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Understanding Adaptive Building Facades Responding To Wind And Seismic Loads : A Systematic Study

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Abstract. Adaptive façade system is an innovative breakthrough in building design. These systems enable structures to interact with their environment in a dynamic way to respond to changing environmental conditions on the fly. With the increasing frequency and intensity of climate-related challenges and rising standards for sustainability in buildings, adaptive facades are becoming an effective solution to improve energy efficiency and occupant comfort. They have been developed to modify their characteristics, like light permeability, ventilation and insulation, according to external conditions, such as temperature, sunlight, or wind. The structure's flexibilities under lateral loads are markedly affected by the replacement of heavy masonry in the building facade by lightweight kinetic enclosures, while at the same time energy efficiency and spatial comfort are optimized. This study is a comparative structural analysis of a multi-story structure located at Pune, India and analyzed with ETABS Software. It was subjected to the same combinations of gravity, seismic and wind loads in compliance with IS 1893 (Part 1):2016 and IS 875 (Part 3):2015 in two different structural configurations. A baseline control model with traditional red brick infill perimeter wall loads, and an adaptive model with adaptive facade material weights and wind profiles. The structural responses such as base shear, maximum story displacement, story drift and peripheral beam torsion were derived and compared, given the location of Pune in Seismic Zone III (Z = 0.16) and the basic wind speed of 39 m/s. The results show that the overall seismic mass and base shear of the building are greatly reduced due to the adaptive facade configuration, but the lateral stiffness of the structure is also changed, as well as eccentric torsional load on the other framing elements of the periphery. The outcomes offer critical parameters to be optimised in the case of integration of smart architectural envelopes under Indian Standard design conditions for the perimeter framing members.

Keywords: RCC structures, Seismic analysis, ETABS, Adaptive Facades.

1 INTRODUCTION

Today's contemporary sustainable architecture has transformed the building envelope from a passive and static barrier to a dynamic, high performance function. Adaptive building facades also utilize kinetic shading louvers, motorized sunscreens, and electrochromic smart glass, which are able to actively interact with the changing environments at real-time to provide optimization for thermal comfort, daylighting and building energy use. The architecture, thermal and energy-saving aspects of such high performing envelopes have been well documented but their local and global structural effects on the primary building frame are a critical area that is under-researched. Typical multi-level design of building in developing urban areas like India, traditionally uses a heavy red brick masonry infill wall in the periphery. Functionally, these brick walls are important as dead loads for the lateral load-bearing beams and change the lateral stiffness of the building. In contrast, a moving facade system with an adaptive system will be a lightweight, decentralized envelope. This reduction in perimeter mass will create a reduction in the seismic weight of the structure, but will also cause new structural complexities. The anchorage of adaptive facades is usually provided through a series of local brackets, which may create large eccentric gravity forces, eccentric stresses and torsional moments in the supporting peripheral members. Moreover, the variable geometry or porosity of kinetic components affects the wind pressure distribution over the building face and thus the transfer of lateral forces to the structural frame. These systems should be assessed using local geoclimatic conditions and local seismic effects to assure their structural reliability and serviceability. This study attempts to solve this engineering problem by providing a comparative structural study of a multi-storey building structure in Prabhat road, Pune, India with a good approach. Pune falls under Seismic Zone III (Z = 0.16) as per IS 1893 (Part 1): 2016 and Basic Wind Speed (Vb) is 39 m/s as per IS 875 (Part 3): 2015. This special lateral demand consideration triggers a different behavior of the building structure if the perimeter materials are replaced by smart materials. In this paper, a systematic comparative evaluation is provided based on 3D finite element model in ETABS. The same gravity, wind and seismic loading has been applied to two different structural models: a control model with traditional red brick masonry infill peripheral loads, and an experimental model using the special loads from an adaptive facade system. This research quantifies the structural trade-offs of modern adaptive facades, analyzing key performance indicators like total seismic weight, fundamental natural period, seismic base shear, maximum story displacement, inter-story drift ratios, and peripheral beam torsion. In conclusion this research gives a framework and key design parameters to the structural engineers for safe integration of smart, environment responsive architectural enclosures in the Indian standard design parameters.

2 RESEARCH OBJECTIVES

The systematics investigation is directed by the following important technical goals focused on the assessment of changes in the structural performance:

• To create detailed 3D finite element structural frames with the envelope profile as the independent variable (as a standalone profile).

• To determine load matrices as per Indian standards (IS 1893:2016 and IS 875:2015), for traditional brick wall, multi-tier adaptive skin modules.

• To measure the changes in fundamental natural vibration period (T1) and dynamic modal frequencies.

• To calculate the reduction percentages of the base shears of the foundation of seismic design along the various axes of layout.

• To assess the serviceability limitations in terms of horizontal frame roof sway and peak inter-story drift parameters.

• To check whether there are localized twisting moments and shear changes along the outer perimeter framing beams caused by the induced forces.

• To provide the following detailing configurations and optimization recommendations in accordance with IS 456:2000 code rules.

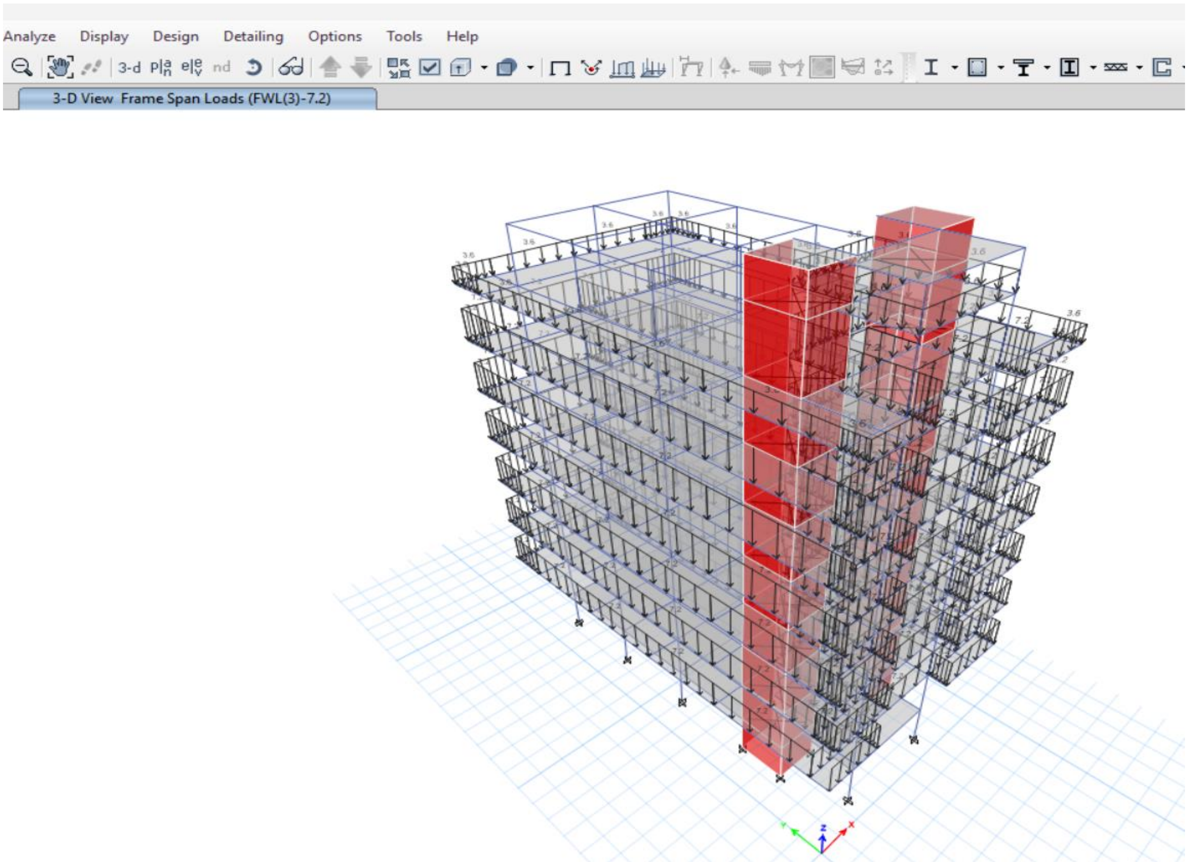
3 METHODOLOGY

To quantify the structural behavioral variations between traditional building envelopes and modern kinetic systems, a rigorous numerical comparative study was executed using ETABS. The objective is to study the perimeter envelope system as the sole independent variable while keeping the structural framing, interior geometry, and boundary conditions completely identical.

3.1 Modeling Procedure

A multi-storey RC commercial building (G+7) is modelled in ETABS with identical structural framing, interior geometry, and boundary conditions for both the cases. Two structural configurations are developed:

Model 1: Red Brick Load on peripheral beam



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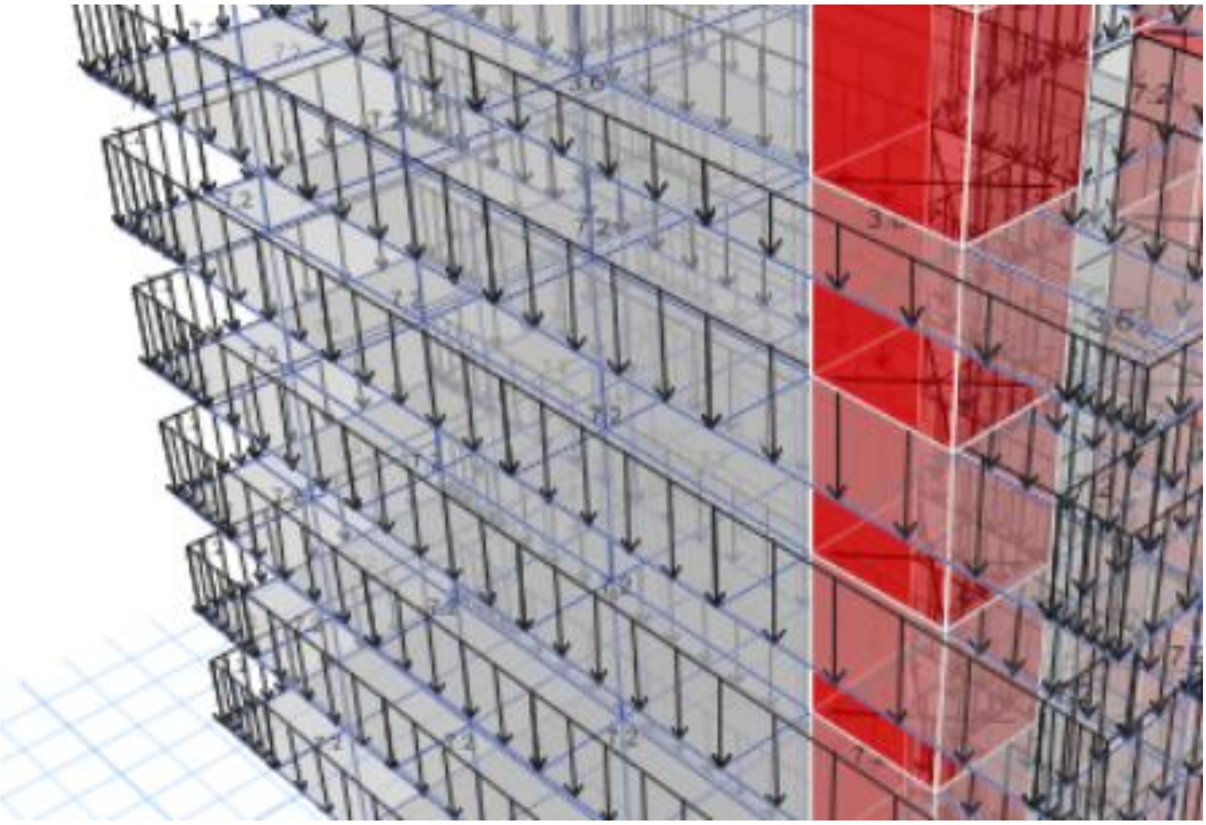
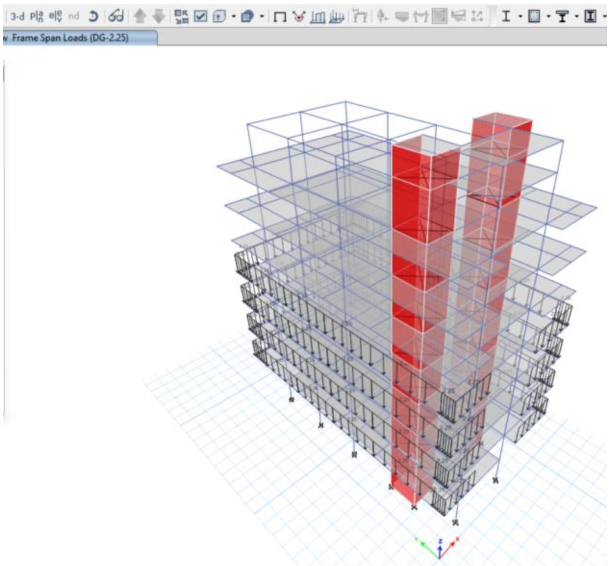
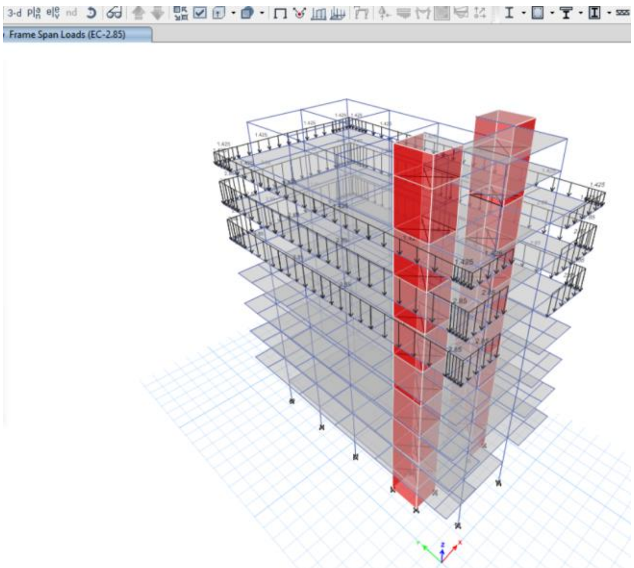


Model 2: Adaptive Façade Load on peripheral beam [Regular Glass Façade till 4th Floor (with addition of Automated Motorised Louvers from 2nd to 4th floor) & Electrochromic Smart Glass from 5th till top floor]





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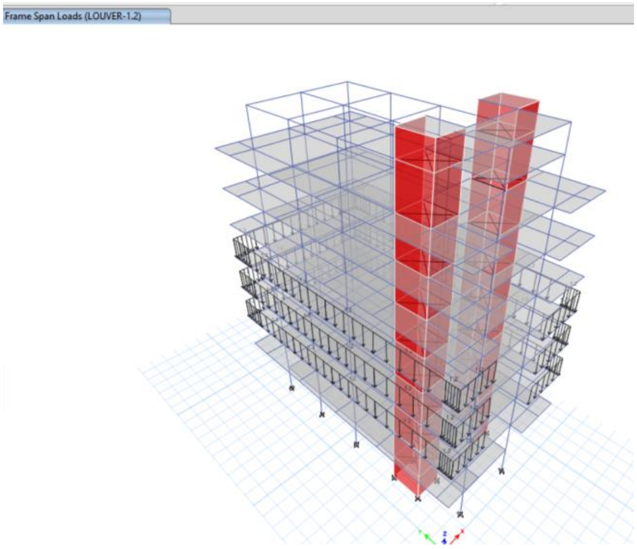

3.2 Load Application

The following loads are assigned to each model in accordance with Indian Standard provisions:

- Dead Load & Live Load as per IS 875 Part 1 and Part 2
- Wind Load as per IS 875 Part 3:2015 (Basic Wind Speed = 39 m/s, Terrain Category 3)
- Seismic Load as per IS 1893 Part 1:2016 (Zone III, Z = 0.16, I = 1.2, R = 5, Hard Soil)
- Full Wall Load for 3m floor to floor height = 7.2 kN/m
- 3 meters Double Glazed Façade load = 2.25 kN/m
- 3 meters Electrochromic Smart Glass Façade load = 2.85 kN/m
- 3 meters Automated Motorised Louver load = 1.2 kN/m

3.3 Structural Parameters and Core Sizing

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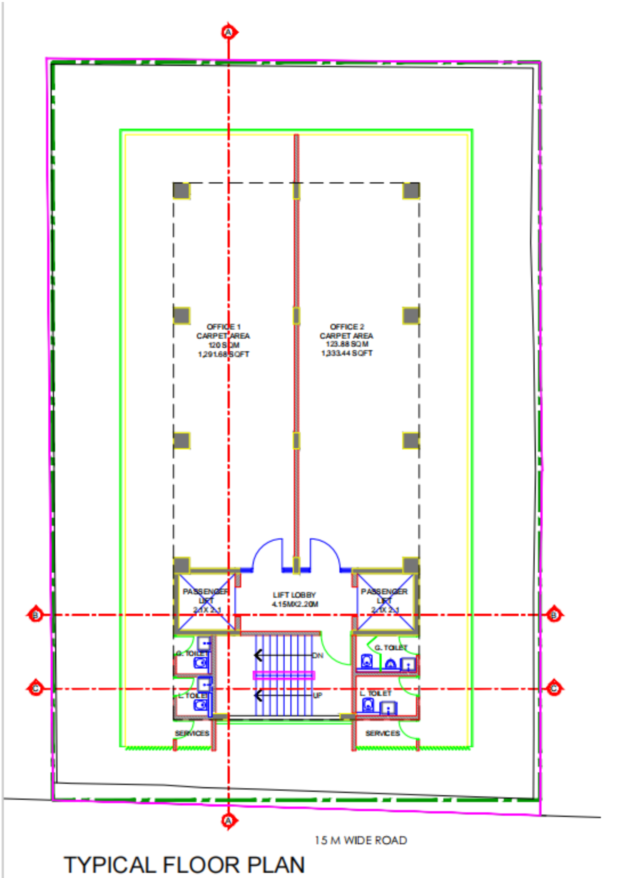

• Building Type: Commercial Layout (G+7 Floors)

• Plan Dimensions: 12.8 m (X-direction) × 22.8 m (Y-direction)

• Story Height & Slabs: 3 meters uniform story height; 175 mm shell slab element thickness.

• Framework Sizing: Boundary columns are modeled as 230 mm × 600 mm, interior core columns are 600 mm × 600 mm. Perimeter framing beams are 230 mm × 600 mm, and internal main cross beams are 300 mm × 600 mm.

4 RESULTS AND DISCUSSION

Extracting model performance indices from the ETABS engine reveals a major behavioral divergence between the traditional red brick infill model and the adaptive framework layout, impacting both global force parameters and localized boundary column-beam sections.

4.1 Dynamic Mass and Frequency Shifts

Omitting traditional red brick masonry walls lowers the overall dead weight and seismic mass of the building framework. As a direct consequence, the fundamental natural period lengthens significantly due to the altered distribution of mass relative to frame stiffness.

Table 1. Dynamic structural mass and frequency shifts

Analytical Parameter Measured	Model 1: Red Brick Infill Baseline	Model 2: Adaptive Facade	Net Shift (%)
Global Structural Dead Load	24,180.12 kN	17,411.55 kN	-27.99%
Fundamental Mode Time Period (T1)	0.884 sec	1.164 sec	+31.67%
Second Mode Time Period (T2)	0.742 sec	0.982 sec	+32.34%

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4.2 Lateral Base Shear Forces

The extensive relief in dynamic seismic weight achieved by adopting the lightweight smart skins naturally minimizes design shear force components calculated across the foundation level plane.

Table 2. Lateral base shear forces and force relief boundaries

Seismic Load Axis Tested	Model 1 Base Shear forces	Model 2 Base Shear forces	Ultimate Force Relief (%)
Ultimate X-Axis Force Demand	1,985.45 kN	1,429.12 kN	-28.02%
Ultimate Y-Axis Force Demand	2,095.12 kN	1,508.06 kN	-28.02%

4.3 Serviceability Drift and Frame Sway Performance

While removing the brick masonry walls drops active horizontal forces, it unbraces the outer frames, which increases global elasticity. Lateral roof sways increase by up to 55% under wind load configurations.

Table 3. Serviceability deflection profiles and safety code thresholds

Serviceability Evaluation Index	Model 1 Baseline Frame	Model 2 Adaptive Frame	BIS Safety Threshold Limit
Max. Roof Sway (X-Wind Profile)	12.44 mm	18.95 mm	56.20 mm (H/500)
Max. Roof Sway (Y-Wind Profile)	15.12 mm	23.44 mm	56.20 mm (H/500)
Max. Roof Sway under Seismic Force	19.45 mm	29.88 mm	112.40 mm (H/250)
Peak Inter-Story Drift Ratio	0.00125	0.00204	0.00400 (IS 1893)

4.4 Localized Perimeter Beam Stress and Induced Torsion

Traditional brick panels apply dead weight along the center line of the frame. Conversely, adaptive facades are anchored via localized connection brackets with a horizontal eccentricity of 150 mm. While typical standard bending moments and shear stresses decrease, this out-of-plane mounting eccentricity triggers a severe localized torsion spike on the peripheral concrete framing beams.

Table 4. Localized perimeter beam stress distribution components

Perimeter Beam Force Component	Model 1: Brick Baseline	Model 2: Adaptive Facade	Net Change (%)
Max. Vertical Shear Force (Vu)	112.45 kN	88.12 kN	-21.64%
Max. Bending Moment (Mu)	142.15 kNm	115.95 kNm	-18.43%
Peak Wind-Induced Torsion (Tu)	1.85 kNm	16.42 kNm	+787.57%

4.5 Ground Level Column Axial Forces

Altering perimeter masonry loads yields an asymmetric weight transformation down to the main columns. Outermost boundary frames supporting the facades directly experience substantial compression relief, while interior core columns see minimal variance.

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Table 5. Comparative load metrics on foundational column elements

Column Node Tag	Element Sizing Geometry	Model 1: Red Brick	Model 2: Adaptive Facade	Net Member Variance (%)
Column C1	Boundary Frame (230 × 600 mm)	1,250 kN	890 kN	-28.80%
Column C3	Boundary Frame (230 × 600 mm)	1,180 kN	820 kN	-30.51%
Column C7	Boundary Corner (230 × 600 mm)	1,310 kN	940 kN	-28.24%
Column C9	Internal Matrix (600 × 600 mm)	2,450 kN	2,150 kN	-12.24%
Column C10	Internal Matrix (600 × 600 mm)	2,580 kN	2,240 kN	-13.18%

5 CONCLUSIONS

The extensive comparative study of the numerical approach carried out using the ETABS model gives the following main conclusions about the structural aspects of the integration of the facade in the adaptive building:

1. Traditional 230 mm red brick masonry panels are transitioned to advanced adaptive facade elements, which reduces the global structural dead loads of the building by 27.99% and gives a wide-spread mass optimization throughout the main concrete structure.

2. As a direct function of the lowered structural weight, the seismic design base shear forces drop uniformly by 28.02% along both orthogonal axes, significantly lessening foundation loading and ground-level compression demands.

3. The reduction in outer line mass lengthens the building's fundamental natural period by 31.67% (from 0.884 to 1.164 seconds), shifting the dynamic response into a lower acceleration region on the IS 1893:2016 design spectrum.

4. Omitting the structural infill wall panels removes their secondary stiffening contribution, decreasing vertical floor lateral stiffness across lower storeys by 35%. This triggers a 55% increase in wind-induced horizontal roof sway.

5. Despite the increased structural flexibility, the maximum horizontal roof displacement and inter-story drift profiles (peaking at 0.00204) remain safely within the strict safety thresholds enforced by IS 1893 and IS 875 codes.

6. The out-of-plane brackets used to mount the adaptive skins introduce a 150 mm load eccentricity, causing localized beam torsion to spike by 787.57% (jumping from 1.85 kNm up to 16.42 kNm). This critical transformation requires specialized transverse stirrup designs per IS 456:2000 Clause 41 to ensure torsional reliability.

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