

Feasibility and Energy Performance Evaluation of Shape Memory Alloy-Based Kinetic Facades in Tropical Climate Buildings

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Abstract - The building sector significantly contributes to global energy consumption, particularly in tropical climates where cooling loads dominate. This study investigates the feasibility and performance of Shape Memory Alloy (SMA)-based kinetic facades as an adaptive building envelope solution. The research evaluates thermal performance, daylight optimization, and energy savings through simulation and comparative analysis. Case studies from Indian commercial buildings and global kinetic façade systems were examined. Results indicate that SMA-driven passive systems can reduce cooling loads, improve daylight distribution, and enhance energy efficiency while minimizing mechanical complexity. The study concludes that SMA-based kinetic facades present a promising, low-energy alternative to conventional dynamic façade systems in tropical regions.

Key Words: Kinetic Facade, Shape Memory Alloy (SMA), Energy Efficiency, Tropical Climate, Adaptive Building Skin, Sustainable Architecture

1. INTRODUCTION

Buildings account for approximately 30–35% of total electricity consumption in India, with cooling demand expected to rise significantly due to rapid urbanization and climate conditions.

Kinetic facades, which dynamically respond to environmental conditions, have emerged as an innovative strategy to reduce solar heat gain and improve indoor comfort. However, most existing systems rely on mechanical or pneumatic actuation, leading to high energy consumption and maintenance challenges.

This study explores the integration of Shape Memory Alloys (SMAs) materials capable of changing shape in response to temperature as a passive or semi-passive actuation mechanism for kinetic facades.

2. METHODOLOGY

- Material Study (SMA behavior and properties)
- Design Proposal BIM Model (SMA-based kinetic facade)
- Simulation & Energy Performance Analysis
- Solar Analysis
- U-value comparison

- Breakeven analysis
- Baseline Comparative Analysis

3. KINETIC FAÇADE AND SHAPE MEMORY ALLOY BASIC CONCEPT

An SMA-based kinetic façade is a building envelope system that can adjust its shape automatically based on temperature changes. It uses Shape Memory Alloy (SMA), a smart material that deforms when heated and returns to its original shape when cooled. In this system, SMA wires or strips are fixed to façade elements like louvers, panels, or shading devices. When sunlight falls on the façade and the temperature rises, the SMA contracts or bends, which causes the panels to close or tilt, reducing the amount of heat entering the building. This helps in maintaining indoor comfort and lowering the need for air conditioning.

When the temperature drops, the SMA relaxes back to its original form, allowing the panels to open again so that natural light and air can enter the space. The entire process happens without motors, sensors, or electricity, as it depends only on the material's natural response to temperature. Because of this, SMA-based kinetic facades are energy-efficient, low in maintenance, and simple in operation. They are especially useful in tropical climates where buildings are exposed to high solar radiation, making it important to control heat gain while still allowing sufficient daylight and ventilation.

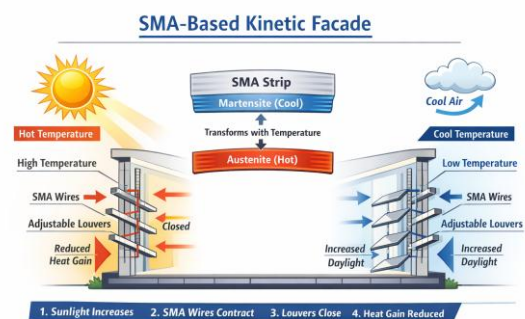


Fig -1: Shape memory alloy (SMA) concept

4. ENERGY PERFORMANCE

Energy performance analysis in BIM starts with building a complete 3D model that includes the structure, materials, and basic system details. First, a baseline model is created to represent how the building would perform under standard conditions. Then, a second model is developed with improvements such as better materials, shading devices, or efficient systems. Solar analysis is done to understand how sunlight falls on the building, which helps in reducing heat gain and improving comfort. After that, lighting analysis is carried out to check how much natural light is available inside and how efficiently artificial lighting is used. This step is important for meeting LEED (Leadership in Energy and Environmental Design) requirements. Finally, the overall annual energy consumption of the building is calculated to compare both models and identify how much energy can be saved through design improvements.

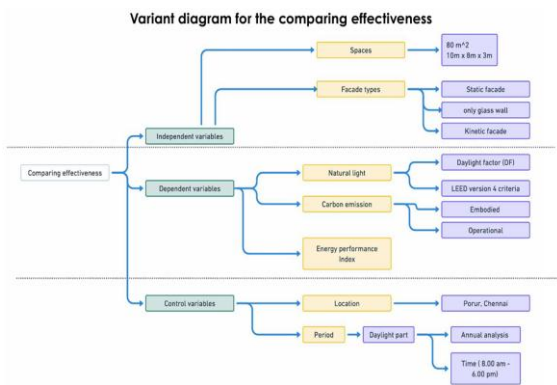


Fig -2: Variant diagram for design development

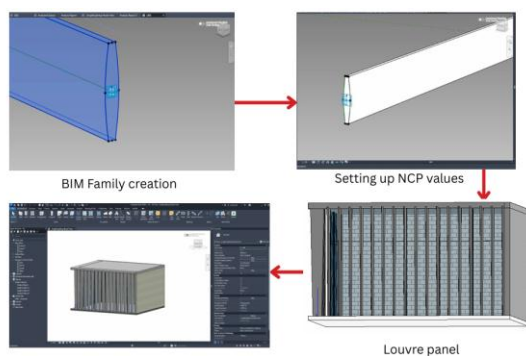


Fig -3: BIM Family and Model

4.1 SOLAR ANALYSIS

The aim of this study is to see how changing the façade area affects the amount of sunlight the surface receives. Two cases with different façade sizes are compared to understand both the total solar energy falling on the surface and how much energy is received per square meter. This comparison helps in identifying how factors like orientation, shading, and

façade shape influence solar exposure and overall building performance.

From the comparison of the two solar analysis results, it can be seen that increasing the façade area from 150 m² to 238 m² led to a rise in total annual insolation from 85,159 kWh to 114,070 kWh.

However, the average insolation per square meter decreased from 567 kWh/m²/year to 478 kWh/m²/year.

This suggests that the additional 88 m² of façade does not receive the same level of solar exposure as the original surface. The reduction in intensity may be due to factors such as orientation, shading from surrounding elements, façade geometry, or the angle of the surface.

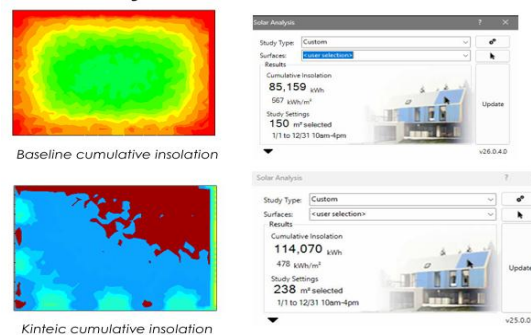


Fig -4: Solar Analysis

4.2 LIGHTING ANALYSIS

Daylight Factor (DF) is a commonly used metric in architecture, lighting, and building performance analysis to measure how much natural daylight is available inside a space compared to the available outdoor daylight at the same time under overcast sky conditions. It is expressed as a percentage, indicating what fraction of the outdoor natural light actually reaches the indoor environment.

Higher DF = better daylight penetration
Lower DF = poor daylighting / artificial light dependency

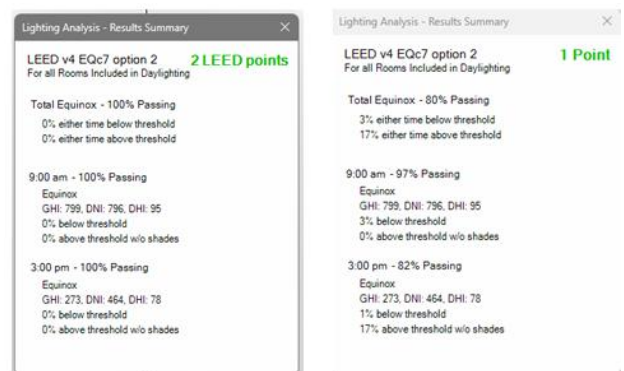


Fig -5: Kinetic model and baseline LEED points

4.3 ENERGY SIMULATION

Energy Simulation is used to study how a building performs in terms of energy use under different environmental conditions. In this study, energy simulation helps to compare the performance of a building with a normal façade and one with an SMA-based kinetic façade.

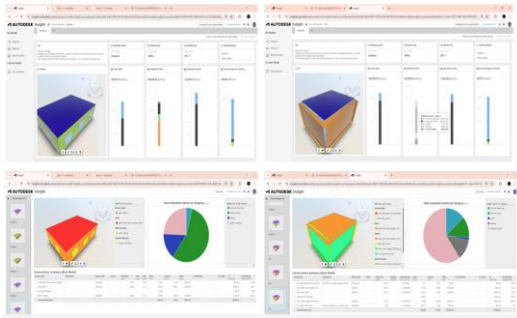


Fig -6: Energy Simulation using Autodesk Insight

The simulation considers factors such as solar radiation, temperature, daylight, and cooling load. By using simulation tools, it is possible to understand how much heat enters the building and how the façade responds to it.

The results show that the kinetic façade reduces solar heat gain by adjusting its position based on temperature, which in turn lowers the cooling demand of the building. It also improves daylight distribution inside the space.

Overall, energy simulation helps in proving that SMA-based kinetic facades can improve energy efficiency and indoor comfort in tropical climates.

Annual energy use intensity

The kinetic façade system performs significantly better than the fully glazed façade. The operational carbon of the kinetic façade (17,212.83 kgCO₂e) is 11,306.56 kgCO₂e lower than that of the fully glazed façade (28,519.39 kgCO₂e), which corresponds to an approximate 65.66% reduction. This indicates that dynamic shading, adaptive control, and reduced heat gain in the kinetic façade substantially lower energy consumption and associated carbon emissions during building operation.

Table -1: Annual Energy use intensity

CASE	BASELINE	KINETIC FACADE
Annual Energy Use Intensity KWh/m ²	1015.32	817.71

Annual energy use intensity of kinetic facade is approx. 22% lesser than fully glass baseline facade.

Total Carbon Emission

Operational carbon of kinetic facade is ≈ 65.66% lesser than fully glass facade.

Table -2: Total carbon emission

CASE	BASELINE	KINETIC FACADE
Embodied Carbon kgCO ₂ e	19,847.72	30,539.24
Operational carbon kgCO ₂ e	28,519.39	17,212.83

Wall Assembly and Glazing

According to IGBC, the building envelope can achieve a maximum of 10 points, based on the performance of wall assembly and glazing (U-value and VLT/SHGC ratio). From the analysis, the kinetic façade system demonstrates significantly better thermal performance compared to the baseline façade. The kinetic façade achieves a lower U-value for both wall assembly and glazing, indicating improved thermal insulation and reduced heat transfer. Additionally, **the kinetic system shows a higher VLT/SHGC ratio, suggesting better daylight utilization with reduced solar heat gain.**

As a result, the kinetic façade scores 8/10 points, outperforming the baseline condition, which scores 6/10 points. This indicates that integrating a kinetic façade improves energy efficiency, enhances envelope performance, and contributes to achieving higher IGBC Green Building credits.

Table -3: IGBC Standards

ACCORDING TO IGBC	
Building envelope - 10 Points	
Wall Assembly	
U- value of wall assembly	5 Points
Glazing	
U- value of glazing	2 Points
Ratio of VLT / SHGC	3 Points

Table -4: Analysis

ACCORDING TO ANALYSIS		
Aspect	Baseline line	kinetic facade
Wall Assembly		
U- value of wall assembly	1.34 W/m ² K	0.87 W/m ² K
Glazing		
U- value of glazing	1.4	0.8
Ratio of VLT / SHGC	2.6	1.84
LEED POINTS	6 / 10 POINTS	8 / 10 POINTS

Envelope Thermal Transmittance Value- ETTV

According to IGBC, **Envelope Thermal Transfer Value (ETTV)** is used to measure how much heat passes into a building through its external walls and windows. It takes into account heat from sunlight, heat conducted through wall materials, and heat entering through glass. This value is important in hot climates because it helps in understanding how much a building heats up during the day. A lower ETTV means less heat is entering, which reduces the need for cooling. In buildings with SMA-based kinetic facades, ETTV can be reduced because the façade adjusts itself based on temperature. When there is strong sunlight, the panels close and block heat, and when it is cooler, they open to allow light and air. This helps in keeping indoor spaces comfortable while also saving energy.

$$ETTV=12(1-WWR) \cdot U_w + 3.4(WWR) \cdot U_f + 211(WWR)(CF)(SC)$$

Where:

- **ETTV** : Envelope Thermal Transmittance Value (W/m^2)
- **WWR** : Window to wall ratio
- **(U_w)** : Thermal transmittance of opaque wall ($W/m^2 \cdot K$)
- **U_f** : Thermal transmittance of fenestration ($W/m^2 \cdot K$)
- **CF** : Correction Factor for solar heat gain through fenestration
- **SC** : Shading Coefficient of fenestration

Geometry:

- Wall heights = 3 m.
- Room Dimension = 10m x 8m
- Individual wall areas:
 - N & S = $10 \times 3 = 30 \text{ m}^2$ each;
 - E & W = $8 \times 3 = 24 \text{ m}^2$ each.
- Total gross exterior wall area = $2(10+8) \times 3 = 108 \text{ m}^2$
- Low-E double glazing (typical argon 6-12-6): $U_f=1.6 \text{ W/m}^2\text{K}$, SHGC (CF) = 0.25.
- SC = 1.0
- Aluminium panel (insulated/composite): $U_w=0.30 \text{ W/m}^2\text{K}$ (typical insulated panel).

If fully glazed (Baseline),

Here WWR = 0.80, opaque panel fraction = 0.20, use $U_w(\text{panel})=0.30$

- **Wall conduction term:** $12 \times (1-0.8) \times 0.30 = 0.72 \text{ W/m}^2$
- **Fenestration conduction term:** $3.4 \times 0.8 \times 1.6 = 4.352 \text{ W/m}^2$
- **Solar term:** $211 \times 0.8 \times 0.25 \times 1.0 = 42.20 \text{ W/m}^2$

Adding these up gives the ETTV (Effective Total Thermal Transfer Value):

$$ETTV=0.72 + 4.352 + 42.20 = \mathbf{47.27 \text{ W/m}^2} \leq \mathbf{50}$$

If Shape memory alloy integrated kinetic facade,

Common constant:

- Fenestration conduction = $3.4 \times 1 \times 1.6 = 5.44 \text{ W/m}^2$
- Solar term = $211 \times 0.20 \times SC = 42.2 \times SC \text{ W/m}^2$

So:

$$ETTV=5.44+42.2 \times SC$$

1. For SC = 0.6: 90° angle

$$ETTV=5.44+42.2 \times 0.6 = 5.44+25.32 = \mathbf{30.76 \text{ W/m}^2}$$

2. For SC = 0.4: 45° angle

$$ETTV=5.44+42.2 \times 0.4 = 5.44+16.88 = \mathbf{22.32 \text{ W/m}^2}$$

3. For SC = 0.2: 0 angle

$$ETTV=5.44+42.2 \times 0.2 = 5.44+8.44 = \mathbf{13.88 \text{ W/m}^2}$$

This meets the ≤ 40 criterion, earning 9 LEED points.

5. CONCLUSION

The kinetic façade outperforms the fully glazed façade in every metric—reducing energy use by 20%, bills by 18.8%, and operational carbon by 66% , while being the only economically viable option.

The SMA-based kinetic façade presents a high-performance, sustainable and future-viable envelope strategy that surpasses fully glazed static façades in energy, comfort and solar performance and stands as the optimal solution where visual transparency, adaptive comfort and environmental responsibility are prioritized.

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