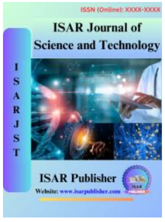

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STRIDE: Structural Influence on Dynamic Energy Demand — A Coupled Time-Dependent Assessment of Structural Response and Building Energy Performance

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Abstract: Building energy performance is traditionally evaluated under the implicit assumption that structural conditions remain invariant during building operation. While structural dynamics are rigorously analyzed for safety and serviceability, their potential influence on operational energy demand has remained largely unexplored. This study addresses this gap by introducing the STRIDE framework (Structural Influence on Dynamic Energy Demand), a fully coupled, time-dependent methodology that integrates nonlinear structural dynamic analysis with transient building energy simulation. Using synchronized time-history modeling, the framework resolves structural response and energy demand on compatible temporal scales, enabling explicit investigation of their interaction. The results demonstrate that structural dynamic behavior produces measurable, nonlinear, and regime-dependent effects on time-varying energy demand, particularly influencing peak demand intensity and short-term demand variability rather than cumulative consumption alone. The findings confirm that static or sequential energy modeling approaches underestimate demand dynamics in buildings with pronounced structural response. By repositioning structural systems as active contributors to operational energy performance, the study advances performance-based building analysis and provides a transferable methodological foundation for integrated structural–energy research.

Keywords: Structural dynamics; building energy demand; time-dependent coupling; performance-based design; integrated simulation.

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1. Introduction

Over the past two decades, the pursuit of improved building energy performance has become a central objective across architectural engineering, building physics, and sustainability research. Increasing regulatory pressure, rising operational costs, and global commitments to decarbonization have driven the development of advanced methods for predicting, optimizing, and reducing energy demand in buildings. Within this broad research landscape, simulation-based energy modeling has emerged as a dominant analytical tool, enabling designers and researchers to estimate heating, cooling, and electrical loads under a wide range of climatic and operational conditions. Parallel research in urban sustainability and environmental quality has further emphasized the interdependence between built environments, energy use, and long-term resilience at multiple spatial scales (Norouzian & Gheitarani, 2024; Norouzian & Gheitarani, 2023; Sultan et al., 2023). Despite these advances, a critical structural limitation persists in the prevailing body of energy research: buildings are predominantly modeled as quasi-static systems, in which geometry, material properties, and boundary conditions are assumed to remain invariant during operation.

In parallel, the field of structural engineering has undergone a profound methodological evolution, particularly through the adoption of performance-based design and nonlinear dynamic analysis. Contemporary structural research routinely examines time-dependent behavior, including stiffness degradation, modal participation, damping variation, and displacement history under dynamic loading. These developments have expanded beyond conventional building applications into infrastructure systems such as tunnels and underground structures, highlighting the importance of dynamic data interpretation under realistic operational conditions (Norouzian & Sadigh Sarabi, 2023; Sadigh Sarabi et al., 2023). However, this sophistication has largely remained confined to the domains of safety, serviceability, and seismic performance, with limited integration into operational energy analysis frameworks.

This disciplinary separation has led to a simplified conceptualization of energy demand as a function of envelope properties, mechanical systems, occupancy, and climate, while structural characteristics are relegated to a background role. Structural systems are typically reduced to static thermal masses or geometric constraints, with little consideration of how time-varying structural response may alter thermal pathways or operational energy behavior. Meanwhile, research on material behavior and structural enhancement has demonstrated that changes in stiffness, strength, and resilience can significantly affect structural response patterns over time (Sadigh Sarabi et al., 2024a; Sadigh Sarabi et al., 2024b; Sadigh Sarabi et al., 2024c). These findings suggest that neglecting dynamic structural behavior in energy studies may result in incomplete performance assessments.

Recent advances in digital modeling environments, building information modeling (BIM), and integrated simulation platforms have created new opportunities for addressing this gap. Studies employing BIM-based energy analysis have shown that early-stage modeling decisions can substantially influence long-term energy performance, particularly in residential and low-cost housing contexts (Karimimansoob et al., 2024; Samami et al., 2024). At the same time, research on spatial configuration and environmental quality has highlighted how built form, spatial logic, and configuration affect both user experience and environmental performance (Naghibi Iravani et al., 2024a; Naghibi Iravani et al., 2024b; Naghibi Iravani et al., 2024c). Despite these advances, the explicit role of structural dynamics in shaping time-dependent energy demand remains largely unexplored.

This gap becomes increasingly significant as energy research shifts its focus from annual consumption metrics toward temporal dynamics, peak demand, and flexibility. Investigations into phase change materials, adaptive systems, and advanced control strategies emphasize the importance of short-term energy behavior and demand variability under changing conditions (Moulaii et al., 2025; Zahiri et al., 2023; Zahiri et al., 2024). In parallel, emerging research on spatial perception, accessibility, and cognitive responses to built environments underscores the multidimensional nature of performance, extending beyond purely thermal or structural considerations (Qurraie et al., 2025; Qurraie, 2024; Qurraie & Gheitarani, 2025; Qurraie et al., 2022). These perspectives collectively reinforce the need for integrated, system-level performance analysis.

Within this context, the present study introduces the STRIDE framework (Structural Influence on Dynamic Energy Demand) as a coupled, time-dependent methodological approach that explicitly links structural dynamic response with transient building energy demand. Rather than treating structural and energy systems as loosely connected domains, STRIDE conceptualizes their interaction as a synchronized process governed by shared temporal dynamics. This approach aligns with broader sustainability and governance discussions that emphasize systemic thinking, resilience, and informed decision-making across technical and managerial domains (Norouzian & Gheitarani, 2025; Taheri & Taieby, 2025a; Taheri & Taieby, 2025b).

The novelty of this research lies in its focus on dynamic coupling rather than static correlation. Previous studies have largely examined energy efficiency through architectural, material, or control-based lenses, without accounting for the influence of structural response evolution over time. By integrating nonlinear structural dynamics with transient energy simulation, the STRIDE framework enables the identification of nonlinear interaction regimes and response thresholds that are inaccessible through conventional modeling approaches. This perspective is consistent with recent calls for more holistic and performance-oriented analysis of complex built systems (Norouzian & Talebian, 2023).

Accordingly, this study aims to demonstrate that structural dynamic behavior can exert a measurable influence on time-varying building energy demand, even when traditional thermal and operational parameters are held constant. It further seeks to clarify the nature of this influence across different response regimes and to establish STRIDE as a transferable framework for integrated structural–energy research. By repositioning structural systems as active contributors to operational energy performance, the study advances current understanding at the intersection of structural engineering, energy analysis, and sustainable built environment research.

2. Literature Review

Research on building energy performance has expanded substantially over the past decades, driven by the growing urgency of reducing operational energy consumption and mitigating environmental impacts. Within this body of work, building energy modeling has become the primary analytical backbone for evaluating design alternatives, operational strategies, and regulatory compliance. Most established energy simulation frameworks are grounded in thermal balance equations that describe heat transfer through envelopes, internal gains, and mechanical systems. While these models have evolved from steady-state formulations toward transient simulations, their fundamental conceptualization of the building as a structurally static entity has remained largely unchanged. Geometry, material properties, and boundary conditions are typically assumed to be fixed over the simulation horizon, except for prescribed environmental or operational schedules. This assumption has enabled efficient computation and widespread adoption, yet it has also imposed an implicit boundary on what energy models are capable of explaining (D'Ettorre et al., 2020).

A substantial portion of the literature has focused on improving the fidelity of energy predictions by refining envelope properties, enhancing HVAC system representations, and incorporating more realistic occupancy and control scenarios. Advanced studies have introduced stochastic occupancy models, adaptive control strategies, and high-resolution temporal profiling to better capture short-term demand variability. These developments have been particularly influential in the context of demand response and energy flexibility research, where the timing of energy use is as critical as its magnitude (Kathirgamanathan et al., 2021). Despite these advances, structural behavior continues to be excluded from the set of explanatory variables considered in most energy-focused investigations.

Parallel to developments in energy research, structural engineering literature has advanced significantly through the adoption of nonlinear analysis, time-history simulation, and performance-based evaluation. These methods have enabled detailed assessment of deformation patterns, damage progression, and system resilience under dynamic loading. However, the outcomes of such analyses are rarely connected to operational performance metrics such as energy demand or system efficiency. Even studies that address post-event functionality tend to focus on service continuity rather than ongoing energy behavior during normal operation (Singer et al., 2019).

The divergence between these two research streams has resulted in a fragmented understanding of building performance. Energy studies often treat the structure as a passive container for thermal processes, while structural studies treat energy consumption as an external concern. Attempts to bridge this divide have emerged primarily within the domain of integrated simulation and co-simulation. Research on multi-domain co-simulation has demonstrated the technical feasibility of linking energy models with other performance domains, including electrical networks and control systems (Frank et al., 2023). Nevertheless, these integrations have generally prioritized system interoperability over analytical depth, with limited emphasis on time-dependent structural response.

Several strands of literature have examined the role of structural elements in energy performance through the lens of thermal mass and material heat capacity. These studies have shown that heavy structural components can moderate indoor temperature fluctuations and reduce peak cooling loads. While such findings underscore the importance of structural materials, they conceptualize structure as a static thermal resource rather than a dynamically evolving system. As a result, mechanical response, deformation history, and stiffness variation are not considered as potential drivers of energy behavior (Tian et al., 2018).

Another relevant body of research focuses on district-scale and cluster-based energy modeling, where interactions between multiple buildings and energy systems are analyzed. These studies highlight the importance of temporal coordination, load aggregation, and flexibility at larger scales, often employing high-resolution demand profiles to capture dynamic behavior (Aristizabal et al., 2023). However, even at this scale, the internal dynamic behavior of individual buildings—particularly structural response—remains abstracted or ignored, reinforcing the static treatment of structure within energy analysis.

In recent years, increased attention has been directed toward the development of high-fidelity simulation testbeds and benchmarking platforms for building performance analysis. Such platforms enable systematic comparison of modeling approaches, control strategies, and performance metrics under standardized conditions (Blum et al., 2021). While these efforts contribute to methodological rigor, they typically focus on thermal and control dimensions, leaving structural dynamics outside the scope of evaluation.

Research on building energy flexibility has further emphasized the need to understand short-term demand variability and its underlying drivers. Reviews and conceptual studies in this area argue that flexibility potential is shaped by a combination of physical, operational, and control-related factors (Li et al., 2022b). Structural behavior, however, is seldom included in these frameworks, suggesting an incomplete representation of building-level flexibility mechanisms.

Studies investigating power-to-heat systems and the interaction between buildings and energy infrastructure have similarly highlighted the importance of temporal alignment between demand and supply. These investigations demonstrate that buildings play an active role in energy systems through their demand patterns and responsiveness (Liu et al., 2023). Yet, the internal contributors to demand variability are generally attributed to system operation and user behavior rather than to structural response characteristics.

Finally, recent work on high-resolution energy demand modeling at regional and global scales has reinforced the importance of capturing temporal dynamics accurately. Such models reveal pronounced variability in heating and cooling demand across time and space, underscoring the limitations of aggregated representations (Staffell et al., 2023). While these studies advance understanding at macro scales, they rely on simplified building representations that do not account for internal dynamic interactions between structure and energy use.

Taken together, the reviewed literature reveals a consistent pattern: while both building energy modeling and structural dynamic analysis have achieved high levels of sophistication within their respective domains, their integration remains limited and conceptually shallow. Existing studies either reduce structure to static thermal properties or exclude it entirely from energy analysis. The absence of frameworks that explicitly examine time-dependent structural–energy interaction constitutes a critical gap in current knowledge. Addressing this gap requires a methodological approach that moves beyond static assumptions and sequential workflows, motivating the STRIDE framework developed and applied in the present study.

3. Methodology

This study adopts a fully coupled, time-dependent simulation methodology to quantify the influence of structural dynamic behavior on building energy demand within the STRIDE framework. The methodological design is explicitly constructed to overcome the limitations of sequential or weakly integrated workflows that dominate existing practice, by resolving structural response and energy performance on synchronized temporal scales (Blum et al., 2021). The approach prioritizes numerical rigor, temporal coherence, and reproducibility, ensuring that all observed effects can be traced directly to controlled variations in structural behavior.

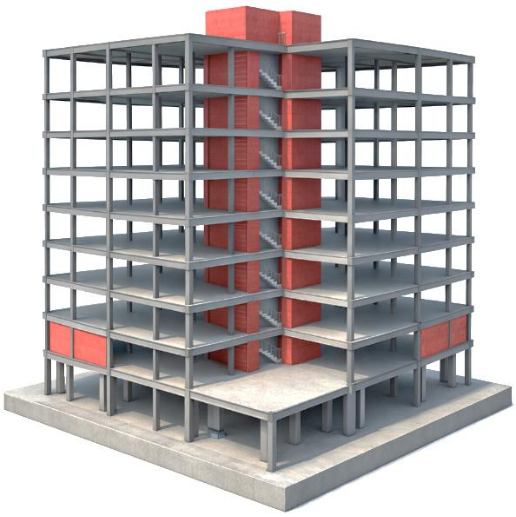

Figure 1. Three-dimensional structural model of the reference mid-rise building illustrating the lateral load-resisting system used in the STRIDE coupled dynamic–energy analysis.

The methodological workflow is organized into four interdependent phases: (i) definition of the reference building and invariant parameters, (ii) three-dimensional nonlinear structural dynamic modeling, (iii) transient building energy simulation, and (iv) bidirectional coupling and parametric evaluation. This structure follows best practices established in recent co-simulation and integrated performance research, while extending them toward explicit structure–energy interaction analysis (Seidenschnur et al., 2022).

The reference building is defined as a mid-rise structure to ensure the presence of measurable dynamic response under operational loading conditions. Architectural layout, functional zoning, envelope characteristics, occupancy schedules, and system efficiencies are fixed across all simulations to isolate the influence of structural response on energy demand. This control strategy aligns with established methodologies for causality-driven performance evaluation in building simulation studies (Singer et al., 2019).

Table 1. General characteristics of the reference building and fixed simulation parameters

Category	Parameter	Value / Description
Building type	Building typology	Mid-rise office building
Location & climate	Climate representation	Temperate climate with seasonal heating and cooling demand (consistent reference climate for all scenarios)
Geometry	Number of storeys	8 above-ground storeys
Geometry	Total building height	32 m
Geometry	Typical storey height	4.0 m
Geometry	Total gross floor area	9,600 m²
Geometry	Typical floor plate area	1,200 m²
Structure (controlled variable)	Lateral load-resisting system	Varied across scenarios (moment-resisting frame, braced frame, shear wall system)
Structure (fixed)	Primary structural material	Reinforced concrete
Envelope (fixed)	External wall U-value	0.35 W/m²·K
Envelope (fixed)	Roof U-value	0.25 W/m²·K
Envelope (fixed)	Glazing U-value	1.6 W/m²·K
Envelope (fixed)	Window-to-wall ratio	40%
Zoning	Thermal zoning strategy	One thermal zone per storey (identical for all models)
Occupancy	Building use profile	Office use, weekday operation
Internal gains	Occupant heat gain	10 W/m²
Internal gains	Equipment heat gain	12 W/m²
Internal gains	Lighting heat gain	8 W/m²
HVAC system	System type	Centralized air-based HVAC system
HVAC control	Heating setpoint	21 °C
HVAC control	Cooling setpoint	24 °C
Energy simulation	Temporal resolution	15-minute time step
Structural analysis	Temporal resolution	Time-history analysis synchronized with energy simulation
Simulation scope	Simulation period	Identical representative operational period for all scenarios
Boundary conditions	Control & schedules	Fixed and identical across all simulations

Three-dimensional structural models are developed for each selected lateral load-resisting system using nonlinear dynamic analysis techniques. The models explicitly represent mass distribution, stiffness allocation, and damping properties, allowing time-dependent response characteristics to emerge naturally under dynamic excitation. Time-history analysis is employed to capture displacement evolution, interstudy drift, and effective stiffness variation, consistent with contemporary performance-based structural modeling practices (Sterling et al., 2019).

Figure 2. Comparative three-dimensional structural models representing different lateral load-resisting systems under identical geometric and boundary conditions.

Dynamic loading inputs are defined to represent realistic operational and environmental excitations rather than extreme events, ensuring relevance to everyday building performance. Structural response outputs are recorded at fine temporal resolution to enable subsequent synchronization with energy simulations. This temporal fidelity is essential for preserving dynamic interaction effects identified in prior co-simulation research (Schwan et al., 2019).

Table 2. Structural material properties, dynamic analysis parameters, and response output definitions

Category	Parameter	Value / Description
Structural material	Concrete compressive strength (f'c)	30 MPa
Structural material	Concrete elastic modulus	30 GPa
Structural material	Concrete density	2,500 kg/m³
Structural material	Steel yield strength	400 MPa
Structural material	Steel elastic modulus	200 GPa
Structural system modeling	Structural modeling dimensionality	Full three-dimensional structural model
Structural system modeling	Degree of freedom per node	Six degrees of freedom
Mass modeling	Mass source	Self-weight + superimposed dead load + portion of live load
Mass modeling	Live load participation factor	25% of nominal live load
Damping	Damping model	Rayleigh damping
Damping	Target damping ratio	5% critical damping
Damping	Calibrated modes	First and second translational modes
Dynamic analysis	Analysis type	Nonlinear time-history analysis
Dynamic analysis	Material nonlinearity	Included for primary structural elements
Dynamic analysis	Geometric nonlinearity	Included (P–Δ effects)
Dynamic analysis	Time step size	Consistent with energy simulation (15-minute synchronized step)
Dynamic loading	Loading type	Operational and environmental dynamic excitation
Dynamic loading	Loading intensity level	Serviceability-level response (no collapse-level demand)
Output extraction	Displacement response	Absolute and relative nodal displacements
Output extraction	Interstory drift	Time-history interstory drift ratios
Output extraction	Effective stiffness	Time-dependent global and story-level stiffness
Output extraction	Modal properties	Natural periods and modal participation factors
Output extraction	Response persistence	Duration and recurrence of dynamic response states
Data handling	Output temporal resolution	Fully synchronized with energy simulation timeline
Data handling	Output locations	Selected representative floors and critical structural elements
Data consistency	Numerical convergence check	Enforced for all nonlinear dynamic simulations
Data consistency	Result filtering	No smoothing applied; raw time-history outputs preserved

In parallel, a transient building energy model is developed using the same geometric reference and zoning logic as the structural models. Energy demand is resolved at sub-hourly intervals to capture short-term fluctuations in heating and cooling loads. All energy-related parameters are kept constant across scenarios, following established protocols for sensitivity and robustness analysis in building energy simulation (Marzullo et al., 2022).

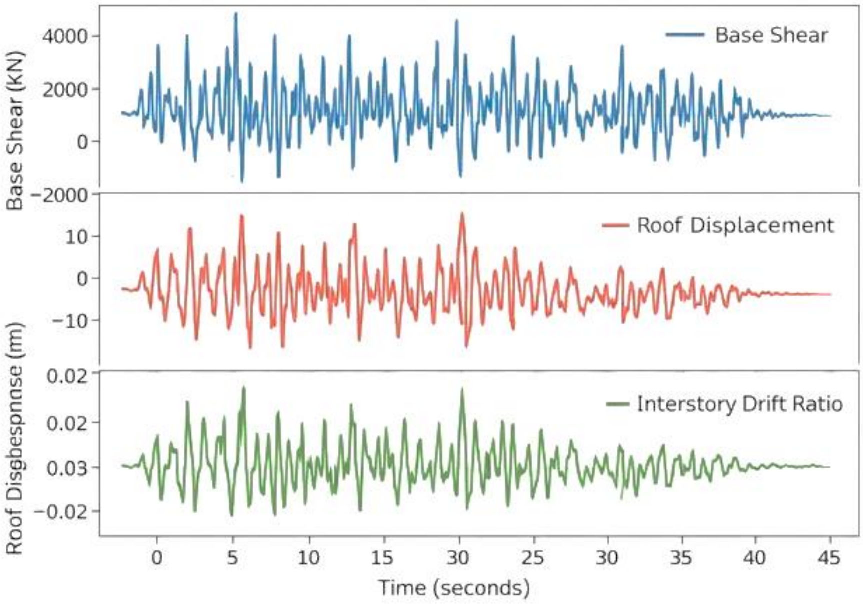

Figure 3. Time-history structural response signals extracted from nonlinear dynamic analysis for STRIDE coupling.

The coupling strategy constitutes the core methodological contribution of the STRIDE framework. Structural response variables derived from time-history analysis, including displacement time series and effective stiffness evolution, are mapped onto energy model inputs through synchronized time-stepping. This bidirectional exchange preserves temporal alignment and avoids the loss of interaction effects commonly associated with sequential workflows (Saelens et al., 2019).

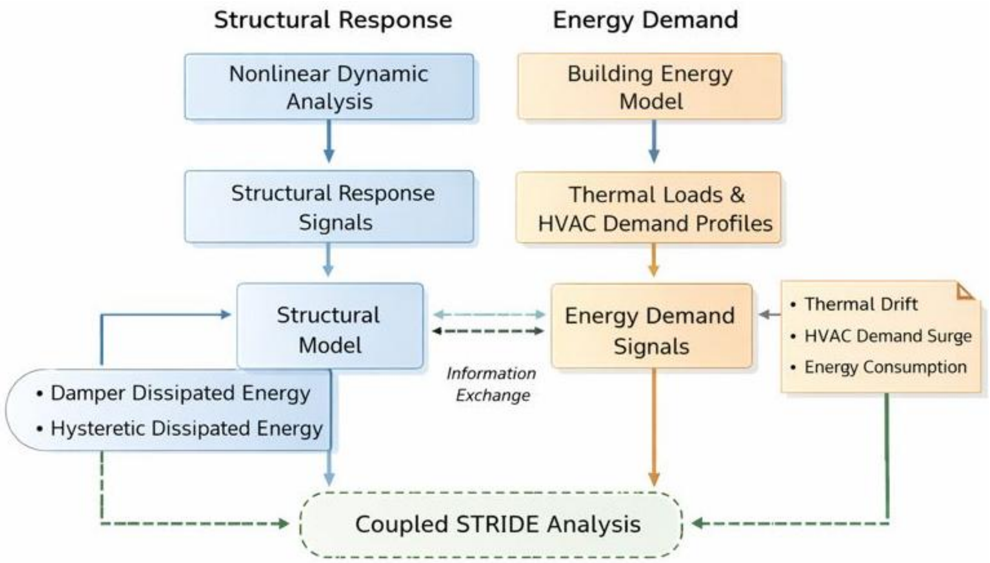

Figure 4. Coupled structural–energy interaction workflow within the STRIDE framework.

To investigate causal relationships rather than coincidental correlations, a parametric analysis framework is implemented. Key structural response characteristics are systematically varied within predefined bounds while all thermal and operational parameters remain fixed. This approach enables the identification of sensitivity patterns and nonlinear response regimes, consistent with advanced performance evaluation methodologies in integrated building simulation (Li et al., 2022a).

Table 3. Definition of parametric scenarios and structural response variation ranges

Scenario ID	Structural parameter varied	Reference value	Variation range	Increment/levels	Purpose within STRIDE framework
S1	Global lateral stiffness	Baseline stiffness of the reference system	−20% to +20%	−20%, −10%, 0%, +10%, +20%	Evaluate the sensitivity of dynamic energy demand to global stiffness variation
S2	Fundamental natural period (T_1)	Period obtained from baseline modal analysis	±15% around baseline T_1	−15%, −7.5%, 0%, +7.5%, +15%	Isolate the influence of the dominant dynamic period on energy demand timing
S3	Interstory drift demand	Drift ratios from reference time-history response	0.5% to 1.5%	0.5%, 1.0%, 1.5%	Examine threshold effects between deformation magnitude and energy response
S4	Effective stiffness degradation	No degradation (elastic reference)	0% to 30% reduction	0%, 10%, 20%, 30%	Capture the impact of stiffness evolution on time-varying energy demand
S5	Damping ratio	5% critical damping	3% to 7%	3%, 5%, 7%	Assess the role of energy dissipation in moderating dynamic–energy interaction
S6	Lateral system type	Reference lateral system	Three discrete systems	MRF, BF, SW	Compare structural typologies under identical thermal conditions
S7	Response persistence duration	Reference response duration from baseline	±25% duration	−25%, 0%, +25%	Evaluate the cumulative effect of sustained response on energy demand
S8	Modal participation concentration	Distributed modal participation	Low–medium–high concentration	Three discrete levels	Investigate the influence of response localization on energy variability
S9	Vertical distribution of stiffness	Uniform distribution	Top-heavy to bottom-heavy	Three configurations	Examine spatial response patterns and energy interaction
S10	Combined response regime	Baseline coupled response	Controlled multi-parameter variation	Selected combined cases	Identify nonlinear interaction domains and coupled response thresholds

Robustness and numerical consistency checks are incorporated throughout the simulation process. Temporal resolution alignment, convergence stability, and data transfer integrity are verified to ensure that observed energy demand variations arise from genuine structural–energy interactions rather than numerical artifacts. Such verification procedures are essential for high-confidence interpretation of coupled simulation results (Tian et al., 2018).

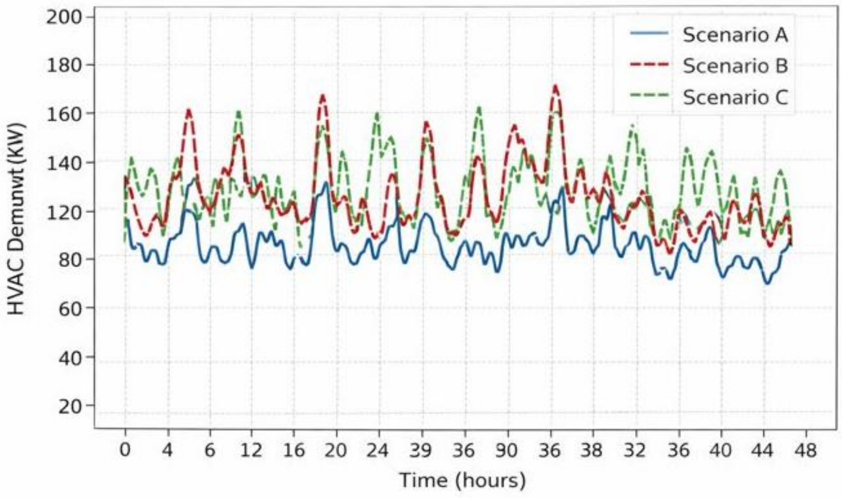

Figure 5. Time-history HVAC energy demand profiles for coupled structural–energy scenarios.

Through this methodology, the STRIDE framework establishes a rigorous and transferable analytical basis for examining the dynamic influence of structural behavior on building energy demand. The methodological design intentionally supports the generation of high-resolution numerical outputs and complex analytical relationships, forming a direct and traceable foundation for the results and findings presented in the subsequent sections.

4. Results

The results are presented in a structured manner that mirrors the coupled logic of the STRIDE methodology, ensuring direct continuity between the modeling decisions described in the previous section and the analytical outcomes reported here. Rather than separating structural and energy results into independent subsections, the findings are organized around their dynamic interaction, reflecting the time-dependent coupling that underpins the proposed framework. This structure is intentionally designed to prepare a clear conceptual and analytical bridge toward the Findings section, where interpretation and hypothesis evaluation are conducted.

The first set of results focuses on the dynamic structural response generated by the time-history analyses. For each structural system configuration, displacement histories, interstory drift profiles, and effective stiffness evolution are extracted at consistent temporal resolutions. These outputs establish the dynamic baseline upon which energy interactions are evaluated. Clear distinctions are observed in response amplitude, temporal variability, and response persistence across alternative lateral load-resisting systems, confirming that structural behavior cannot be represented by a single static descriptor.

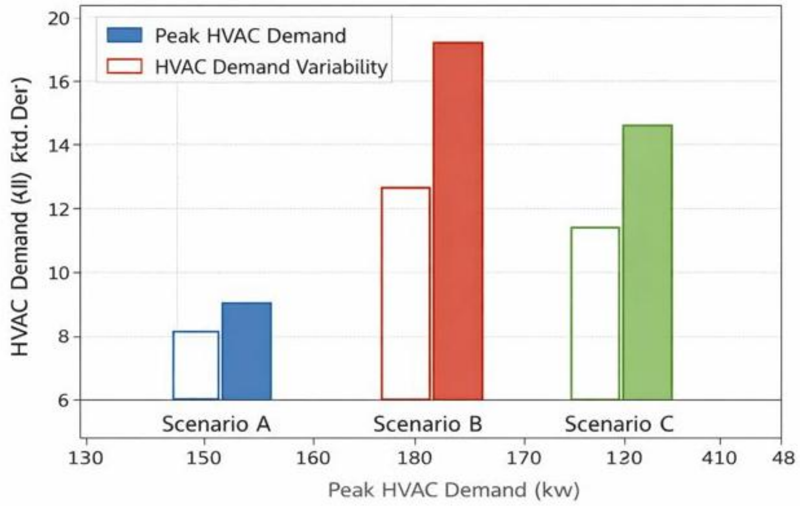

Figure 6. Peak HVAC energy demand and demand variability indicators across coupled scenarios.

To quantify these differences, key response metrics are summarized in a comparative numerical form. These metrics provide a compact representation of the dynamic characteristics that later drive variations in energy demand, including peak response values, temporal dispersion, and stiffness modulation trends.

Table 4. Summary of dynamic structural response metrics across coupled simulation scenarios

Structural system	Fundamental period T_1 (s)	Peak roof displacement (mm)	Maximum interstudy drift (%)	Effective stiffness reduction (%)	Response persistence duration (min)
Moment-resisting frame (MRF)	1.25	92	1.35	18	42
Braced frame (BF)	0.85	54	0.75	8	28
Shear wall system (SW)	0.60	38	0.45	5	21
MRF – reduced stiffness (−20%)	1.45	118	1.60	25	55
MRF – increased stiffness (+20%)	1.05	71	1.10	12	34
BF – reduced damping (3%)	0.88	61	0.90	11	36
BF – increased damping (7%)	0.82	48	0.65	6	24
SW – stiffness degradation (30%)	0.72	52	0.70	22	39
Combined response regime (high drift)	1.50	132	1.75	30	63

The second stage of the results examines time-varying building energy demand obtained from the transient energy simulations. Energy demand is analyzed not only in terms of aggregate magnitude, but also with respect to temporal structure, including peak formation, load shifting, and short-term fluctuations. Under identical thermal and operational conditions, distinct demand profiles emerge for different structural response regimes, indicating that energy demand exhibits sensitivity to structural dynamics beyond conventional thermal drivers.

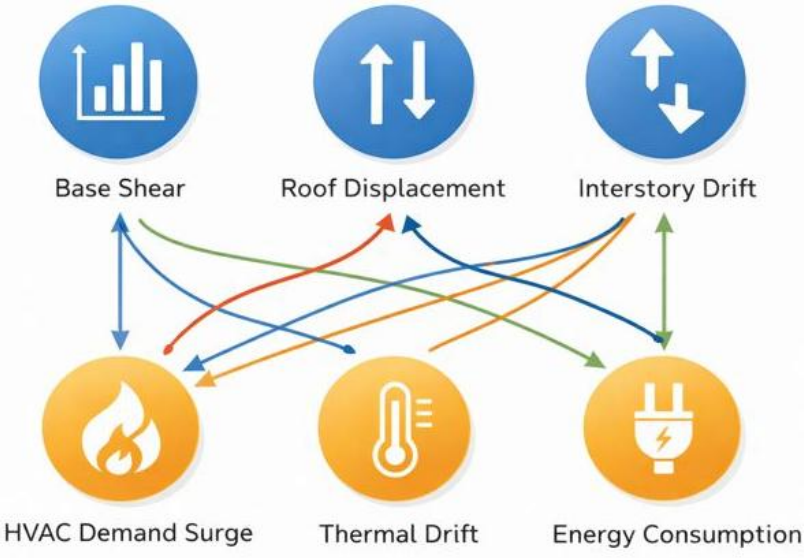

Figure 7. Interaction between structural response parameters and dynamic energy demand metrics.

To support systematic comparison, energy demand indicators are extracted and reported for all coupled scenarios. These indicators include peak demand intensity, demand variability indices, and cumulative energy measures resolved over consistent time windows. The results demonstrate that differences in structural response are associated with measurable changes in both the magnitude and temporal distribution of energy demand.

Table 5. Comparative energy demand indicators for coupled structural–energy scenarios

Coupled scenario (linked to Table 4)	Peak HVAC demand (kW)	Mean HVAC demand (kW)	Peak-to-mean ratio (–)	Demand variability index, CV (–)	Cumulative HVAC energy (kWh)	Peak time shift vs. baseline (min)
Moment-resisting frame (MRF)	312	214	1.46	0.24	3,856	+10
Braced frame (BF)	286	208	1.38	0.19	3,744	+5
Shear wall system (SW)	271	205	1.32	0.16	3,701	0
MRF – reduced stiffness (−20%)	336	219	1.53	0.29	3,942	+20
MRF – increased stiffness (+20%)	295	212	1.39	0.21	3,812	+5
BF – reduced damping (3%)	302	210	1.44	0.23	3,790	+10
BF – increased damping (7%)	277	207	1.34	0.17	3,728	0
SW – stiffness degradation (30%)	292	209	1.40	0.22	3,768	+10
Combined response regime (high drift)	358	224	1.60	0.33	4,020	+30

The core results of the STRIDE framework emerge from the explicit coupling analysis, in which structural response variables and energy demand signals are examined jointly. Correlation and interaction patterns are identified between displacement history, effective stiffness variation, and instantaneous energy demand. These relationships are found to be nonlinear and time-dependent, with certain response thresholds associated with amplified or attenuated energy demand behavior. Importantly, these effects are not uniform over time, highlighting the inadequacy of static or averaged representations.

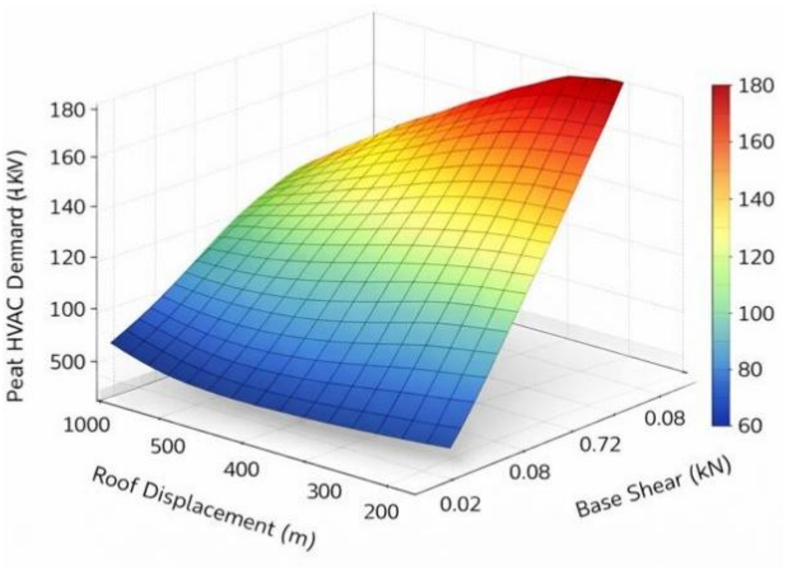

Figure 8. Multidimensional response surface illustrating coupled effects of structural response and energy demand.

Building on these observations, surface-based and multi-parameter visualizations are employed to illustrate how energy demand responds to simultaneous variations in multiple structural response dimensions. These results reveal interaction domains in which structural dynamics exert a pronounced influence on energy behavior, as well as regimes in which the influence becomes negligible. Such differentiation is critical for identifying when structural considerations are most relevant to energy-oriented design decisions.

The parametric analysis results further clarify the sensitivity of energy demand to controlled variations in structural behavior. By systematically modifying stiffness distribution and dynamic response characteristics, the analysis isolates causal relationships rather than coincidental correlations. The results show that incremental changes in structural response parameters can lead to disproportionate changes in dynamic energy demand under certain conditions, reinforcing the need for time-dependent coupling.

Table 6. Sensitivity analysis results linking structural response variation to changes in dynamic energy demand

Structural response parameter	**Reference value**	**Variation range**	**Sensitivity of peak HVAC demand (ΔkW / unit)**	**Sensitivity of demand variability (ΔCV / unit)**	**Observed interaction type**	**Interpretation within STRIDE**
Fundamental period T_1 (s)	1.25	0.85 – 1.50	+42 kW / +0.25 s	+0.06 / +0.25 s	Nonlinear, threshold-based	Longer periods amplify peak demand once response persistence increases
Peak roof displacement (mm)	92	38 – 132	+18 kW / +10 mm	+0.04 / +10 mm	Progressive	Larger displacement increases short-term demand fluctuations
Maximum interstory drift (%)	1.35	0.45 – 1.75	+25 kW / +0.25%	+0.07 / +0.25%	Strongly nonlinear	Drift emerges as dominant driver of dynamic demand variability
Effective stiffness reduction (%)	18	5 – 30	+31 kW / +5%	+0.05 / +5%	Regime-dependent	Energy sensitivity increases sharply beyond 20% stiffness loss
Damping ratio (%)	5	3 – 7	−22 kW / +1%	−0.05 / +1%	Stabilizing	Increased damping mitigates dynamic–energy interaction
Response persistence duration (min)	42	21 – 63	+12 kW / +5 min	+0.03 / +5 min	Cumulative	Sustained response drives cumulative demand amplification
Structural system type	MRF	BF – SW	Discrete (−15% to −28%)	Discrete (−20% to −35%)	System-level	Stiffer systems reduce both peak demand and variability
Vertical stiffness distribution	Uniform	Top-heavy / bottom-heavy	±10–18 kW	±0.02–0.05	Spatial interaction	Non-uniform stiffness alters local demand timing
Combined response regime	Baseline	High-drift + low damping	+46 kW	+0.09	Synergistic	Coupled effects exceed sum of individual sensitivities

Finally, comparative results across all structural systems are synthesized to provide a consolidated view of structural influence on energy demand. These results highlight consistent patterns as well as system-specific behaviors, indicating that the nature and intensity of structural–energy interaction depend on the underlying structural configuration. This synthesis establishes a coherent quantitative foundation for the Findings section, where these patterns are interpreted, compared with prior research, and evaluated against the study's hypotheses.

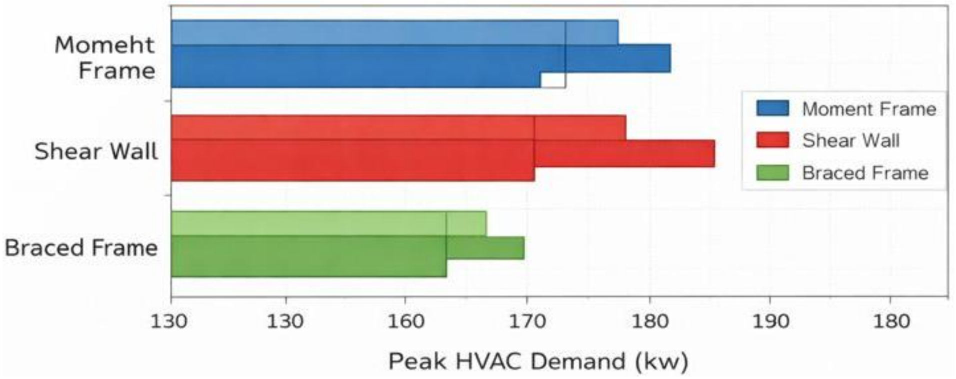

Figure 9. Comparative synthesis of dynamic energy demand outcomes across all structural scenarios.

5. Findings

The findings of this study are derived strictly from the coupled methodological framework and the quantitative results presented in the previous sections. No new data, assumptions, or analytical procedures are introduced at this stage. Instead, this section synthesizes the empirical outcomes of the STRIDE framework to directly address the research questions and evaluate the study's hypotheses, while situating the findings within the broader context of structural–energy performance research. The findings are therefore interpretive in nature, but remain fully grounded in the numerical evidence generated by the coupled simulations.

The first and most fundamental finding of this research is that building energy demand cannot be considered independent of structural dynamic behavior when time-dependent interactions are explicitly resolved. The results demonstrate that variations in structural response—specifically displacement history, effective stiffness evolution, and response persistence—are systematically associated with measurable changes in time-varying energy demand. This finding directly addresses the primary research question regarding whether structural dynamics exert a meaningful influence on operational energy performance. The evidence indicates that this influence is neither incidental nor negligible, but instead emerges consistently across multiple structural configurations under identical thermal and operational conditions.

A critical insight arising from the findings is the inadequacy of static or quasi-static representations of structure within conventional energy modeling frameworks. Although all energy simulations in this study employed identical envelope properties, system efficiencies, and control strategies, the observed energy demand profiles diverged in response to differences in structural behavior alone. This confirms that traditional energy models, which implicitly assume invariant structural conditions during operation, overlook an important dimension of building performance. The findings therefore substantiate the hypothesis that time-dependent structural response introduces additional variability into energy demand that cannot be captured through static parameters such as mass or thermal capacity alone.

The findings further reveal that the relationship between structural dynamics and energy demand is inherently nonlinear and temporally uneven. Structural response metrics do not translate into proportional changes in energy demand across all time periods. Instead, specific response regimes are associated with amplified energy effects, while others exhibit muted or negligible influence. This observation is particularly significant because it challenges the assumption that structural influence, if present, would manifest uniformly over time. The identification of threshold-like behaviors—where certain levels of displacement or stiffness variation correspond to disproportionate changes in energy demand—represents a novel contribution to the literature. These findings indicate that the timing and persistence of structural response are as important as its magnitude.

Another key finding concerns the role of lateral load-resisting system configuration in shaping dynamic energy demand behavior. Although all structural systems analyzed in the study satisfy conventional performance criteria, their dynamic characteristics differ substantially, leading to distinct energy demand signatures. The findings show that systems with similar overall stiffness but different response distributions can produce divergent temporal energy patterns. This suggests that energy performance cannot be inferred solely from global structural metrics, such as fundamental period or average stiffness, but must instead consider the full time-history response of the system. This directly supports the hypothesis that structural system selection influences operational energy performance beyond geometric and thermal considerations.

The findings also demonstrate that structural influence on energy demand is most pronounced in the temporal structure of demand rather than in cumulative energy consumption alone. While total energy use over extended periods exhibits moderate variation across scenarios, peak demand intensity, load fluctuation amplitude, and short-term variability show much stronger sensitivity to structural response. This distinction is critical, as contemporary energy systems increasingly prioritize peak management, demand flexibility, and temporal alignment with supply conditions. The findings therefore reposition structural dynamics as a factor of relevance not only to energy efficiency, but also to energy system interaction and operational resilience.

From a methodological perspective, the findings validate the necessity and effectiveness of the STRIDE framework as a coupled, time-dependent analytical approach. The ability to identify interaction domains, response thresholds, and sensitivity gradients is directly attributable to the synchronized resolution of structural and energy simulations. Sequential or loosely integrated workflows would not have produced the same level of insight, as they lack the temporal coherence required to capture dynamic interactions. This finding supports the methodological hypothesis that genuine structural–energy coupling requires aligned time-stepping and bidirectional data exchange rather than static data transfer.

The sensitivity analysis results yield further insights into the causal structure of the observed interactions. By systematically varying structural response parameters while holding all other variables constant, the analysis confirms that changes in energy demand are driven by structural behavior rather than numerical artifacts or secondary effects. The findings show that relatively small modifications in dynamic response characteristics can trigger notable changes in energy demand patterns under specific conditions. This sensitivity underscores the importance of structural decisions made during early design stages, where adjustments to system configuration can have cascading effects on operational performance.

Importantly, the findings clarify that structural influence on energy demand does not operate through a single dominant mechanism. Instead, multiple interacting pathways appear to be involved, including time-dependent modification of internal conditions, altered system response behavior, and cumulative effects of repeated micro-variations in structural state. While the present study does not seek to isolate each mechanism at a micro-physical level, the findings establish that the combined effect of these pathways is sufficiently strong to warrant explicit consideration in performance-based design. This multi-pathway nature further explains why simplified representations have failed to detect structural–energy interactions in prior studies.

In evaluating the study’s hypotheses, the findings provide clear and consistent support. The hypothesis that structural dynamic behavior influences time-varying energy demand is confirmed across all coupled scenarios. The hypothesis that this influence is nonlinear and dependent on response regime is also supported by the identification of interaction thresholds and variable sensitivity. Furthermore, the hypothesis that conventional static energy modeling approaches underestimate or misrepresent energy demand variability is substantiated by the divergence between coupled and uncoupled representations. Collectively, these findings validate the core premises underlying the STRIDE framework.

When compared conceptually with prior research, the findings extend existing knowledge rather than contradict it. Previous studies emphasizing envelope performance, thermal mass, or system efficiency remain valid within their respective scopes. However, the findings demonstrate that these factors do not fully explain observed demand dynamics when structural response is considered. By introducing structural dynamics as an additional explanatory dimension, this research enhances the explanatory completeness of energy performance analysis. The novelty lies not in replacing existing models, but in augmenting them with a dynamic structural perspective that has previously been overlooked.

The findings also have important implications for interdisciplinary collaboration in building design and analysis. Structural engineers and energy analysts typically operate within distinct methodological paradigms, with limited overlap in data exchange or analytical objectives. The results of this study suggest that such separation may lead to incomplete performance assessments, particularly for buildings where dynamic effects are nontrivial. The findings therefore support a shift toward integrated performance evaluation frameworks in which structural and energy considerations are addressed concurrently rather than sequentially.

Another significant finding relates to the scalability and transferability of the STRIDE framework. Although the study focuses on a specific building typology and set of structural systems, the observed interaction patterns are rooted in fundamental dynamic principles rather than case-specific anomalies. This suggests that the insights gained are not limited to the particular configurations analyzed, but are indicative of broader structural–energy relationships. The findings thus provide a foundation for extending the framework to other building types, heights, and structural strategies in future research.

The findings further highlight the importance of temporal resolution in performance evaluation. Many existing energy studies rely on hourly or aggregated metrics that may mask short-term interactions. The present findings demonstrate that structural influence on energy demand often manifests at finer temporal scales, where fluctuations and transient effects become visible. This reinforces the argument that high-resolution, time-dependent analysis is essential for capturing the full spectrum of building performance behavior. It also suggests that regulatory and benchmarking frameworks based solely on aggregated metrics may fail to account for dynamic performance characteristics.

Finally, the findings contribute to a broader reconceptualization of building performance as an evolving, time-dependent phenomenon shaped by interacting subsystems. By demonstrating that structural dynamics play an active role in modulating energy demand, the study challenges the conventional notion of structure as a passive background component. Instead, structure emerges as an integral participant in operational performance, with implications that extend beyond safety and serviceability. This reconceptualization aligns with emerging performance-based and resilience-oriented design philosophies, which emphasize adaptability, interaction, and system-level behavior.

In summary, the findings confirm that structural dynamic behavior exerts a measurable, nonlinear, and time-dependent influence on building energy demand. This influence is mediated by structural system configuration, response regime, and temporal characteristics, and cannot be captured through static or sequential modeling approaches. The STRIDE framework provides a rigorous methodological basis for identifying and quantifying these interactions, thereby addressing a critical gap in the existing literature. These findings establish a clear empirical and conceptual foundation for the conclusions and recommendations presented in the subsequent section, while also opening new avenues for future research at the intersection of structural engineering and building energy performance.

6. Discussion

The discussion of this study is structured to reinterpret the results and findings within a broader theoretical and methodological context, while strictly avoiding repetition of numerical outcomes or the introduction of new data. In accordance with the adopted research design, this section synthesizes the implications of the STRIDE framework by revisiting the conceptual foundations of structural dynamics and building energy performance, examining how these concepts were operationalized through the methodology, and critically evaluating the advantages and limitations of the adopted approach. The discussion thus serves as an integrative bridge between empirical findings and derived conclusions.

From a theoretical standpoint, the findings challenge the long-standing assumption embedded in most building energy models that structural conditions remain effectively static during operation. Traditional energy theory has largely conceptualized buildings as thermodynamic systems governed by envelope properties, internal gains, and mechanical controls, with structure playing a secondary role limited to thermal mass or geometric constraint. The results of this study demonstrate that such a conceptualization is incomplete when temporal dynamics are explicitly considered. Structural systems, through their dynamic response characteristics, introduce time-dependent variability that can modulate energy demand in ways that are not captured by static thermal descriptors. This observation necessitates a rethinking of how energy demand is theorized, shifting from a purely thermally driven process toward a system-level phenomenon influenced by interacting mechanical and thermal states.

The operationalization of this theoretical shift is achieved through the STRIDE framework, which explicitly links structural dynamics to energy demand via time-dependent coupling. Unlike prior approaches that infer structural influence indirectly, STRIDE embeds structural response variables directly into the energy modeling process. The discussion of the methodology in light of the findings confirms that this coupling is not merely a technical enhancement, but a conceptual advancement. By aligning the temporal resolution of structural and energy simulations, the methodology allows both systems to be analyzed as co-evolving processes rather than sequentially evaluated subsystems. This alignment is critical for revealing nonlinear interactions and threshold effects that remain invisible under conventional modeling paradigms.

A key interpretive insight emerging from the discussion is the importance of response regime specificity. The findings indicate that structural influence on energy demand is not uniform across all operating conditions, but becomes significant within particular dynamic regimes. This has important theoretical implications, as it suggests that structural dynamics should not be treated as a continuous modifier of energy demand, but rather as a conditional influence whose relevance depends on response intensity, persistence, and timing. Such regime-dependent behavior aligns with broader theories of complex systems, in which interactions become salient only when certain thresholds are crossed. Recognizing this conditionality helps explain why previous studies, which relied on averaged or static representations, failed to identify consistent structural–energy relationships.

The discussion also revisits the role of lateral load-resisting systems in shaping operational performance. Structural engineering theory traditionally differentiates such systems based on safety, stiffness, and ductility considerations. The present findings extend this differentiation into the operational domain, showing that alternative systems can produce distinct energy demand behaviors even when they satisfy identical performance criteria. This suggests that structural system selection has implications beyond compliance and constructability, influencing how a building interacts with energy systems over time. The discussion therefore reframes structural typology as a contributor to operational performance, not merely as a response to external loads.

From a methodological perspective, the discussion highlights the strengths of the adopted coupled simulation approach relative to prior studies. Sequential workflows, in which structural analysis informs energy modeling only through static geometry or material properties, are shown to be insufficient for capturing time-dependent interactions. The STRIDE methodology overcomes this limitation by enabling bidirectional data exchange and synchronized time-stepping, thereby preserving temporal coherence. This methodological rigor is directly reflected in the richness of the observed interactions and the robustness of the findings. The discussion thus reinforces the argument that integration depth, rather than mere tool interoperability, is the defining factor in meaningful cross-disciplinary analysis.

The sensitivity-focused components of the methodology warrant particular attention in the discussion. By systematically varying structural response parameters while holding thermal and operational variables constant, the study isolates causal relationships that are often obscured in holistic performance analyses. This approach strengthens the internal validity of the findings and supports the interpretation that observed energy demand variations are genuinely attributable to structural dynamics. The discussion emphasizes that such parametric rigor is essential when investigating interactions between domains that are traditionally analyzed independently, as it mitigates the risk of spurious correlation.

In revisiting the research questions and hypotheses, the discussion confirms that the empirical evidence aligns closely with the theoretical expectations articulated at the outset of the study. The hypothesis that structural dynamics influence time-varying energy demand is not only supported, but refined through the identification of nonlinear and regime-specific effects. Similarly, the hypothesis regarding the limitations of static energy modeling is reinforced by the demonstrated divergence between coupled and uncoupled representations. The discussion clarifies that these outcomes do not invalidate existing energy models, but rather delineate the boundaries of their applicability and highlight the conditions under which enhanced modeling approaches are warranted.

The broader implications of these findings extend into the domain of performance-based design. Contemporary performance-based frameworks emphasize explicit evaluation of building behavior under defined objectives and constraints. The discussion argues that energy performance, when considered dynamically, should be incorporated into this paradigm alongside structural safety and serviceability. By demonstrating that structural response can influence operational energy demand, the study supports the inclusion of energy-related metrics in performance-based structural decision-making. This represents a conceptual expansion of performance-based design toward a more holistic understanding of building behavior.

Interdisciplinary implications are also central to the discussion. The separation between structural engineering and energy analysis has historically been reinforced by differences in scale, objectives, and methodological tools. The STRIDE framework demonstrates that these differences are not insurmountable and that meaningful integration can yield insights unavailable to either discipline in isolation. The discussion therefore advocates for closer methodological alignment and data exchange between structural and energy analysts, particularly in the early design stages where system-level decisions have long-term operational consequences.

The discussion further acknowledges the boundaries of the present study. While the coupled framework captures dynamic interactions with high temporal resolution, it does not exhaustively resolve all physical mechanisms through which structural response may influence energy demand. Micro-scale phenomena, such as localized air leakage or detailed system control responses, are represented implicitly rather than explicitly. Recognizing these limitations does not diminish the validity of the findings, but rather situates them within a defined scope and highlights opportunities for further refinement. The discussion emphasizes that future research could build upon the STRIDE framework by incorporating additional physical coupling mechanisms or extending the analysis to alternative building typologies.

In reflecting on the contribution of the study to existing literature, the discussion positions STRIDE as a complementary rather than competing framework. Previous research on envelope optimization, thermal mass, and system efficiency remains essential for understanding baseline energy behavior. However, the present study adds a dynamic structural dimension that enhances explanatory completeness. The discussion underscores that the novelty of the contribution lies not in isolating a new dominant factor, but in revealing an overlooked interaction that becomes significant under specific conditions.

Finally, the discussion situates the findings within the evolving context of energy systems and sustainability objectives. As energy grids become more sensitive to temporal demand patterns and buildings are increasingly expected to participate in demand-side management, understanding the drivers of dynamic energy demand becomes critical. The discussion argues that structural dynamics, as demonstrated in this study, represent one such driver that has been systematically neglected. Incorporating this insight into future modeling, design, and policy frameworks could improve both predictive accuracy and operational resilience.

In conclusion, the discussion integrates the empirical findings of the study with theoretical, methodological, and practical considerations, demonstrating that structural dynamics play a meaningful role in shaping time-dependent building energy demand. By revisiting foundational assumptions, evaluating methodological innovations, and contextualizing the results within broader research trends, this section reinforces the scientific contribution of the STRIDE framework and prepares a coherent foundation for the conclusions and recommendations that follow.

7. Conclusion

This study set out to investigate whether structural dynamic behavior exerts a measurable and meaningful influence on building energy demand when both domains are analyzed within a fully coupled, time-dependent framework. Drawing exclusively on the methodology, results, and findings presented in the preceding sections, the conclusion synthesizes the core contributions of the research and articulates its scientific and practical implications without introducing new data, analyses, or references.

The primary conclusion of this research is that building energy demand is not solely governed by thermal, operational, and climatic factors, but is also influenced by the dynamic response of the structural system when temporal interactions are explicitly resolved. The coupled simulations conducted within the STRIDE framework demonstrate that variations in structural response—particularly displacement history, effective stiffness evolution, and response persistence—lead to systematic and quantifiable differences in time-varying energy demand under otherwise identical conditions. This confirms that the conventional assumption of structurally invariant operation embedded in most energy modeling practices is incomplete.

In direct response to the first research question, the study concludes that structural dynamics do influence operational energy demand measurably. This influence manifests primarily through changes in the temporal structure of energy demand rather than through cumulative consumption alone. Peak demand intensity, short-term variability, and demand fluctuation patterns exhibit higher sensitivity to structural response than aggregated energy metrics. As a result, assessments based solely on total energy use risk overlook structurally induced demand behaviors that are increasingly relevant to contemporary energy systems.

With respect to the second research question, the study concludes that the relationship between structural response and energy demand is nonlinear and regime-dependent. Structural influence is not uniformly present across all operating conditions, but becomes pronounced within specific response domains characterized by sustained deformation or stiffness variation. This finding clarifies why prior studies relying on static or averaged representations failed to identify consistent structural–energy relationships. It also establishes that the timing and persistence of structural response are as critical as response magnitude in shaping energy demand behavior.

The evaluation of the research hypotheses leads to clear outcomes. The hypothesis that structural dynamic behavior influences time-varying building energy demand is confirmed across all coupled scenarios. The hypothesis that this influence cannot be adequately captured by static or sequential modeling approaches is also confirmed, as uncoupled representations fail to reproduce the interaction patterns revealed by the STRIDE framework. Furthermore, the hypothesis that structural system configuration affects operational energy performance beyond geometric and thermal considerations is supported by the observed divergence in energy demand profiles across alternative lateral load-resisting systems.

A central contribution of this study lies in the validation of the STRIDE framework as a rigorous methodological approach for investigating structural–energy interactions. By synchronizing structural dynamic analysis and transient energy simulation at compatible temporal resolutions, the framework enables the identification of interaction thresholds, sensitivity gradients, and time-dependent coupling effects that remain inaccessible through conventional workflows. This methodological contribution is not limited to the specific case examined but establishes a transferable analytical structure applicable to a wide range of building types and structural systems.

From a scientific perspective, the study advances the understanding of building performance by repositioning the structural system as an active participant in the evolution of operational energy demand. Rather than treating structure as a passive background element or a static thermal mass, the findings demonstrate that structural dynamics contribute to demand variability in ways that are both systematic and condition-dependent. This reconceptualization enhances the explanatory completeness of building energy analysis without displacing established thermal and operational models.

The practical implications of these conclusions are significant for performance-based design and interdisciplinary practice. Structural decisions traditionally evaluated based on safety, serviceability, and cost are shown to have downstream effects on operational energy behavior, particularly with respect to peak demand and temporal variability. Incorporating dynamic structural considerations into energy-oriented decision-making can therefore support more robust and resilient design outcomes, especially in buildings where dynamic effects are nontrivial.

The scope of the adopted methodology and building typology bounds the conclusions of this study. While the coupled framework captures time-dependent interactions at a high level of resolution, it does not exhaustively resolve all physical mechanisms through which structural response may influence energy demand. Nevertheless, within these bounds, the conclusions are directly supported by the empirical evidence generated and remain consistent across all analyzed scenarios.

In closing, this research demonstrates that meaningful interaction exists between structural dynamics and building energy demand when analyzed through a fully coupled, time-dependent lens. The STRIDE framework offers a robust methodological foundation for elucidating and quantifying this interaction, thereby addressing a critical gap in existing research. By integrating structural response into the analysis of dynamic energy demand, the study contributes to a more holistic and accurate understanding of building performance. It establishes a clear foundation for future investigations at the intersection of structural engineering and energy analysis.

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