Climate-Responsive Residential Architecture: The Role of Kinetic Facades in Achieving Thermal Comfort

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***Abstract*—This study focuses on using kinetic facades in residential architecture to create thermal comfort, and increase climate responsiveness. The difference between commercial buildings and residential is, residential buildings should provide users easy to use systems at a low cost, or it might include some costs for increased comfort. Each will have varying levels of kinetic facades and context-dependent variations in climate and climate responsiveness. The study includes passive and active kinetic systems, the use of smart materials and several case studies on climate-sensitive housing in different geographical locations. The focus of the study is to show how kinetic facades in residential buildings can reduce overall energy consumption, increase comfort, and enable sustainable living.**

***Index Terms*—Kinetic facades, Residential architecture, Thermal comfort, Passive design, Climate-responsive, Smart materials.**

I. INTRODUCTION

As climate-related issues become more pressing, climate-responsive residential architecture is becoming crucial for sustainable living. Thermal comfort, which integrates temperature, ventilation, and humidity, is crucial in houses for both health and energy efficiency. Kinetic facades, which create a dynamic system of buildings that respond to heat, ventilation, and sunshine by responding to exterior environmental circumstances, satisfy this need. Although kinetic facades were formerly common in the commercial sector, people are quickly learning how to use passive yet user-friendly techniques to increase thermal comfort in domestic areas. This is due to the fact that modern buildings need to be energyefficient and consumptive.

II. LITERATURE STUDY

A. Climate-Responsive Architecture

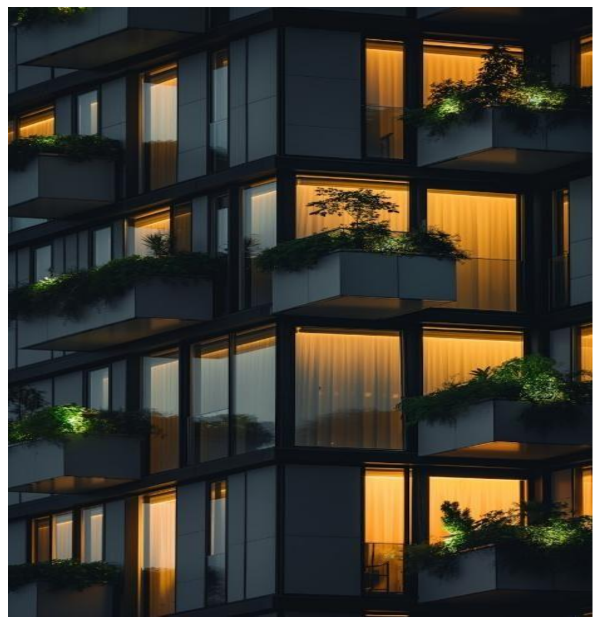

Figure 1: - Twilight Urban Serenity
Source: - https://www.lummi.ai/photo/twil 1

Climate-responsive architecture seeks to maximize thermal comfort and energy efficiency by ensuring building design works with local climates through orientation, shading, insulation, and ventilation. Buildings designed according to bioclimatic principles will respond more naturally to the sun's paths and wind flows. Passive strategies, like thermal mass, courtyards, and cross ventilation, are most effective in moderate climates and reduce energy use by up to 50%. Yet, extreme climates usually require an active system, such as an HVAC unit, to achieve comfortable indoor conditions. (Attia, 2012) discussed how passive measures achieve up to 30% energy savings when passive measures are applied at the beginning of the design process. Balancing passive and active strategies implement climate-responsive residential design and analysis. (Givoni, 1998) (Olgyay, 2015).

Figure 2: - Futuristic Architectural Design at Twilight
Source: -https://www.lummi.ai/photo/futur 1

B. Thermal comfort in residential buildings

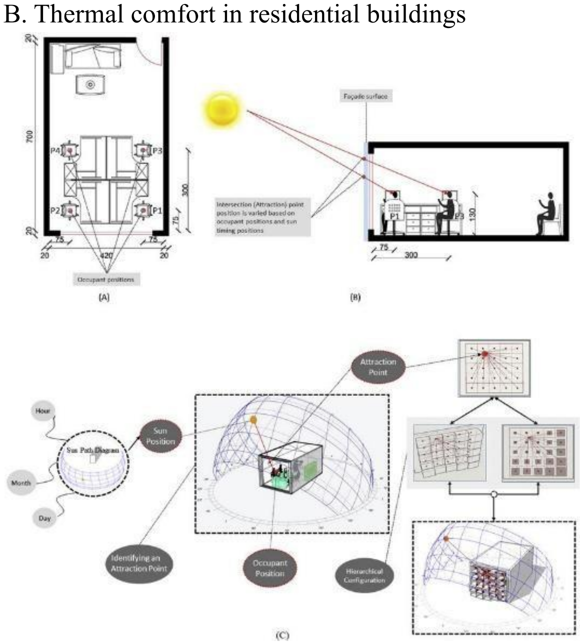

Figure 3The kinetic façade interaction with sun timing position and occupant
Source: - https://www.researchgate.net/fi 1

A function of several parameters, including air temperature, relative humidity, air velocity, mean radiant temperature, clothing insulation, and metabolic rate. According to, (Heinzerling, 2021) indoor thermal comfort is achieved when occupants' express satisfaction with the thermal environment, regardless of whether conditions are steady-state or adaptive.

Naturally ventilated homes are particularly well suited for adaptive comfort models because they account for occupants modifying behaviors based on seasonal or daily variations. (J.F. Nicol, 2002) provided evidence that people have a greater tolerance for a wider range of temperatures when able to adapt, showing evidence for thermal comfort in warm climates between 20°C and 28 °C. This is particularly relevant for residential buildings where occupants have the flexibility to modify clothing to adapt, open windows, and/or utilize fans.

C. Kinetic Facades

Kinetic facades employ a shifting position to be responsive to the environmental conditions it meets or to improve performance; they include an element of motion as part of the building envelope. While movement is not new to buildings (the mechanical shading system described in the 1960s is an early example of this), the development of kinetic facades has developed over time with advancements in materials, actuators, and computational design. Kinetic facades can be categorized as responsive, adaptive, and dynamic systems based on their ability to react and adapt to climate, interact with user inputs, or are operated with automated control systems (Fox, 2001). Responsive systems react to changing external stimuli, namely solar radiation and wind; adaptive facades adjust and respond to occupant behavior, internal or external conditions. The materials that are used in these systems range from ETFE membranes and aluminum panels to smart materials such as shapememory alloys and electrochromic glass. These systems can help improve thermal comfort, reduce energy loads, and provide more flexibility to aesthetics. (D. Michelle Addington, 2005),
(Dohotariu, 2021)

Figure 4: - Residential building in Zurich, Switzerland
Source: - https://www.threads.net/@lerich 1

D. Integration of Kinetic Facades in Residential Architecture

Residential architecture is increasingly adopting kinetic facades as they can potentially enhance thermal comfort and energy efficiency. Existing research has been able to generate case studies that include a mashrabiyan-inspired kinetic skin at the Al Bahar Towers in Abu Dhabi which produces an up to 50 % reduction of incoming solar gains that subsequently improves occupied temperature and lessens energy use (Fathy, 1986). The same is true for the One Ocean Pavilion at South Korea with a dynamic aluminum clad façade system that varies based on light performance that show to improve thermoregulation. (Carlos E. Ochoa, 2009) reported reductions of 20 - 40% of cooling loads attributed to dynamic facades in hot climates. Occupants' feedback finds that dynamic systems improve users' comfort and interaction because it allows an adjustment that responds to personal comforts and environmental conditions.

E. Integration of Kinetic Facades in Residential Architecture

The efficacy of kinetic facades can vary considerably based on regional-climatic context. In hot-arid regions, kinetic shading systems will mitigate solar heat gain while permitting daylight; the result negligible cooling-energy use, achieving as much as 50% savings (bahadori, 2007). In hot-humid climates, operable facades further achieve indoor comfort via active cross-ventilation increasing air movement. For temperate climates, dynamic systems help to address both heating and cooling, maximizing solar gain in the winter while providing shading in the summer. In cold climates, double-skin kinetic facades can reduce heat loss while also addressing glare. Nonetheless, although (Safarzadeh, 2004) parametric study found responsive facades could provide between 30 – 45% improvement based on climatic context and control strategies, the results amplify the need to devise a responsive facade, as techniques to design and optimize through simulations through RH- r Forsythe can enhance thermal performance as high as 30-45 based on iterative technique according to climatic context and use via RH- r Forsythe and based on infrared sensing throughout using augmented reality subsequent to any simulation.

F. Technological Innovations and Sustainability

Electrochromatic glass, thermobimetal, and shape memory alloys all highlight the versatility of products that can dictate the performance of facades by responding automatically according to solar radiation and temperature (dimming, reflectivity) and daylighting conditions. These systems have the capability to adapt the performance of buildings in a responsive manner by modifying their transparency, reflectivity, or geometry in the real-time world. According to (Loonen, 2013), smart dynamic facades can reduce HVAC use from 23-50% depending on climate and building control strategies. Daylighting and natural ventilation can be optimized for occupants' comfort via automated sensors (and actuators), and the reliance on mechanical lighting can be reduced. These innovations assist in supporting sustainable design, and sustainably reduce operational energy use and operating costs, while increasing the viability of adaptive buildings to environmental changes.

III. CASE STUDY

A. Bentley Residence Mami

Owner: **-** Dezer Development, in partnership with Bentley Motors
Location: - Sunny Isles Beach, Miami, Florida
Residences: - 216 luxury condominiums

Architect: - Sieger Suarez Architects
Building: - Bentley Residence

The Bentley Residences in Sunny Isles Beach, Florida illustrates the mixing of luxury design with sustainable architectural approaches. An unique feature of the building is the cylindrical form enriched by triangulated glass and reflective silver diamonds -- all paying tribute to the unique designs associated with Bentley. This design not only increases aesthetic richness but also provides for higher energy efficiency by utilizing natural light and minimizing solar heat gain.

The residences' smart climate controls feature digital thermostats to provide for accurate temperature control and better energy use. The building was also built to the Florida Green Building Coalition certification to guarantee environmental responsibility and the care of the surrounding ecosystem.

Figure 5: - Bentley Residence
Source: - https://bentleyresidencesmiami. 1

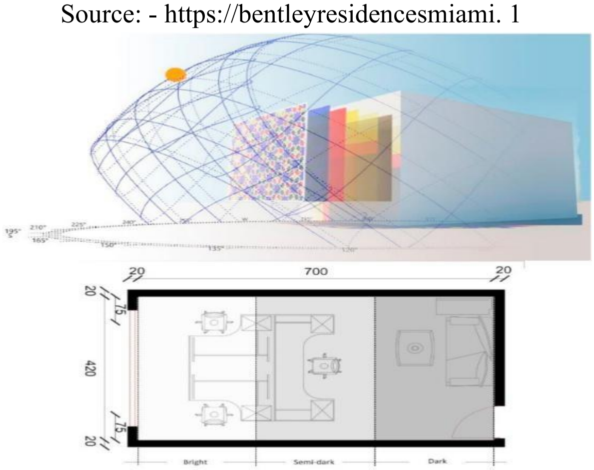

Figure 6: - Integrating interactive kinetic façade design with colored glass to improve daylight performance based on occupants' position
Source: - http://sciencedirect.com/scienc 1

The research does not offer specific data on energy savings, but the sustainable strategy of employing an innovative façade design, coupled with an intelligent climate system, indicates a strong intent to offer a higher level of thermal comfort and sustainability in the residential narrative. Seemingly, the embodiments of kinetic façades have proved to reduce energy consumption through the design variables, which in certain climate zones have reported reductions in energy consumption, upwards of 32–56%. (Architects, 2024)

B. Phoenix Kessaku Bangalore

Owner: - The Phoenix Mills Ltd.
Location: - Rajajinagar, West Bangalore
Residences: - 216 luxury condominiums
Architect: - RSP Design Consultants
Building: - Phoenix Kessaku

Figure 7The Phoenix Mills Kessaku
Source: - https://www.commonfloor.com/the 1

Phoenix Kessaku, situated in Rajajinagar, Bangalore, is the epitome of high-end residential architecture that includes climate-responsive features and, while it does not include kinetic facades, it is still highly dynamic.

It was designed by Callison and RSP Design Consultants for the developer Phoenix Mills. The project consists of five towers based on themes—Sora, Niwa, Mizu, Faia, and Zefa—that are inspired by natural elements. There were passive design strategies included in the facade treatment, which featured highperformance glazing, aluminum cladding, vertical fins, and deep cantilevered balconies that create shadow for shading and lessen solar heat gain. There are ample floor-to-ceiling operable windows that provide natural daylighting and cross-ventilation, providing thermal comfort without needing heavy reliance on mechanical cooling. The apartments have a spatial zoning of private, semi-private, and service areas, which also is a strategy to create better internal climate and privacy. The landscape, designed by Design Cell, also contributes to the thermal buffer space through shaded gardens, green terraces, and reflective water bodies. It has sustainable features, such as rain water harvesting, sewage treatment plants, low-E glass and organic waste converters, which are also climate responsive. While the facade is a static building envelope, the attaching passive systems are an effective demonstration of how architecture planning and articulated facade can achieve good thermal performance.

In contrast, kinetic facades have the flexibility to respond directly to changes in built or natural environmental conditions in real-time – as Phoenix Kessaku suggests through its performance based, yet fixed envelope. The element of comparison gives frame of reference to the changing nature of residential architecture from passive systems through to kinetic systems, to create environmental benefit and user comfort.

C. Hive House, Surat

Owner: - Kamalbhai Mistry.

Location: - Vesu, Surat, Gujarat, India

Residences: - 216 luxury condominiums

Architect: - OpenIdeas Architects

Building:- Luxury Residence

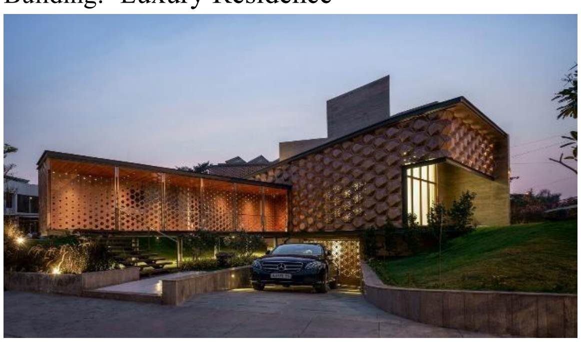

Figure 8: - HIVE House

Source:- https://www.archdaily.com/94196 1

The Hive House, designed by OpenIdeas Architects in Surat, India, is a wonderful demonstration of kinetic facade architecture exercising thermal comfort. The project is located in a hot semi-arid climate with solar responsive glass facade that adapts to solar intensity through the lens of biomimetic structures, like beehives, activated automatically through sensorcontrolled panels based on solar heat gain, The interior space gained by optimizing natural daylight while controlling solar heat gain produces a thermal comfortable space.

A year-long solar path analysis was conducted to guide the project's design to ensure the orientation and window placement maximized building envelope to prevent overheating. The V-structure with cross ventilation also help improved natural cooling, therefore not causing impact when adding air conditioning. The green roof acts as thermal insulation while creating a passive cooling effect by reducing heat from being absorbed into the occupant's space.

By employing smart technology, the facade can dynamically adjust in real-time with a microcontroller, providing adaptable and energy-efficient solutions. The Hive House can exemplify how kinetic facades can provide climate responsive solutions that reduce energy needs and maximize indoor comfort in warm climates.

Figure 9: -Hoive House

Source: -https://www.archdaily.com/941969 1

Figure 10: - HIVE House

Source: - https://www.archdaily.com/94196 2

IV. CONCLUSION

Kinetic facades offer a promising approach to enhance energy efficiency and thermal comfort in residential buildings. Kinetic facades help achieve energy reductions and comfort levels through the adaptation of the facade to external environmental changes. Kinetic facades are more suitable for hot climates, but can also be beneficial in temperate climates, as they can contribute to reducing heating and cooling loads in a building. Technological advances in smart glass, electrochromic glass and shape memory alloys have further enhanced kinetic facade capabilities. As illustrated in the case studies, using kinetic facades can lead to energy reductions and indoor comfort improvements, and therefore represent a promising opportunity to support the development of sustainable and responsive residential buildings.

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