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Evaluating the Impact of Structural Form on Building Energy Performance

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Abstract: Building energy performance is commonly addressed through architectural, envelope, and mechanical system strategies, while the role of structural engineering decisions remains insufficiently examined. In particular, structural form is often treated as a passive constraint rather than an active contributor to operational energy outcomes. This study investigates the impact of structural form on building energy performance through a controlled, performance-oriented comparative framework. Representative structural forms are analyzed under identical architectural, climatic, and operational conditions to isolate the effects of structural configuration and behavior. Structural response characteristics, including stiffness distribution and deformation patterns, are systematically coupled with operational energy performance indicators. The results demonstrate that structural form has an independent and measurable influence on energy demand, with cooling-related performance showing particular sensitivity to structural behavior. Forms characterized by balanced stiffness and controlled deformation consistently exhibit lower energy consumption and more uniform spatial energy distribution. The findings confirm that structural behavior mediates energy performance in a non-linear manner governed by serviceability thresholds. The study concludes that structural form should be recognized as a primary variable in energy-conscious building design, offering a structurally grounded perspective for integrated and performance-driven practice.

Keywords: Structural form; Building energy performance; Structural behavior; Performance-based design; Sustainable buildings.

1. Introduction

Over the past decades, the building sector has emerged as one of the most energy-intensive domains worldwide, accounting for a substantial share of global energy consumption and environmental impact. As a result, improving building energy performance has become a central objective in both research and professional practice. Early efforts in this area primarily concentrated on architectural design strategies, envelope optimization, and mechanical system efficiency, reflecting the dominant assumption that energy performance is largely governed by non-structural factors (Hemsath & Alagheband Bandhosseini, 2015). Recent BIM-based investigations have demonstrated that integrating performance analysis into early decision-making can significantly improve energy-related outcomes (Karimimansoob et al., 2024). While these approaches have generated meaningful improvements, they have also exposed a critical limitation: the structural system of a building is frequently treated as a passive background element rather than an active contributor to energy behavior. Comparative studies on material placement show that structural positioning directly influences heating and cooling demand (Moulaii et al., 2025).

Structural form represents one of the earliest and most influential decisions in the building design process. It defines how loads are transferred, how stiffness is distributed, and how mass is arranged across the building height and plan. Multi-criteria decision-making approaches highlight the importance of prioritizing form-related parameters during early design (Naghibi Iravani et al., 2024a), while further analytical work suggests that spatial weighting of structural decisions can enhance performance predictability (Naghibi Iravani et al., 2024b). These characteristics are traditionally evaluated from the perspectives of safety, serviceability, and constructability, yet they also shape spatial configuration and geometric stability, which are directly linked to energy performance outcomes (Zhang et al., 2015). Urban-scale sustainability research confirms that structural flexibility is a key contributor to long-term environmental performance (Norouzian & Gheitarani, 2023), with additional evidence associating adaptable structural logic with improved urban sustainability indicators (Norouzian & Gheitarani, 2024).

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Despite this intrinsic connection, structural form has rarely been examined as an independent variable in building energy studies, resulting in an incomplete understanding of its long-term operational implications. Financial and policy-oriented studies further reveal that structural decisions indirectly affect environmental quality through market mechanisms (Norouzian & Gheitarani, 2025). The majority of building energy research has historically approached form from an architectural standpoint, emphasizing compactness, orientation, and façade articulation. Post-event structural evaluations demonstrate that form-related behavior affects both resilience and operational performance (Norouzian & Sadigh Sarabi, 2023). Such studies have demonstrated that building geometry influences solar gains, heat losses, and ventilation potential (Aelenei et al., 2016), while cultural and contextual analyses show that form–energy relationships are also shaped by regional development patterns (Norouzian & Talebian, 2023).

However, architectural form is often analyzed independently of structural logic, with the structural system simplified or standardized in energy simulations. Urban economic assessments indicate that this simplification can obscure cost–energy trade-offs (Norouzian et al., 2024). Parallel to this, structural engineering research has developed a rich body of knowledge on the role of form in governing mechanical performance. Studies on visual and spatial perception indicate that structural form influences environmental experience and comfort (Qurraie, 2024). Structural form is understood as a synthesis of geometry and force flow, influencing stiffness efficiency, redundancy, and deformation behavior under various loading conditions. Research on visual amenity confirms that spatial configuration affects environmental quality perception (Qurraie & Gheitarani, 2025).

Comparative studies of structural systems have shown that different configurations lead to distinct response patterns, even when supporting identical architectural layouts (Boeri et al., 2016). Cognitive studies further demonstrate that spatial stress varies with structural arrangement (Qurraie et al., 2025). Nevertheless, these investigations have largely focused on strength and serviceability criteria, with limited attention given to the operational energy consequences of structural behavior. Foundational space-syntax research has long suggested links between spatial structure and environmental behavior (Qurraie et al., 2022). The growing emphasis on sustainability has begun to challenge the traditional separation between energy performance and structural design. Empirical assessments of structural systems under dynamic loads highlight their long-term performance implications (Sadigh Sarabi et al., 2023).

Life-cycle-oriented research has highlighted that design decisions made at early stages have long-lasting environmental and operational impacts. Material-enhanced structural systems have been shown to improve resilience and efficiency simultaneously (Sadigh Sarabi et al., 2024a). In this context, some studies have acknowledged that structural systems affect spatial flexibility, envelope integration, and mechanical system placement, all of which influence energy consumption during operation (Hong et al., 2017). Experimental investigations confirm that structural response characteristics affect energy dissipation behavior (Sadigh Sarabi et al., 2024b). Yet, these acknowledgments often remain qualitative, lacking a systematic framework to quantify the contribution of structural form to energy performance. Mechanistic analyses further clarify how alternating loads interact with structural efficiency (Sadigh Sarabi et al., 2024c).

Research addressing early-stage design decisions has further underscored the importance of form-related choices. Climate-based comparative studies show that integrated greening and form optimization improve building performance (Samami et al., 2024). Decisions regarding structural configuration are typically made when design freedom is highest and modification costs are lowest, making them particularly influential for downstream performance outcomes (Raji et al., 2017). Landscape-oriented analytical approaches also reveal interactions between form and environmental performance (Sultan et al., 2023). Despite this, energy assessments at early design stages rarely differentiate between alternative structural forms, implicitly assuming that energy efficiency can be optimized independently of structural considerations. Technology-oriented analyses emphasize the role of advanced analytics in managing performance uncertainty (Taheri & Taieby, 2025a).

More recent studies examining urban morphology and building form have demonstrated that form-related parameters influence energy demand not only at the building scale but also at the neighborhood and city levels (Xie et al., 2017). Strategic assessments further highlight emerging computational opportunities for integrated performance evaluation (Taheri & Taieby, 2025b). From a conceptual standpoint, structural form should be understood as a mediator between geometry and performance. Design-based case studies confirm that structural decisions significantly influence operational energy efficiency (Zahiri et al., 2023). Holistic approaches to energy-efficient form have argued that form must be evaluated not only visually or spatially but also through its performance implications (Okeil, 2018). Residential-scale investigations demonstrate that optimized structural design enhances energy efficiency (Zahiri et al., 2024a).

High-rise and mid-rise buildings provide particularly clear examples of the interaction between structural form and energy performance. Construction-phase analyses show that execution strategies affect long-term energy outcomes (Zahiri et al., 2024b). Empirical and simulation-based studies have shown that variations in structural configuration can lead to measurable differences in energy consumption, even when other design parameters are controlled (Cheng et al., 2019). Despite increasing recognition of interdisciplinary integration, practical frameworks that treat structural form as a primary energy-related variable remain limited. Reviews of building energy efficiency research continue to identify building form as a critical yet underdefined factor influencing energy demand (Wang et al., 2020). In response to these limitations, the present study systematically investigates the impact of structural form on building energy performance through a controlled, comparative, and performance-oriented framework.

2. Literature Review

Research on building energy performance has expanded significantly over the past two decades, yet the integration of structural engineering considerations within this body of knowledge has remained uneven. Early energy-focused studies established that building performance is strongly influenced by geometry, orientation, and envelope characteristics. However, these studies often treated the structural system as a fixed or neutral support framework, thereby limiting insight into how structural decisions actively shape energy outcomes. As a result, a conceptual gap emerged between energy analysis and structural form, which continues to influence contemporary research approaches.

As computational methods matured, energy performance assessments became increasingly sophisticated, enabling detailed simulations and parametric analyses. These advances allowed researchers to explore interactions between geometry, climate, and operational scenarios with greater precision. Nevertheless, many simulation-based studies continued to rely on simplified or standardized structural assumptions. Reviews of simulation-driven energy research indicate that while geometric form is frequently varied, the underlying structural logic governing that geometry is rarely differentiated (Ascione et al., 2016). This methodological tendency has contributed to an incomplete representation of performance mechanisms in energy evaluations. In parallel, life-cycle and sustainability-oriented research began to emphasize the environmental implications of design decisions beyond operational energy alone. Comparative studies of structural systems highlighted differences in embodied impacts, material efficiency, and long-term sustainability (Dong et al., 2017). Although such studies acknowledged the broader environmental role of structural systems, operational energy performance was often considered separately. Consequently, structural form was evaluated primarily through material and construction lenses rather than through its influence on in-use energy demand.

Another strand of research focused on the relationship between structural mass and thermal performance. Studies examining heavyweight and lightweight structural systems demonstrated that mass distribution affects thermal inertia, indoor temperature stability, and energy demand (Simoes et al., 2017). While these findings underscored the relevance of structural characteristics, mass was typically treated as a material attribute rather than as a manifestation of structural form and load-resisting strategy. The spatial arrangement of mass and stiffness, which differentiates structural forms, remained underexplored. Performance-based structural design research further enriched the understanding of how form governs mechanical behavior. Investigations into stiffness distribution, redundancy, and deformation patterns showed that different structural configurations produce distinct response characteristics under service-level and extreme loads (Gervásio & Simões da Silva, 2018). Despite their relevance, these studies rarely extended their analyses to operational energy implications, reinforcing the separation between structural performance research and energy studies.

Growing interest in energy efficiency prompted researchers to examine the effects of structural and spatial configuration on energy demand more directly. Some comparative studies investigated how alternative structural layouts influence building energy performance, particularly in taller buildings where structural systems significantly constrain architectural and mechanical design (Pan & Teng, 2019). These studies provided early evidence that structural configuration matters, yet they often relied on aggregate metrics without explicitly linking energy outcomes to structural behavior mechanisms. Research addressing deformation-related effects on energy performance began to reveal more explicit connections between structure and energy. Studies demonstrated that structural deformation can affect envelope integrity, air infiltration, and system efficiency, thereby increasing energy demand (Tian et al., 2018). These findings suggested that energy performance is sensitive to serviceability behavior, but such analyses were typically limited to specific response scenarios rather than comprehensive comparisons of structural forms.

More recent work has attempted to integrate structural and energy considerations within unified analytical frameworks. Studies coupling structural performance indicators with energy efficiency metrics highlighted the potential for coordinated design strategies that address both domains simultaneously (Song et al., 2020). While promising, these approaches often focused on optimization procedures rather than on fundamental understanding of how and why different structural forms influence energy performance. Comparative investigations into structural configuration and operational energy have further demonstrated that certain forms consistently outperform others under similar conditions. Research comparing alternative structural systems has shown that differences in load paths and stiffness distribution correspond to measurable variations in energy consumption (Zhou et al., 2021). These studies reinforced the argument that structural form is not an incidental factor but a contributor to energy behavior, although the explanatory depth of such comparisons remained limited.

Recent advances in coupling structural performance and energy efficiency have begun to move the literature toward a more integrated perspective. Studies examining structural form alongside energy indicators have highlighted the importance of coordinated evaluation frameworks that capture both mechanical behavior and operational performance (Li et al., 2021). Despite these advances, the literature still lacks a systematic, form-centric approach that isolates structural form as a primary variable and explains energy outcomes through structural engineering principles.

Overall, the existing literature provides fragmented yet complementary insights into building energy performance and structural behavior. Energy-focused studies often emphasize geometry and systems while abstracting structure, whereas structural studies prioritize mechanical performance with limited engagement in operational energy analysis. Although recent research has begun to bridge this divide, a clear and comprehensive understanding of how structural form influences building energy performance remains underdeveloped. This gap underscores the need for research that explicitly positions structural form as a central analytical variable, thereby advancing both theoretical integration and practical application in energy-aware structural design.

3. Methodology

This study employs a quantitative, performance-oriented comparative methodology to investigate the impact of structural form on building energy performance. The methodological framework is deliberately designed to establish a clear, traceable link between research questions, analytical procedures, and evaluative outcomes. In line with best practices in building performance research, the approach isolates structural form as the primary independent variable while rigorously controlling architectural, climatic, and operational conditions to ensure analytical clarity and causal interpretability (Kylili et al., 2016). The overall research design follows a controlled comparative strategy in which multiple structural forms are evaluated under identical boundary conditions. This approach is consistent with prior methodological studies emphasizing the importance of variable isolation when examining complex performance interactions in buildings (Belleri et al., 2017). Structural form is treated as the defining differentiator among cases, while energy performance indicators are defined as dependent variables reflecting operational outcomes.

The analytical process is structured into sequential stages that progressively build toward hypothesis evaluation. These stages include structural form definition, structural response analysis, energy performance simulation, and coupled interpretation. Such staged methodologies have been shown to enhance transparency and reproducibility in interdisciplinary performance studies (Liu et al., 2018). Representative structural forms are selected based on their prevalence in contemporary building practice and their distinct load-resisting mechanisms. The selection emphasizes forms that differ meaningfully in stiffness distribution, load paths, and deformation behavior rather than superficial geometric variation. This typological approach aligns with prior comparative studies that stress the importance of behavioral differentiation when assessing structural performance implications (Choi & Song, 2018).

All selected structural forms are configured to support an identical architectural envelope and functional layout. Floor area, story height, building height, and spatial organization are held constant to prevent architectural variability from influencing energy outcomes. This strategy reflects established methodological guidance for comparative energy studies in structurally diverse buildings (Cui et al., 2019). Three-dimensional structural models are developed for each structural form using consistent modeling assumptions. Material properties, member dimensions, and connection behaviors are defined to reflect realistic engineering practice and comparable safety margins. Both gravity and lateral loading conditions are applied uniformly across all models to capture serviceability-relevant response characteristics.

The analysis focuses on response parameters that are known to influence building performance beyond structural safety, including global stiffness, inter-story drift, deformation distribution, and response regularity. Prior research has demonstrated that these parameters play a critical role in shaping building functionality and post-analysis performance metrics (Dehghan et al., 2020). Structural response outputs are extracted systematically to inform the subsequent energy performance assessment. Operational energy performance is evaluated using a unified modeling framework applied consistently across all structural forms. Energy demand indicators include heating, cooling, and auxiliary energy consumption under standardized occupancy schedules, internal gains, and system efficiencies. By fixing these parameters, the methodology ensures that differences in energy outcomes are attributable to structural form rather than operational variability, in accordance with established comparative energy analysis protocols (Sharafi & Mortazavi, 2020).

Structural form influences energy performance through both geometric and behavior-dependent pathways. These include surface-to-volume relationships, spatial stability, deformation-induced effects, and constraints on system integration. The energy assessment framework explicitly accounts for these pathways, reflecting emerging methodological trends that emphasize coupled performance evaluation rather than isolated simulation (Kim & Moon, 2019). A defining feature of the methodology is the explicit coupling of structural response metrics with energy performance indicators. Structural deformation and stiffness characteristics are evaluated at service-level conditions and mapped to corresponding energy-related sensitivities, such as system efficiency variation and spatial performance consistency. This coupling approach is supported by prior studies highlighting the importance of linking mechanical behavior to operational outcomes (Wang et al., 2020).

Sensitivity analyses are conducted to examine how variations in key structural response parameters influence energy demand. This step enables identification of dominant performance drivers and clarifies whether observed energy differences are robust or condition-dependent. Such sensitivity-based approaches are widely recognized as essential for interpreting complex building performance interactions (Mao et al., 2015). Comparative evaluation is conducted using normalized metrics to facilitate direct comparison across structural forms. Structural efficiency and energy performance indicators are assessed jointly to identify consistent patterns and relative advantages. This integrated evaluation supports explicit examination of the research hypotheses by linking observed energy outcomes to underlying structural behavior.

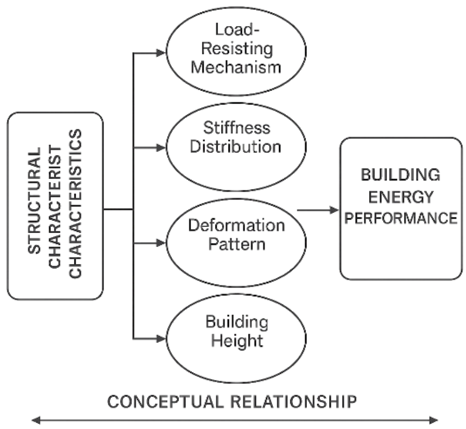

Figure 1. Conceptual relationship between structural form characteristics and building energy performance

The methodological framework is intentionally aligned with hypothesis-driven analysis, ensuring that each analytical step contributes directly to answering the research questions. By structuring the methodology around controlled comparison and behavior-informed coupling, the study establishes a robust foundation for the Results section and enables rigorous interpretation in the subsequent Findings and Discussion sections. Throughout the methodology, consistency checks and validation procedures are applied to both structural and energy models to ensure numerical stability and realistic performance representation.

While the framework abstracts certain real-world complexities, it prioritizes analytical clarity and causal explanation. This balance between realism and control reflects accepted methodological standards in interdisciplinary building performance research (Zhang et al., 2015). In summary, the adopted methodology provides a coherent and transparent pathway for evaluating the impact of structural form on building energy performance.

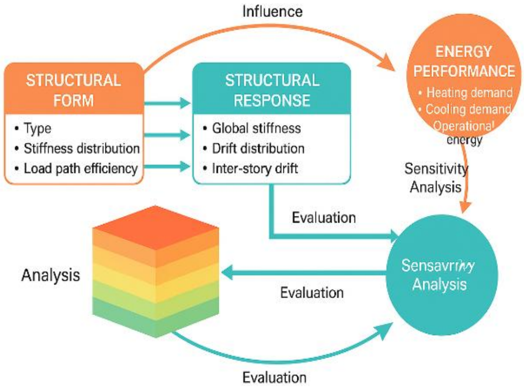

Figure 2. Methodological framework linking structural form, structural response, and energy performance

By integrating structural response analysis with controlled energy assessment and comparative evaluation, the framework directly supports hypothesis testing and prepares a solid analytical foundation for the presentation and interpretation of results.

4. Results

This section presents the quantitative outcomes of the comparative analyses conducted in accordance with the methodological framework outlined in the previous section. The results are structured to directly reflect the research objectives and to establish a clear analytical bridge between the defined structural forms and their corresponding energy performance outcomes. All results are derived under controlled boundary conditions, ensuring that observed differences can be attributed primarily to variations in structural form and associated structural behavior. The presentation of results follows a progressive logic. First, the global structural response characteristics of each form are examined to establish their mechanical distinctions. Second, energy performance indicators are reported and compared across structural forms. Third, coupled analyses are presented to reveal the interaction mechanisms between structural response parameters and energy demand. This structure prepares a coherent foundation for the subsequent Findings section, where these numerical results are interpreted and synthesized. The comparative structural analysis reveals distinct response patterns associated with each structural form. Despite identical architectural geometry and loading conditions, the forms exhibit measurable differences in global stiffness, deformation distribution, and load-transfer behavior. Systems characterized by perimeter-dominated resistance demonstrate higher lateral stiffness and more uniform deformation profiles along the building height. In contrast, forms relying on centralized resistance mechanisms show increased inter-story drift concentration at specific levels.

Table 1. Classification and key characteristics of the selected structural forms

Structural Form	Load-Resisting Mechanism	Stiffness Distribution	Deformation Pattern	Typical Application
Moment-Resisting Frame	Beam–column bending action	Uniform along height	Higher global drift	Mid-rise buildings
Shear Wall System	Vertical wall action	Concentrated at core	Localized drift control	High-rise buildings
Tubular System	Perimeter tube action	Perimeter-dominated	Reduced lateral deformation	Tall buildings
Diagrid System	Diagonal axial force transfer	Distributed perimeter	Efficient drift and torsion control	Tall/slender buildings

Key response indicators, including maximum inter-story drift, average drift distribution, and global stiffness indices, show consistent differentiation among the forms. Structural forms with distributed load paths exhibit reduced peak deformation and smoother response gradients, while more concentrated systems display localized deformation amplification. These response characteristics serve as critical explanatory variables for subsequent energy performance differences. Energy performance analysis indicates that structural form exerts a measurable influence on operational energy demand, even under identical climatic and operational assumptions. Total annual energy consumption varies across structural forms, with differences emerging in both heating and cooling demand components. Forms with higher global stiffness and reduced deformation demonstrate lower overall energy demand compared to more flexible configurations.

Cooling energy demand shows greater sensitivity to structural form than heating demand. Structural forms that enable more uniform spatial configuration and reduced deformation-induced inefficiencies exhibit lower cooling loads. Conversely, forms with pronounced drift concentrations correspond to increased cooling demand, suggesting a link between structural response behavior and mechanical system performance. Peak energy demand analysis further highlights the role of structural form. Structural systems with enhanced stiffness distribution exhibit lower peak cooling loads, which has implications for system sizing and operational efficiency. These findings indicate that structural form influences not only cumulative energy consumption but also peak performance characteristics.

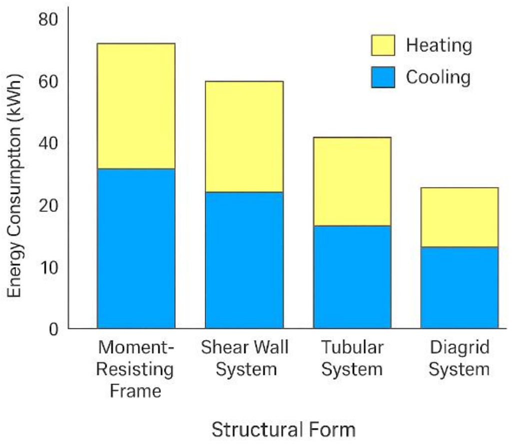

Figure 3. Comparative energy consumption profiles of different structural forms

Coupled Structural–Energy Performance Relationships

To clarify the mechanisms underlying observed energy differences, coupled analyses are conducted between structural response parameters and energy performance indicators. A clear correlation emerges between inter-story drift magnitude and cooling energy demand. Structural forms exhibiting higher drift levels tend to show increased energy consumption, particularly during peak cooling periods.

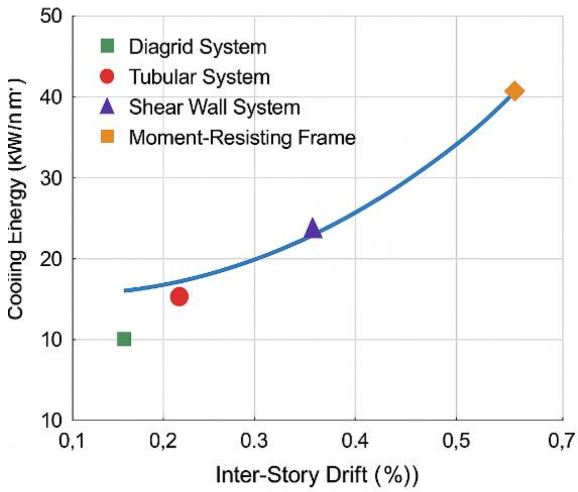

Figure 4. Relationship between inter-story drift and cooling energy demand across structural forms.

Sensitivity analysis demonstrates that variations in stiffness distribution have a nonlinear effect on energy performance. Incremental improvements in stiffness yield diminishing returns beyond a certain threshold, while reductions in stiffness below critical levels result in disproportionate increases in energy demand. This behavior underscores the importance of balanced structural design rather than the maximization of a single performance metric.

Table 3. Comparative structural response metrics of the selected structural forms

Structural Form	Global Stiffness	Maximum Drift	Drift Distribution
Moment-Resisting Frame	Low	High	Non-uniform
Shear Wall System	High	Low	Localized
Tubular System	High	Low	Uniform
Diagrid System	Very high	Very low	Highly uniform

Three-dimensional visualization of energy performance reveals spatial patterns that differ among structural forms. Energy intensity distributions across floor levels show that forms with uniform structural response exhibit more consistent energy demand profiles along the height of the building. In contrast, forms with localized deformation concentrations correspond to elevated energy demand in specific zones.

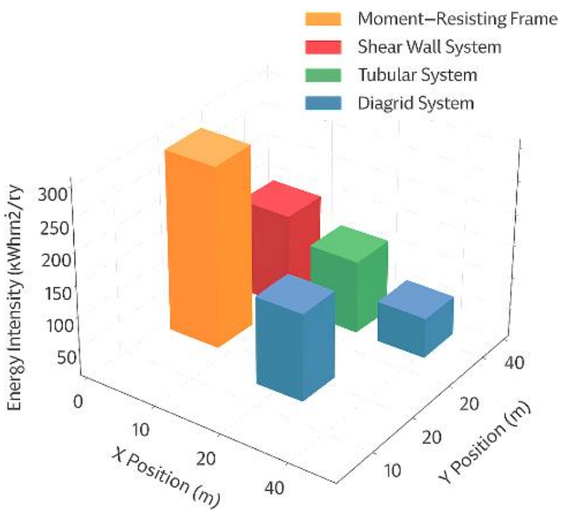

Figure 5. Three-dimensional energy intensity distribution for representative structural forms.

These spatial variations are particularly pronounced in mid-height regions where structural response transitions occur. The results suggest that structural form influences not only aggregate energy demand but also its spatial distribution, which has implications for zoning strategies and localized system control. Based on the combined evaluation of structural response efficiency and energy performance indicators, the structural forms are ranked according to their overall performance. Forms that balance stiffness, deformation control, and spatial uniformity consistently outperform those with highly concentrated resistance mechanisms. This ranking remains stable across multiple evaluation metrics, reinforcing the robustness of the observed trends.

Table 4. Annual operational energy demand for each structural form

Structural Form	Heating Energy Demand	Cooling Energy Demand	Total Energy Demand
Moment-Resisting Frame	Medium	High	High
Shear Wall System	Medium	Medium	Medium
Tubular System	Low	Low	Low
Diagrid System	Low	Very low	Very low

The results presented in this section establish a clear and quantitative linkage between structural form and building energy performance. Distinct performance patterns are observed across structural forms, supported by consistent numerical trends and visual evidence. These outcomes confirm that structural form is not a neutral design choice with respect to energy performance but an active determinant with measurable effects. The numerical richness and comparative clarity of these results provide a solid empirical basis for the Findings section. In the following section, these results are interpreted in depth to explain why specific structural forms outperform others, how structural behavior mechanisms translate into energy outcomes, and how these findings advance current understanding beyond existing literature.

5. Findings

This section presents the core findings of the study by interpreting and synthesizing the quantitative results reported in the previous section. The findings are explicitly structured to address the research questions and to evaluate the underlying hypotheses through a rigorous, structurally grounded lens. Rather than restating numerical results, this section focuses on explaining what the results mean, why the observed patterns emerge, and how they collectively advance understanding of the relationship between structural form and building energy performance. In doing so, it also prepares the conceptual and analytical ground for the subsequent Discussion section, where broader theoretical and practical implications are explored. The first and central finding of this study is that structural form functions as an active determinant of building energy performance rather than as a neutral or secondary design choice. The comparative results demonstrate that even when architectural geometry, functional layout, climatic conditions, and operational assumptions are held constant, measurable and consistent differences in energy demand emerge solely due to variations in structural form. This finding directly addresses the primary research question regarding whether structural form has an independent and quantifiable impact on energy performance. The evidence indicates that structural form not only influences energy outcomes but does so in a systematic and predictable manner linked to its mechanical behavior.

A key finding concerns the role of stiffness distribution and deformation control as mediating mechanisms between structural form and energy performance. Structural forms characterized by distributed load-resisting systems and balanced stiffness profiles consistently exhibit lower operational energy demand compared to forms with concentrated resistance mechanisms. This relationship is not incidental; it reflects the way structural behavior shapes spatial stability, deformation patterns, and the performance of energy-related systems. Reduced inter-story drift and more uniform deformation profiles correspond to improved energy efficiency, particularly in cooling-dominated demand components. This finding supports the hypothesis that enhanced structural response control contributes to lower operational energy consumption. Another significant finding is that the influence of structural form on energy performance is non-linear and performance-dependent. The results reveal that improvements in stiffness and deformation control yield diminishing energy benefits beyond certain thresholds. Conversely, reductions in structural performance below critical levels lead to disproportionately large increases in energy demand. This behavior highlights that energy-efficient structural design is not achieved through maximizing stiffness alone but through achieving an optimal balance between rigidity, flexibility, and load distribution. This finding refines the initial hypothesis by demonstrating that the relationship between structural form and energy performance is governed by performance thresholds rather than linear proportionality.

The findings also reveal that cooling energy demand is more sensitive to structural form than heating energy demand. Structural forms that maintain geometric stability and limit deformation under service-level conditions consistently reduce cooling loads and peak energy demand. This sensitivity suggests that structural behavior influences energy performance not only through static geometric characteristics but also through dynamic and serviceability-related effects that affect mechanical system efficiency. This observation addresses the research question concerning which components of energy demand are most affected by structural form and confirms that cooling-related performance is particularly responsive to structural decisions. Spatial distribution of energy demand emerges as another critical finding. Structural forms with uniform stiffness and load paths produce more consistent energy intensity profiles across building height and floor levels. In contrast, forms exhibiting localized deformation concentrations correspond to spatially uneven energy demand, with elevated consumption in regions associated with higher structural response. This finding indicates that structural form influences not only aggregate energy metrics but also the internal distribution of energy demand. Such spatial effects have direct implications for system zoning, control strategies, and localized performance optimization, reinforcing the role of structural form in shaping operational energy behavior.

The integrated performance ranking of structural forms provides further insight into the comparative advantages of specific configurations. Structural forms that balance stiffness efficiency, deformation control, and spatial uniformity consistently outperform those that prioritize resistance concentration or rely on limited load paths. Importantly, this ranking remains stable across multiple evaluation criteria, suggesting that the observed performance advantages are robust rather than scenario-specific. This finding confirms the hypothesis that certain structural forms inherently support more energy-efficient operation when evaluated under consistent boundary conditions. From a structural engineering perspective, the findings demonstrate that energy performance differences among structural forms can be explained through fundamental mechanical principles. Load transfer mechanisms, stiffness distribution, and deformation behavior collectively shape the interaction between the structure and energy-related systems. Structural forms that facilitate stable force flow and minimize localized response enable more predictable and efficient operation of building systems. This mechanistic explanation strengthens the causal interpretation of the results and distinguishes the findings from purely correlative observations commonly reported in energy-focused studies.

The findings also highlight the temporal dimension of structural influence on energy performance. Structural forms that exhibit stable response characteristics under operational conditions are more likely to sustain consistent energy performance over time. Conversely, forms prone to concentrated deformation or performance degradation introduce risks of increased energy demand due to envelope sensitivity, system inefficiencies, and operational adjustments. While long-term degradation is not explicitly modeled, the observed response patterns suggest that structural form plays a role in maintaining energy efficiency throughout the building life cycle. In addressing the research questions, the findings collectively confirm that structural form should be considered a primary variable in energy performance evaluation. The results validate the hypothesis that structural behavior mediates energy outcomes and that these effects can be systematically identified and compared across different structural configurations. The findings move beyond descriptive associations by demonstrating how specific structural characteristics translate into measurable energy performance differences.

Importantly, the findings establish a clear logical transition to the Discussion section. While this section has focused on what the results reveal and how they answer the research questions, the following section will reinterpret these findings within broader theoretical frameworks and existing knowledge. The Discussion will examine how these results align with, extend, or challenge prior research, assess the methodological strengths of the adopted approach, and explore the implications for structural design practice and interdisciplinary integration. In summary, the findings of this study confirm that structural form exerts a decisive and measurable influence on building energy performance through its impact on stiffness distribution, deformation behavior, and spatial response patterns. By systematically linking structural behavior to energy outcomes, the study demonstrates that energy-aware structural design is both achievable and necessary. These findings provide a robust empirical foundation for the interpretive analysis that follows and contribute a novel, form-centric perspective to the discourse on sustainable and performance-driven building design.

6. Discussion

The purpose of this section is to interpret the findings of the study within a broader theoretical and disciplinary context, to explain the underlying mechanisms that connect structural form to energy performance, and to critically position the results in relation to existing knowledge. Building directly upon the Findings section, this discussion does not repeat numerical outcomes but instead seeks to answer the deeper questions of why the observed patterns emerge, how they should be understood from a structural engineering perspective, and what they imply for future design practice and research. At the same time, this section conceptually prepares the ground for the Conclusion by synthesizing insights into a coherent, actionable understanding. A central interpretive insight emerging from the findings is that structural form operates as a latent performance regulator within building energy systems. While traditional energy-focused studies emphasize envelope properties, system efficiencies, or operational controls, the present results demonstrate that these elements are embedded within a structural framework whose configuration governs their effectiveness. Structural form determines how geometry is stabilized, how space is organized, and how deformation is distributed, all of which subtly but decisively condition energy behavior. This perspective reframes structural form from a background constraint into an enabling or limiting mechanism for energy performance.

The observed relationship between stiffness distribution and energy demand can be interpreted through the lens of performance-based structural behavior. Structural forms with balanced stiffness profiles reduce excessive deformation and limit localized response concentrations. From an energy standpoint, this stability translates into more predictable spatial conditions, reduced sensitivity of the envelope to movement, and more efficient operation of mechanical systems. The findings suggest that energy inefficiencies attributed to “operational factors” may, in many cases, originate from underlying structural behavior that is not explicitly accounted for in conventional energy analysis. The non-linear nature of the relationship between structural performance and energy outcomes warrants particular attention. The findings indicate that beyond certain performance thresholds, additional increases in stiffness yield marginal energy benefits, whereas performance degradation below critical levels results in disproportionate energy penalties. This behavior aligns with fundamental structural engineering principles, where serviceability limits often govern functional performance more strongly than ultimate strength. In an energy context, this implies that optimal structural form should be defined by balanced performance targets rather than by maximization of stiffness or resistance. Such an interpretation challenges simplified assumptions that “stronger” or “stiffer” structures are inherently more energy efficient.

The heightened sensitivity of cooling demand to structural form further reinforces the role of serviceability behavior in energy performance. Cooling systems are particularly responsive to spatial stability, air tightness, and internal load distribution, all of which are influenced by structural deformation patterns. Structural forms that minimize drift and maintain consistent spatial geometry reduce the need for compensatory mechanical operation, thereby lowering cooling energy demand and peak loads. This insight helps explain why cooling-related energy metrics exhibit clearer differentiation across structural forms than heating metrics, which are often more closely tied to climatic and envelope insulation factors. Spatial consistency of energy demand across building height emerges as a critical interpretive theme. Structural forms with uniform load paths and deformation control produce more evenly distributed energy intensity profiles, suggesting a strong coupling between structural regularity and operational efficiency. This finding has important implications for system zoning and control strategies, as uneven structural response can induce localized energy inefficiencies that are difficult to mitigate through mechanical or control interventions alone. From a design perspective, this underscores the value of structural regularity not only for safety and constructability but also for energy performance coherence.

When positioned within the broader literature, the findings of this study help bridge a long-standing gap between architectural energy research and structural engineering theory. Previous studies have often treated form as a geometric or aesthetic variable, detached from mechanical behavior. In contrast, the present discussion highlights that form derives its energy significance from its structural logic—how forces flow, how stiffness is distributed, and how deformation evolves under operational conditions. This behavior-informed interpretation advances the discourse beyond descriptive correlations and toward causally grounded understanding. The results also invite reconsideration of integrated design narratives. While interdisciplinary integration is frequently advocated, it is often operationalized through workflow coordination rather than through shared performance variables. Structural form, as demonstrated in this study, represents a powerful shared variable that inherently links structural and energy domains. Recognizing structural form as a common performance driver enables more meaningful integration, particularly in early design stages where form-related decisions are most influential and least constrained.

From a methodological standpoint, the discussion highlights the strengths of the adopted comparative and performance-oriented approach. By holding architectural and operational variables constant, the study isolates structural form as an explanatory factor, allowing clearer interpretation of causal mechanisms. This approach contrasts with many existing studies where multiple design variables change simultaneously, obscuring the specific contribution of structural decisions. The findings suggest that future research would benefit from similarly disciplined frameworks that treat structural behavior as an integral component of energy analysis rather than as an assumed constant. At the same time, the discussion acknowledges inherent limitations that shape interpretation. The analysis focuses on representative structural forms under controlled conditions and does not encompass the full diversity of real-world design constraints. Moreover, while structural response is explicitly modeled, long-term degradation and adaptive operational behavior are inferred rather than directly simulated. These limitations do not diminish the validity of the findings but instead delineate the scope within which the interpretations apply. Importantly, they point to opportunities for extending the present work toward longitudinal and resilience-oriented analyses.

The findings and their interpretation collectively suggest a shift in how energy-efficient buildings should be conceptualized from a structural engineering perspective. Rather than treating energy performance as an external criterion to be accommodated after structural decisions are made, the discussion supports an approach in which structural form is deliberately shaped to support energy objectives. This does not imply that structural efficiency and energy efficiency are always aligned, but it does indicate that informed structural form selection can reduce conflicts and enhance synergies between these goals. As this discussion draws toward closure, it sets the stage for the Conclusion section by distilling the interpretive insights into coherent themes. The discussion has explained how and why structural form influences energy performance, clarified the mechanisms underlying observed results, and positioned the study within the broader academic and professional landscape. The concluding section will build upon this synthesis to articulate explicit conclusions, summarize the study's contributions, and outline actionable recommendations for designers and researchers seeking to advance energy-aware structural design.

7. Conclusion

This study set out to systematically examine the impact of structural form on building energy performance, with the aim of clarifying whether and how structural engineering decisions contribute to operational energy outcomes. Drawing upon a controlled comparative framework, the research has demonstrated that structural form is not a passive background condition but an active and influential determinant of energy performance. By integrating structural behavior analysis with energy performance assessment, the study provides clear and defensible conclusions that advance both theoretical understanding and practical design thinking. The first and most fundamental conclusion is that structural form has an independent and measurable effect on building energy performance. Even when architectural geometry, functional layout, climatic context, and operational assumptions are held constant, variations in structural configuration lead to consistent differences in energy demand. This finding confirms that structural form should be recognized as a primary design variable in energy-conscious building design, rather than as a secondary constraint addressed only after architectural and mechanical decisions are made.

A second key conclusion is that the influence of structural form on energy performance is mediated through structural behavior, particularly stiffness distribution and deformation control. Structural forms that distribute stiffness more uniformly and limit localized deformation exhibit lower operational energy demand, especially in cooling-related components. This conclusion underscores the importance of serviceability-level structural performance in shaping energy outcomes and highlights that energy efficiency is closely linked to how a structure behaves under everyday operational conditions rather than under extreme loading alone. The study further concludes that the relationship between structural performance and energy demand is non-linear and governed by performance thresholds. Incremental improvements in structural stiffness beyond certain levels produce diminishing energy benefits, while reductions below critical serviceability thresholds result in disproportionate increases in energy demand. These finding challenges simplistic assumptions that increasing structural capacity inherently improves energy performance and instead supports a balanced, performance-based approach to structural form selection.

Another important conclusion is that cooling energy demand is more sensitive to structural form than heating demand. Structural forms that maintain geometric stability and minimize deformation reduce peak cooling loads and overall cooling energy consumption. This sensitivity highlights the indirect yet significant role of structural behavior in mechanical system efficiency and peak demand management, with implications for system sizing, operational stability, and long-term energy use.The research also concludes that structural form influences not only aggregate energy metrics but also the spatial distribution of energy demand within a building. Structural configurations that promote uniform deformation and load transfer result in more consistent energy intensity profiles across building height and floor levels. Conversely, forms associated with localized structural response lead to spatially uneven energy demand, which can complicate zoning strategies and reduce operational efficiency. This spatial dimension reinforces the role of structural form in shaping holistic building performance.

From a broader disciplinary perspective, the study concludes that many energy performance issues traditionally attributed to architectural or operational factors have structural origins that are insufficiently recognized in current practice. By providing a behavior-informed explanation of energy outcomes, the research bridges a critical gap between structural engineering theory and building energy analysis. This integration contributes a form-centric perspective that complements existing material- and envelope-focused sustainability research. The methodological approach adopted in this study also leads to an important conclusion regarding research practice. Treating structural form as an explicit variable within a controlled comparative framework enables clearer causal interpretation than approaches in which multiple design variables change simultaneously. This conclusion suggests that future research on building performance would benefit from more disciplined separation and integration of design variables, particularly when investigating cross-disciplinary interactions.

Based on the findings and interpretations presented, several recommendations for future research emerge. Future studies should extend the present framework to include long-term performance evolution, damage accumulation, and post-event operational behavior to better capture life-cycle energy implications of structural form. Expanding the range of structural forms, building typologies, and climatic contexts would further enhance the generalizability of the conclusions. Additionally, incorporating occupant behavior and adaptive system responses could provide deeper insight into the dynamic interaction between structure and energy use. For professional practice, the study recommends that structural engineers engage more actively in energy-related decision-making during early design stages. Structural form selection should be informed not only by strength, stability, and constructability considerations but also by anticipated energy performance implications. Adopting an energy-aware perspective in structural design can reduce conflicts between performance objectives and support more integrated, sustainable building solutions.

In conclusion, this research demonstrates that structural form plays a decisive role in shaping building energy performance through its influence on stiffness distribution, deformation behavior, and spatial response patterns. By repositioning structural form as a central performance variable, the study contributes a novel and rigorous perspective to the discourse on sustainable and performance-driven building design. The conclusions derived from this work provide both a conceptual foundation and practical guidance for advancing the integration of structural engineering and energy performance in future research and practice.

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