Bio-Inspired Adaptive Facade Using Smart Materials

Yasmin Moussa[1], Ahmed Faggal[2], Ashraf Nessim[3], Rasha Abdelateef[4]

[1,2,3]*Architecture department, Faculty of Engineering, Ain Shams University, Cairo, Egypt*
[4]*Faculty of Energy and Environmental Engineering, The British University in Egypt, Cairo, Egypt*

Abstract

Currently the energy performance of many existing buildings in Egypt is hindered by poorly insulated and inadequately sealed facades, which allow excessive heat gain and loss. This inefficiency significantly increases the dependence on active cooling systems, resulting in high energy consumption. Addressing these shortcomings, this research proposes a passive, climate-responsive facade system that enhances thermal performance while reducing energy demand. Biomimetic architecture offers innovative strategies for sustainable design by emulating nature's adaptation mechanisms. This study introduces a bio-inspired adaptive facade modeled after the temperature-sensitive petal behavior of the mangrove flower. The mangrove flower exhibits adaptive petal behavior in response to temperature—a trait abstracted and translated into architecture using bimetal smart material. Composed of two bonded layers with differing thermal expansion coefficients, bimetal bends predictably with temperature changes, eliminating the need for mechanical or electrical inputs. Creased bimetal sheets were designed to mimic the flower's responsive movements— expanding in high temperatures to provide shading and folding in lower temperatures to permit solar gain. Prototypes and tests demonstrated the biomodules' potential as energy-free, self-regulating shading devices suitable for building facades. Dynamic thermal simulations using Rhino/Grasshopper and Ladybug tools compared the baseline curtain-wall facade with the proposed adaptive skin. The biomimetic system resulted in indoor peak temperature reductions of up to 3.8°C and cut cooling energy demand by approximately 30%, while enhancing overall thermal comfort. These results validate the integration of biomimetic principles and smart materials as a viable solution for improving facade performance in hot-arid climates such as Egypt. Additionally, the Thermal Comfort Percentage (TCP) improved significantly from 0% to 60%, and cooling energy savings reached up to 0.8 kWh, further demonstrating the system's effectiveness in optimizing energy efficiency and occupant comfort.

Keywords: Biomimetic architecture, adaptive facade, smart materials, thermal comfort, passive design