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# A comparative evaluation of the effectiveness of glazed and open balconies in low-rise residences in moderate climates via field measurements and simulations

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## ABSTRACT

A global phenomenon currently prevails in installing an extensive array of glazing systems in multi-unit residential edifices. Some urban occupants are opting to sheath their balconies predominantly with glass to mitigate issues associated with open balconies (OBs), such as glare, pollution, wind, insects, birds, safety and noise and to augment their living space. The effectiveness of glazed balconies (GBs) in cold and warm climates has been extensively debated, and their advantages and disadvantages have been highlighted. Nonetheless, these studies have not examined the issues related to GBs in moderate climates. Hence, this research adopted a comprehensive approach towards user satisfaction, diverse design parameters, climatic conditions and simulation outcomes. This study explored occupants' satisfaction levels and perceptions towards OBs and GBs via surveys and determined the issues that warranted attention. Furthermore, OBs and GBs were compared and juxtaposed against thermal comfort, temperature and humidity variation, daylight, and wind via field measurement and simulation. Daylight simulations were performed using Rhino and wind analyses using IESVE. The findings indicated that GBs perform better in moderate climates. Moreover, individuals with OBs were inclined towards installing balcony enclosures in the future. GBs considerably increased the temperature and reduced the humidity in comparison with their open counterparts.

**Keywords:** glazed balcony; open balcony; thermal performance; daylight and wind analysis; adaptive thermal comfort model

## 1. INTRODUCTION

As land availability is shrinking in urban areas, multi-unit residential buildings (MURBs) are becoming more common to accommodate the demands of the increasing population and to effectively use the limited available land. Such buildings consume enormous natural resources and energy, and their carbon footprints are considerably high. Hence, efforts must be taken to make new and existing MURBs more energy efficient and environment friendly (Mirabi & Nasrollahi, 2019). Energy efficiency can be achieved in several ways, and changing the type of balcony is one of them, which is the focus of this study.

According to their form, boundary conditions and system, glazed balconies (GBs) can be defined as a closed system with a boundary between the inside and outside space or those closed by glass on the outer edge (Omrani et al., 2017). Nowadays, courtyards and gardens are being replaced by balconies as a desired private outdoor space. Moreover, the recent pandemic highlighted a collective will among users to have a private outdoor space in their living area. Therefore, an efficient balcony design that fulfils the needs of the user adequately could enhance the energy performance and indoor environmental conditions of such units. Daylighting and natural ventilation can substantially influence indoor environmental conditions and impact the ambience, space conditioning, visual comfort, well-being and health of occupants (Aadithya et al., 2023; Kaushik S et al., 2023; Varghese & Kaushik, 2022).

It is observed that now balconies are covered with walls and glasses. The motivation for the use of glass as covering material in balconies was caused by a desire for an increase in living space and attaining privacy (Omrani et al., 2017), and sometimes when occupants want an outside view with a reduction in traffic noise and air pollution (Kim & Kim, 2007). Previous research confirmed that balconies with closed construction (built with parapets or side walls) and having glass windows installed on the edge of balconies offer a considerable reduction in noise than the open type (Li et al., 2003; Cui et al., 2016). Another study found that double glazing increased the ability of the GBs to keep heat in during the winter and out during the summer by 42.8%, which means that lower heating and cooling costs can be expected (Afshari et al., 2023).

Initially, a pilot survey was performed via telephonic conversations, followed by a field survey in selected apartments in the city of Bengaluru (Figure 1), India, before proceeding to the actual study. The pilot survey showed that balconies of apartments, whether high-rise, low-rise, or near a high-traffic road, were mostly covered with glazing. The reasons were similar in all apartments and included protection from rain, security of children at home, reduction of noise pollution, achieving privacy, etc.

In metropolitan cities where outdoor pollution is a major issue, the open balconies (OBs) might impact occupants' health (Wang et al., 2022). Regardless of whether someone is a tenant or owner, the issues and needs related to balcony spaces are the same for both. According to Omrani et al. (2017) who reviewed more than 217 papers, many studies conducted in India focused on OBs, but there is a lack of research on the impact of GBs on indoor environments.

Thus, changes in balcony design can affect visual comfort, daylight illuminance levels and indoor environments, with the potential for increased darkness depending on the type of glass used. Studies have observed that maximum comfort levels can be achieved and the above-mentioned problems can easily be overcome if the designer provides a design that can be changed as per occupants' requirements rather than providing a fixed balcony (Shamseldin, 2023). Inadequate design of GBs can lead to problems such as overheating and increased energy consumption. Recent studies on a warm climatic region of Japan confirmed that GB design is most applicable in low-rise multi-dwelling units during the winter season in comparison to OB with insulation (Yuan et al., 2022). Previous studies have identified positive and negative factors associated with GBs, including improved thermal insulation and acoustic protection, reduced air filtration flow rate, and natural ventilation in indoor spaces.

The objectives of this work are to study the satisfaction levels and perceptions of occupants towards OBs and GBs in moderate climates through survey; to evaluate the effect of OBs and GBs for different climatic parameters such as temperature, humidity, airflow pattern, and velocity; to analyze the impact of glazing on daylight and glare; and to explore the influence of a GBs on thermal comfort using the adaptive thermal comfort model for naturally ventilated residential buildings.


**Figure 1.** Apartment buildings in Bengaluru having glazed balconies

## 2. MATERIALS AND METHODS

### 2.1 Location and climate study

This study was conducted in Bengaluru, which is located at 12°59′N 77°35′E. The climate in this city is moderate as per National Building Code 2016 (Bureau of Indian Standards, 2016a, 2016b), it is situated in mountainous and high plateau terrains, and it has abounding flora and fauna. In summer, the temperature varies from 30°C to 34°C during the daytime and from 17°C to 24°C at night. In winter, the temperature varies from 27°C to 33°C during the daytime and from 16°C to 18°C at night. The relative humidity of the air is low during summer and winter and varies from 20% to 55%; however, during the monsoon season, it may reach 55%–90%. A detailed climate study of Bengaluru city was conducted using the Climate Consultant v6 software to determine the opportunity for GBs by studying the major wind direction and direct or diffused solar gain.

### 2.2 Field study

#### 2.2.1 Building details

This study was conducted in the Gangotri Slv Meadows apartment residential unit near Kudlu Gate Bengaluru, which has G+4 floors and 40 dwelling units. This building has both OBs and GBs. For this study, the GB of Flat 204 on the third floor and the OB of Flat 004 on the ground floor, which share the same orientation, were selected (Figure 2).


*Note:* Case study building and the case study unit are indicated by black boundaries

**Figure 2.** Case study building plan (middle) and surroundings (left)

#### 2.2.2 Field measurement

Full-scale measurements of parameters such as air temperature, humidity, lux level and air velocity were acquired (Table 1). Data loggers were placed at a height of 700 mm (working plane height) in spaces adjacent to the balcony and the outdoor balcony area to assess the illuminance level (Sigalingging et al., 2019). Temperature and humidity sensors were placed at 1.2 m above the floor level (at seated human head level), along with an anemometer to measure air velocity inside the room. This fixed placement might have posed limitations in capturing variations at different heights within the space.

### 2.3 Online survey

In addition, a questionnaire survey was conducted online to evaluate residents' subjective perceptions of comfort regarding OBs and GBs. The survey aimed to assess occupant satisfaction levels based on quantitative factors such as daylight, glare, noise, humidity, temperature, air quality and natural ventilation in spaces adjacent to the balcony and the balcony space itself. Furthermore, certain qualitative factors, such as personal control over the comfort of one's private space and occupant privacy perceptions, were considered. Moreover, the survey attempted to identify the most common balcony material and type in Bengaluru as well as the changes made by the respondents to their balcony door/window to achieve comfort and the issues that required attention. Finally, respondents' preferences for the balcony design were documented. This survey was circulated among several apartments in Bengaluru and garnered 53 responses. The shared questionnaire did not inquire about the dimensions of dwellings, such as the size of rooms, ceiling heights or balcony depths.

**Table 1.** Sensor specifications

| Equipment | Parameter | Range | Resolution | Accuracy |
|---|---|---|---|---|
| Infrared thermometer (model: IRT380T/IRT550T) | Surface temperature | -50°C to 550°C/-58°F to 1022°F, °C/°F | 0.1°C/0.1°F (precision) | ±1.5°C |
| Digital lux meter | Brightness/ lux level | 4 ranges: 200 lux; 2000 lux; 20,000 lux; 200,000 lux | - | 4% rdg  0.5% f.s % rdg  10 |
| DHT 11 temperature & humidity sensor | Humidity, indoor and outdoor temperature | Humidity range: 10% ~ 99%RH; temperature measuring range: -50 + 70 | Humidity: 1%; temperature: 0.1°C | Humidity accuracy: -/+10%RH; temperature accuracy: ±1°C (±1.8°F) |

*Note:* RH - Relative Humidity; rdg - reading; f.s - Full scale; °C - Celsius; °F - Fahrenheit

### 2.4 Simulation-based approach

#### 2.4.1 Daylight analysis

This case study was modelled in Rhino + Honeybee using a radiance plug-in. A correlation analysis was performed between the measured and simulated lux levels to validate the honeybee script, whereas temperature, humidity and wind velocity were validated using the software IESVE 2019 with macro flow and thermal plug-ins. This study leveraged climate-based daylight modelling, which employs realistic sun and sky conditions sourced from climatic data. The radiance rendering parameters are listed in Table 2, and the material properties used in the case study model for annual daylighting simulations are given in Table 3. Occupancy for the case study was assumed to be from 6 am to 6 pm during which daylight is available. For the analysis grid, working plane height was taken as 700 mm for the dining space (study area). The properties of the opaque materials (walls, roof, and floor) were assigned based on the guidelines provided by the Chartered Institution of Building Services Engineers (2022) in the SLL Code for Lighting, while the visible light transmittance values of the glass were assigned according to manufacturer specifications. Table 4 provides the simulation inputs and their corresponding outputs. The limitations of this daylight include assumptions about occupancy and the reliance on climate-based modelling.

**Table 2.** Radiance rendering parameters

| Ambient bounces | Ambient divisions | Ambient super-samples | Ambient resolution | Ambient accuracy |
|---|---|---|---|---|
| 5 | 1000 | 20 | 300 | 0.1 |

**Table 3.** Material parameters

| S. No. | Example | Surface reflectance/transmittance |
|---|---|---|
| 1 | Floor | 0.2 |
| 2 | Wall | 0.55 |
| 3 | Ceiling | 0.7 |
| 4 | Surroundings | 0.2 |
| 5 | Outside ground | 0.20 |
| 6 | Balcony, intermediate | 0.6 |

*Note:* Source: CIBSE code for interior lighting 1994, Tables 5.8 and 5.9, for typical reflectance.

**Table 4.** Daylight simulation inputs

| S. No. | Simulation inputs | Benchmark |
|---|---|---|
| 1 | Target illuminance 200 lux (daylight autonomy) | SP: 41 (S and T) 1987 |
| 2 | sDA target is 200 lux for 50% of the occupied period | SP: 41 (S and T) 1987; LEED v4 |
| 3 | UDI less than 100 lux | Needs supplementary lighting |
| 4 | UDI between 100-2000 lux | Daylight alone is enough for carrying out daily activities |
| 5 | UDI above 2000 lux | Direct sun exposure |
| 6 | ASE (spaces should be less than 10%) | Lighting measurement 83 (LM-83) guide accepted by LEED |

*Note:* sDA - spatial daylight autonomy; UDI - useful daylight illuminance; ASE - annual sun exposure;
LEED - leadership in energy and environmental design

#### 2.4.2 Wind analysis

The IESVE 2019+ macro flow plug-in was utilized to perform wind environment analysis in which parameters such as wind velocity, air flow pattern (Aflaki et al., 2016) and air change effectiveness (ACE) in accordance with ANSI/ASHRAE 55 (ASHRAE, 2010) were compared for both OBs and GBs. Measurements were taken at noon of December 19th, with the wind flowing from east to west. The wind analysis was limited to the assumed wind conditions.

#### 2.4.3 Adaptive thermal comfort analysis

The percentage of comfortable hours was assessed based on the operative temperature of the spaces and the adaptive thermal comfort temperature prescribed for a naturally conditioned residential building in a moderate climate zone in IMAC (Kishore, 2022).

## 3. RESULTS AND DISCUSSION

### 3.1 Climate analysis

The average monthly outdoor temperature was within the thermal comfort zone of 22°C–27°C for most of the year. This range offered an opportunity for natural ventilation or flushing of bad air at night for a few months of the year (Figure 3). However, the average relative humidity value exceeded the comfort range (i.e. 40%–60%) for more than half a year, and the annual average sky cover was over 50%. These observations signify that the solar heat gain and direct sunlight will be low for most of the year (Figure 4). As per ANSI/ASHRAE 55 (ASHRAE, 2010), the need for shading begins when DBT is above 23.8°C. Therefore, in this case, shading will be required only during March, April and May. Thermal comfort can be achieved during these summer months either by providing external shading or by dimming control to the GB.

### 3.2 Field measurement and outcome

When the measured and simulated temperature results for GB and OB on December 29, 2020, at 1.5 m above the floor were compared, the root mean square error and mean absolute error of the measurement fell within the 5% permissible error range (Figure 5). From both simulated and measured values, it was evident that an OB provides more glare into the indoor spaces. On the contrary, glazing allows a smoother transition from highest to lowest lux, and hence, causes less strain to visual comfort (Figure 6 and 7). In addition, the air temperature in the space adjacent to the balcony was higher in GB than that in OB, and the humidity level was higher in OB than that in GB (Figure 8). Hence, in climatic regions where humidity is high and the temperature is lower than the comfort level, buffer spaces such as GBs are an appropriate design option.

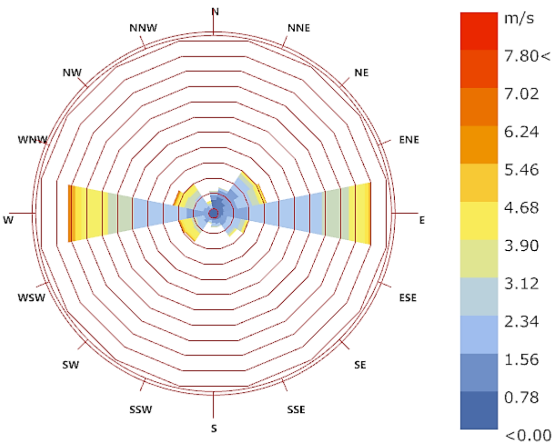
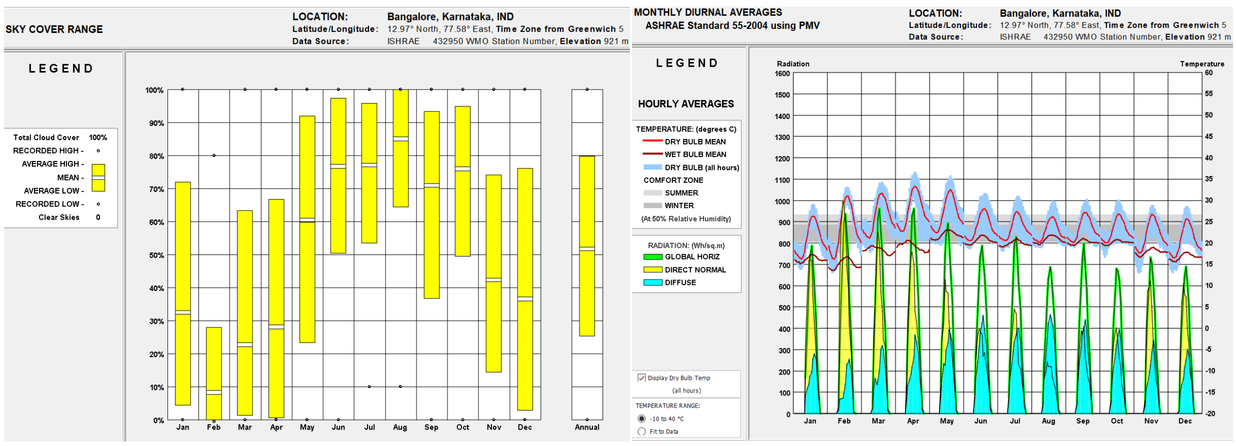



**Figure 3.** Wind rose diagram for Bengaluru




(source: climate consultant)

**Figure 4.** Sky cover range and monthly diurnal averages

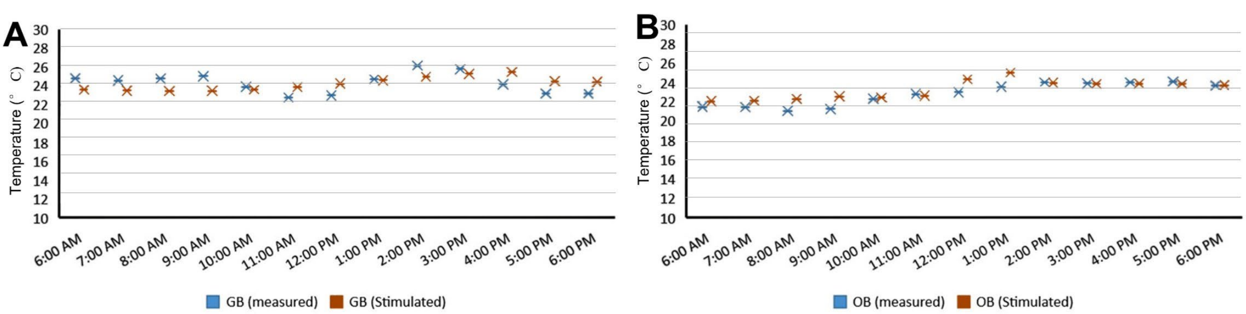



**Figure 5.** Measured vs simulated temperature for a glazed balcony (A) and an open balcony (B)

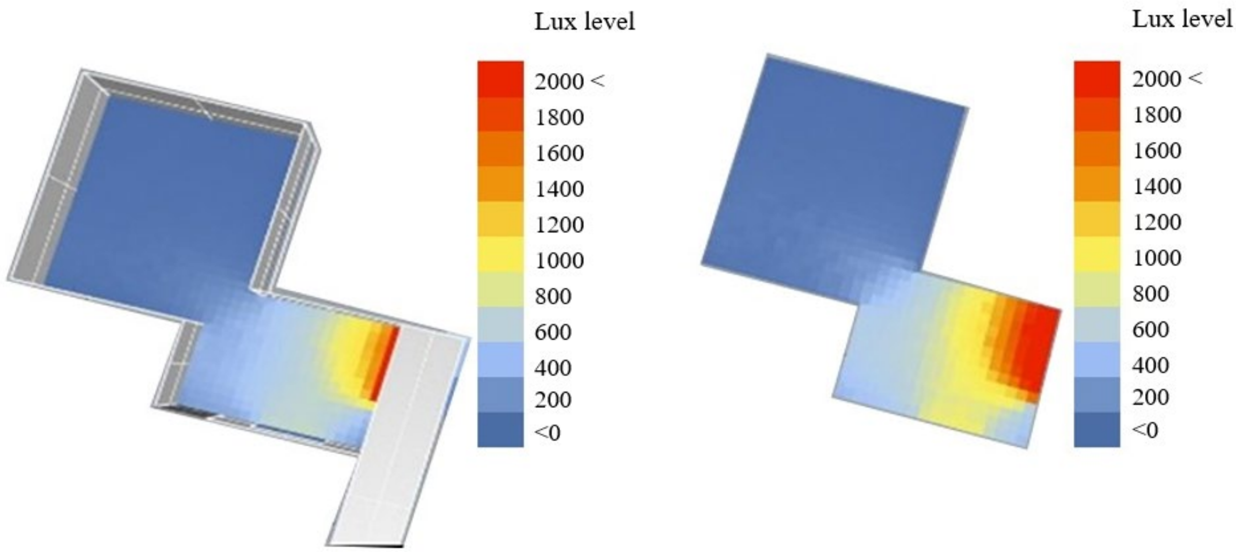



**Figure 6.** Daylight illuminance for a glazed balcony (A) and an open balcony (B)

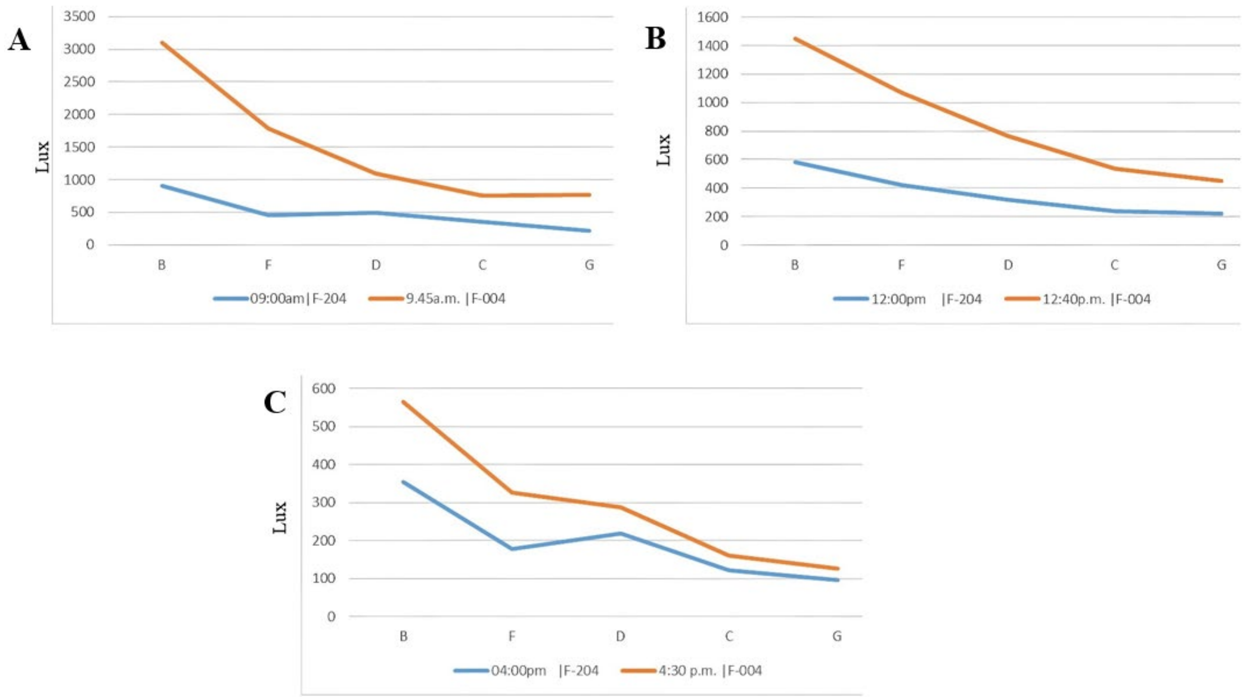



**Figure 7.** Comparison of lux level variation during the morning (A), afternoon (B), and evening (C)

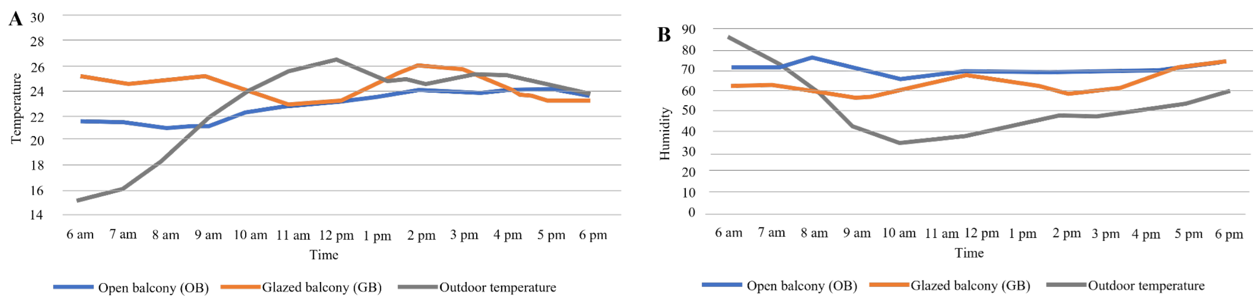



**Figure 8.** Air temperature (A) and humidity (B) variations

### 3.3 Inferences from the online questionnaire survey

A subjective evaluation was performed via an online questionnaire, which was distributed among individuals residing in diverse apartment complexes in Bengaluru. Respondents with a GB expressed high levels of satisfaction with it. Conversely, those with an OB reported various issues, including noise, lack of privacy, insects, limited space, bats inhabiting the balcony and difficulties in utilizing the space after dark. Moreover, such balconies were prone to pollution and traffic noise, glare during periods of intense sunlight and inadequate natural light. The presence of high traffic, dust, and strong air movement exacerbates some of these problems. On average, 36% of the occupants with OBs chose not to cover them, whereas the remaining 64% expressed dissatisfaction with OBs. In this dissatisfied cohort, 61% requested partial or adjustable glazing as a solution to the previously mentioned issues. Occupants with a GB generally kept their balcony doors and windows open throughout the day (Figure 9). Approximately 50% of respondents had opted to cover their balcony to mitigate noise and air pollution and utilize the space more effectively, with 66% expressing high satisfaction with the decision to retain glazing in their balconies. Furthermore, none of the respondents with a GB expressed a desire to remove the glazing altogether. In conclusion, the responses suggest that occupants with a GB may not be entirely satisfied with the current design and may seek modifications, but all respondents with a GB preferred not to change their balcony to an open one.

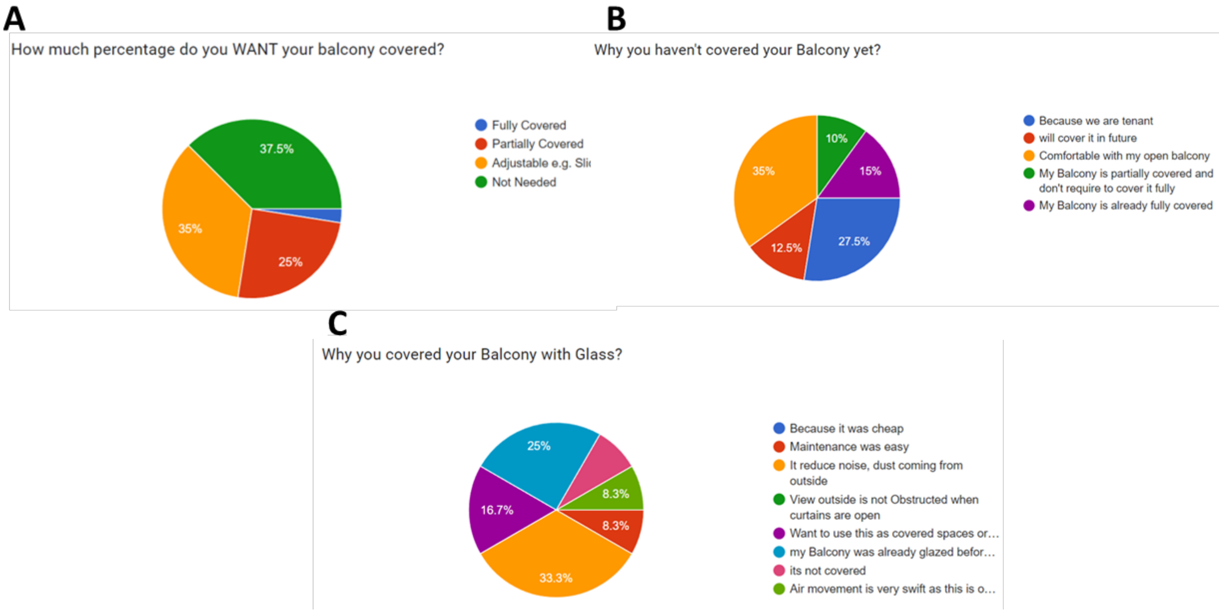



**Figure 9.** Residents' perceptions of glazed balconies: (A) intention to cover balconies, (B) reasons for not covering, and (C) reasons for covering with glass

### 3.4 Comparison of simulation outcomes

The findings of the daylighting simulation for GB and OB are displayed in Figure 10, which indicates that the UDI range of 100–2000 lux was similar for both types of balconies. However, the sDA value for GB was merely 55%, whereas it was 95% for OB, which warrants further research to improve the performance of the former. Although the ASE values for both GB and OB were comparable, glare is not a prominent issue in residential building design as it can be mitigated using simple measures such as blinds or curtains. In contrast, addressing insufficient daylighting is more challenging once the design is built (Dogan & Park, 2019). An adaptive approach was used in this study to estimate the indoor temperature that the occupants are most likely to find comfortable, especially during the winter months when heating is required (Figure 11). In addition, wind environment analysis (Figure 12) was performed, which demonstrated that OBs can become uncomfortably windy with wind speeds above 5 m/s, whereas GBs offer more control because of the provision to open and close the balcony panels.

Based on the simulations (Figure 13), it is apparent that the wind speed is higher inside the indoor space of an OB compared with that of a GB. According to prevailing studies, the highest velocity is achieved when the wind angle is normal to the openings. In Bengaluru, the wind mostly flows from either the east or the west; hence, building models should be orientated in either of these directions (Omrani et al., 2017).

Regarding indoor air quality, maintaining a minimum hourly air change rate to remove air pollutants and ensure a healthy indoor environment is important in case of GB (Fernandes et al., 2020). The simulation results in Figure 14 illustrate the air exchange per hour (ACH), which suggests that ACH is superior for GBs relative to OBs. Consequently, it can be inferred that GBs offer a more comfortable and manageable indoor environment of low wind and enhanced ACH. Furthermore, the simulations signify that the air exchange in corners is more efficient for GBs than for OBs, a feature worth considering in future design modifications.

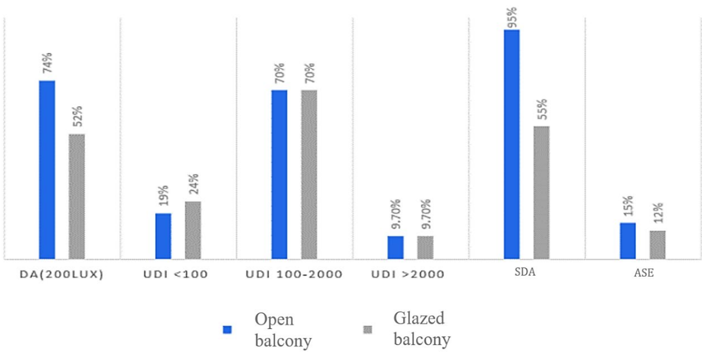



**Figure 10.** Comparison of daylight for a glazed balcony and an open balcony

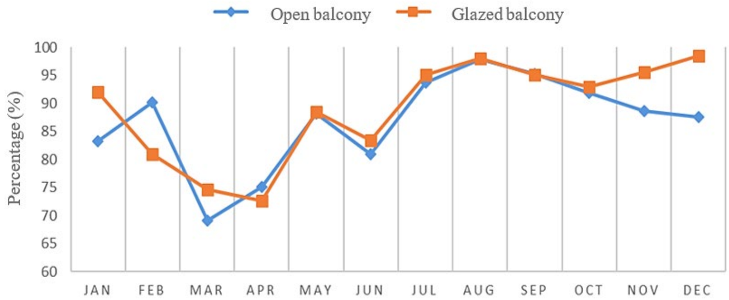



**Figure 11.** Percentage of comfortable hours using operative temperature as per IMAC

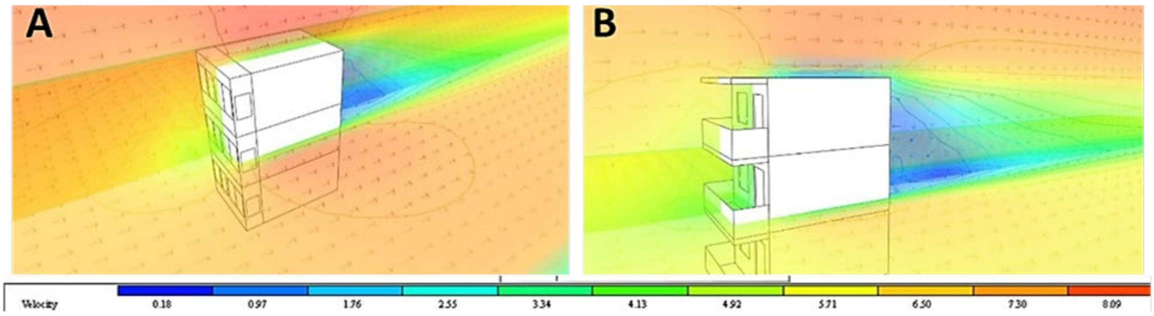



**Figure 12.** Wind velocity variation on the façade of a glazed balcony (A) and an open balcony (B)

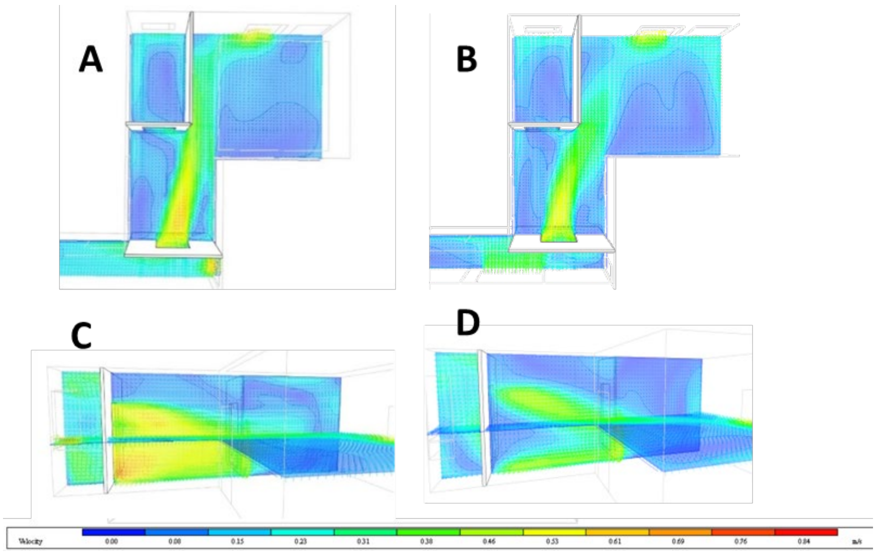



**Figure 13.** Average wind velocity and flow pattern at a height of 1.2 m for a glazed balcony (A) and an open balcony (B); average wind velocity and flow pattern at vertical plane of door opening for a glazed balcony (C) and open balcony (D)

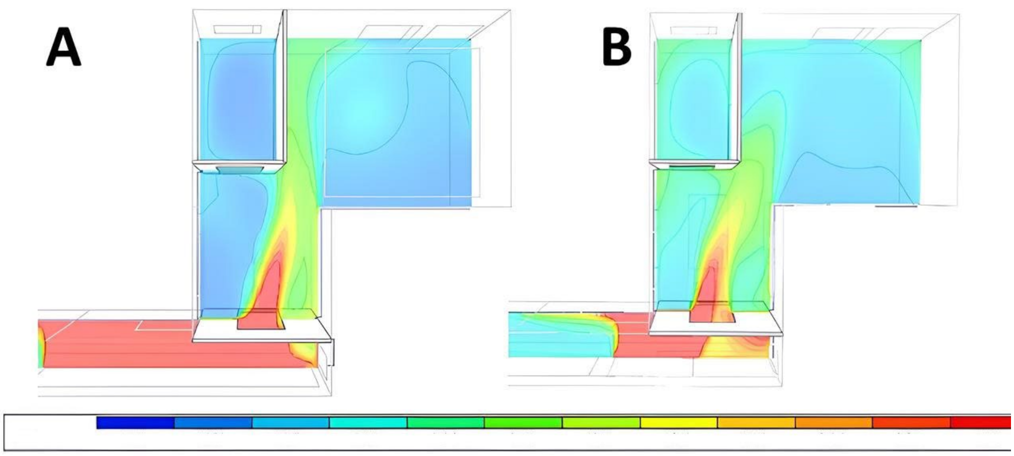



**Figure 14.** Air change effectiveness (ACE) shown in plane at a height of 1.2 m for a glazed balcony (A) and an open balcony (B)

## 4. CONCLUSION

The findings from the questionnaire survey conducted on occupants with differing balcony types have unveiled interesting features with potential implications for balcony design and occupant satisfaction. The survey has elucidated that individuals with OBs are inclined to prefer the installation of balcony enclosures in the future. Furthermore, although certain occupants with GBs expressed dissatisfaction with their balcony design, they were satisfied with their balcony type. Hence, by alternating some design parameters such as size, glass placement, opaqueness ratio orientation, handrail system, and various glazing properties such as SHGC, U-value, direct solar and light transmission used in GBs, there is immense scope to enhance the performance of the indoor environment and the satisfaction level of the occupants (Shamseldin, 2023; Wilson et al., 2000).

The study has also examined the indoor environmental quality (IEQ) of varying balcony types with measured values revealing that GBs exhibit significantly higher air temperatures and lower humidity than their open counterparts. GBs might help to improve occupant health by restricting indoor exposure to PM2.5 from the outdoor environment (Wang et al., 2022; Fernandes et al., 2020). Additionally, GB design interventions such as glazing are shown to mitigate glare and direct sunlight exposure within the living space, a benefit that OBs lack. Furthermore, adding a dimming control facility to glazing could help reduce glare and solar direct heat gain. On the other hand, thermal gains from conduction and solar radiation are lower in GBs than in OBs, resulting in higher temperatures inside the living spaces.

In addition, the outdoor environmental conditions were compared, and OBs were found to be susceptible to uncomfortably high wind speeds. In contrast, GBs enabled the occupants to regulate their balcony experience by opening or closing the glazed panels while simultaneously addressing problems such as pollution, insects, birds, safety, noise, privacy, and protection from rain (Mirabi & Nasrollahi, 2019). ACE within the living zone was shown to be less efficient in OBs than in GBs.

This study has provided a nuanced perspective on the benefits of GB design in moderate climates and has highlighted the potential to further optimize these structures. The findings are expected to be useful for designers and architects aiming to enhance IEQ while accommodating occupant preferences for balcony use.

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