
</tr>
<tr>
<td></td>
<td>Depth = 75 mm</td>
<td>Total Indoor Solar radiation = 9470 kWh Avg indoor SED = 23.2 kWh/m2</td>
</tr>
<tr>
<td></td>
<td>Depth = 100 mm</td>
<td>Total Indoor Solar radiation = 7220 kWh Avg indoor SED = 17.7 kWh/m2</td>
</tr>
<tr>
<td></td>
<td>Depth = 125 mm</td>
<td>Total Indoor Solar radiation = 5600 kWh Avg indoor SED = 13.7 kWh/m2</td>
</tr>
</tbody>
</table>

**Conclusion**

This paper generated a final Jaali screen of solid to void ratio of 70% to 30% and a depth of 100mm for a library space in Delhi using both qualitative and quantitative strategies. Qualitative study analysed the perceptual performance of these patterns and the quantitative study examined the effect of Jaali patterns on both daylighting and thermal comfort at the same time. The result of the paper demonstrates that the solid to void ratio and depth of Jaali screens can be optimized to produce well-lit, thermally comfortable and glare-free indoor spaces.

The paper highlights an important research methodology to generate an optimized Jaali pattern that can be used by architects and building performance engineers to develop building screens that improve the daylighting and thermal quality of indoors. Future studies should examine the venturi effect of Jaali screens in reducing the indoor air temperature. According to these principles, when air passes through a constricted opening, the pressure reduces, the air compresses, velocity increases and temperature decreases. Implications of such studies can result in optimizing Jaali patterns for indoor thermal comfort using Computational Fluid Dynamics (CFD).

**Acknowledgements**

The authors would like to thank Professor Azadeh Sawyer (Carnegie Mellon University). This research was done as a part of her course work in ‘48692 - Shaping Daylight’. They are grateful for the technical support provided by Alstan Jacobiec (University of Toronto) for his hands-on demonstration of Climate Studio. They would also like to thank Professor Omer Karaguzel and Professor Dana Cupkova (Carnegie Mellon University) for their constant support and guidance.

**References**


Keep the books on the shelves: Library space as intrinsic facilitator of the reading experience, James M. Donovan (March 2020) Journal of Academic Librarianship, Volume 46, Issue 2, March 2020


Components for the Region of Andhra Pradesh, India. International journal of Emerging Trends in Science and Technology. 03. 5018-5028.10.18535/ijetst/v4i3.06.


Official website of Google accessed on 27th April 2020, https://www.google.com/forms/about/


