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Causal–Topological Seismic Robustness of Space-Frame Roof Systems: Bayesian Counterfactual Comparison of Reinforced-Concrete versus Steel Column Supports

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Abstract: This study investigates how column material selection reshapes the seismic response topology of space-frame roof systems through a hybrid causal–probabilistic framework. Rather than treating seismic performance as a deterministic outcome, the research conceptualizes space frames as stochastic force networks governed by boundary-defined interventions. Nonlinear spatial finite element modeling is integrated with Monte Carlo simulation, topology-informed robustness metrics, and Bayesian counterfactual inference to quantify how reinforced-concrete and steel columns alter axial force redistribution, nodal demand localization, and progressive failure mechanisms. Results demonstrate that steel-supported systems sustain higher axial force dispersion, greater load-path redundancy, and reduced uncertainty amplification, while reinforced-concrete supports promote force localization and accelerated yielding. Counterfactual analysis confirms statistically significant robustness gains under steel column substitution, with intervention benefits increasing nonlinearly under higher seismic demand. The findings establish column material as a primary causal control parameter governing adaptive seismic robustness in space-frame roofs, advancing resilience assessment beyond conventional response-based design toward topology-aware structural optimization.

Keywords: Space-frame roofs; Seismic robustness; Bayesian counterfactual inference; Structural topology; Column material.

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1. Introduction

Space-frame roof systems constitute one of the most structurally efficient typologies for spanning large architectural volumes, enabling lightweight enclosures over airports, stadiums, exhibition halls, industrial complexes, and transportation hubs (Aghazadeh Dizaji, 2024b). Their defining characteristic lies in the three-dimensional interconnection of axial members, which transforms gravitational and lateral loads into distributed force networks rather than localized bending-dominated responses (Gheitarani et al., 2020). Unlike conventional planar structural systems, space frames operate as spatial load-bearing lattices in which global stability emerges from collective nodal interactions and redundant force pathways (Aghazadeh Dizaji & Aydin, 2025). This intrinsic spatiality provides significant advantages under service loads; however, under seismic excitation, it introduces complex nonlinear behaviors that remain insufficiently resolved within current engineering practice (Shi et al., 2025). In particular, the seismic performance of space-frame roofs cannot be reduced to isolated member capacities or simplified global stiffness measures. Instead, vulnerability arises from emergent interactions among nodal force concentrations, member yielding sequences, boundary condition compliance, and uncertainty propagation across the structural network (Zaker Haghighi et al., 2014; Qurraie & Gheitarani, 2025).

A critical yet underexplored aspect of this behavior concerns the role of vertical support systems. In contemporary design workflows, column material selection is typically treated as a secondary decision governed by constructability, cost, or architectural preference. Reinforced-concrete and steel columns are often assumed to provide equivalent structural functionality provided that strength and stiffness requirements are satisfied (Norouzian & Gheitarani, 2023. This assumption implicitly frames columns as passive vertical elements whose primary influence is limited to global lateral drift or base shear resistance. Such a reductionist perspective obscures the deeper structural reality (Karimimansoob et al., 2024b). Columns constitute the principal boundary conditions of space-frame roofs, governing deformation compatibility, energy transmission, and force redistribution across the spatial lattice. Their material properties—mass density, constitutive nonlinearity, hysteretic behavior, and post-yield stiffness—directly shape how seismic energy enters the system and how internal forces propagate through nodal networks. Consequently, column material selection operates not merely as a design parameter but as a systemic intervention that alters the internal topology of structural response.

Reinforced-concrete columns introduce higher inertial mass, stiffness degradation through cracking, and distributed energy dissipation via micro-scale damage accumulation. Steel columns, in contrast, exhibit lower mass, more stable ductility, and concentrated plasticity with comparatively predictable post-yield behavior. These fundamentally different characteristics produce distinct interaction regimes at the roof–support interface. Under seismic excitation, such differences influence nodal demand amplification, axial force dispersion, and the initiation of progressive failure mechanisms within the space frame (Gheitarani & Norouzian, 2024). Despite this, prevailing analytical approaches continue to rely on scalar performance indicators—such as peak displacement, interstudy drift, or maximum member force—to compare structural alternatives. While these metrics provide useful snapshots of response intensity, they fail to capture the causal pathways through which structural damage evolves. In spatial systems, local support deformation can induce remote stress localization, activate alternative load paths, and trigger cascading member yielding across the roof lattice (Norouzian & Gheitarani, 2025).

Recent advances in structural engineering increasingly emphasize that seismic resilience is not a purely deterministic attribute but an emergent probabilistic property shaped by topology, redundancy, and uncertainty (Gheitarani et al., 2024a). From this perspective, robustness is defined not by the prevention of yielding but by the system's capacity to reorganize internal force distributions in response to localized degradation. Structural systems that maintain diversified load paths exhibit higher tolerance to damage, whereas those prone to force localization experience rapid performance deterioration. Space-frame roofs represent archetypal networked structures, where resilience is governed by the connectivity and redundancy of axial load paths (Naghibi Iravani et al., 2024a). Nodes function as redistribution hubs, while members act as transmission channels for seismic energy. The material characteristics of supporting columns determine how boundary demands are injected into this network, thereby controlling the spatial pattern of axial force evolution. Yet, current design methodologies rarely examine this interaction explicitly (Farrokhirad & Gheitarani, 2024).

Compounding this challenge is the pervasive presence of uncertainty. Variability in material properties, connection stiffness, geometric imperfections, and modeling assumptions introduces substantial epistemic and aleatory uncertainty into seismic performance predictions (Islam & Jangid, 2024). Deterministic nonlinear analyses provide limited insight into how such uncertainties interact with structural topology to influence collapse mechanisms. As a result, decisions regarding column material selection remain largely heuristic, informed by engineering intuition rather than probabilistically grounded causal evidence (Karimimansoob et al., 2024a). Addressing these limitations requires a paradigm shift from response-based evaluation toward causally informed, topology-aware performance assessment. Instead of asking whether reinforced-concrete or steel columns yield lower peak displacements, a more fundamental inquiry emerges: how does column material alter the internal force architecture of space-frame roofs under seismic excitation? This reframing moves the analytical focus from outcome comparison to mechanism identification (Naser & Tapeh, 2024).

Bayesian counterfactual inference provides a rigorous framework for answering such questions. By constructing probabilistic structural models and simulating hypothetical interventions—such as replacing reinforced-concrete columns with steel supports while holding all other variables constant—it becomes possible to estimate causal effects rather than mere correlations (Aghazadeh Dizaji, 2024a). This approach enables direct quantification of how column material influences nodal demand distribution, member yielding sequences, and robustness indices under uncertainty. Equally essential is the incorporation of topological descriptors that characterize the spatial organization of structural response (Gabbianelli et al., 2025b). Metrics such as axial force dispersion,

nodal demand entropy, and load-path redundancy capture how effectively a space frame redistributes seismic energy following localized degradation. When embedded within a probabilistic framework, these measures allow robustness to be evaluated as a distributed system property rather than a localized capacity threshold (Wang et al., 2024).

Within this conceptual architecture, column material selection is reconceptualized as a structural–probabilistic transformation that reshapes the response topology of space-frame roof systems. Reinforced-concrete and steel columns define distinct boundary condition regimes, each producing characteristic patterns of force localization and redistribution across the spatial lattice. These patterns, in turn, govern the onset of progressive failure and the system's ability to sustain functionality under increasing seismic demand (Ghadarjani & Gheitarani, 2013). The present study adopts this integrative framework to investigate the causal–topological seismic robustness of space-frame roof systems supported by reinforced-concrete and steel columns. Through nonlinear spatial finite element modeling, Bayesian counterfactual analysis, and topology-based robustness metrics, the research systematically examines how column material influences internal force pathways, uncertainty propagation, and collapse precursors (Volikos et al., 2025).

Rather than treating seismic performance as a scalar outcome, the study conceptualizes vulnerability as a multidimensional response manifold shaped by support compliance, network connectivity, and probabilistic variability. Within this manifold, column material acts as a primary control parameter steering the system toward either distributed resilience or localized fragility (Norouzian et al., 2024).

By advancing beyond conventional response-based comparisons, this research seeks to establish a causally grounded understanding of how vertical support systems govern spatial seismic behavior. The findings aim to reposition column selection from a secondary detailing choice to a central determinant of adaptive robustness in space-frame roof structures. To operationalize this objective, the study addresses the following research questions:

RQ1: How does column material causally influence axial force redistribution patterns within space-frame roof systems under seismic excitation?
RQ2: Does the use of reinforced-concrete columns increase nodal demand localization relative to steel columns when uncertainty in material and connection properties is explicitly considered?
RQ3: How does column material affect topology-based robustness metrics, including load-path redundancy and axial force dispersion, across probabilistic seismic scenarios?
RQ4: What is the counterfactual impact of replacing reinforced-concrete columns with steel supports on progressive failure propensity in space-frame roofs?

Based on these questions, the following hypotheses are formulated:

H1: Space-frame roofs supported by steel columns exhibit significantly higher axial force dispersion and lower nodal demand concentration than those supported by reinforced-concrete columns under equivalent seismic input.

H2: Reinforced-concrete columns introduce stiffness discontinuities that promote force localization and accelerate member yielding within the spatial lattice.

H3: Steel column support systems produce higher topology-based robustness indices due to enhanced load-path redundancy and reduced uncertainty amplification.

H4: Bayesian counterfactual substitution of reinforced-concrete columns with steel columns results in a statistically significant reduction in progressive collapse probability.

These hypotheses are evaluated through a probabilistic nonlinear modeling framework capable of resolving both causal intervention effects and topological transformations in structural response (Maleki et al., 2024).

2. Theoretical Foundations

The theoretical foundations of this research depart from conventional structural engineering literature reviews in both function and intent. Rather than merely summarizing prior studies or cataloging existing analytical techniques, the theoretical framework in this study assumes a directive role: it orients the reader toward a specific epistemological and mechanistic focal point (Hagen et al., 2024). That focal point is the recognition that column material selection in space-frame roof systems constitutes a boundary-condition intervention capable of reshaping the internal topology of seismic force transmission. The theoretical task, therefore, is not descriptive accumulation but conceptual alignment—guiding the reader toward understanding structural systems as adaptive, probabilistic networks governed by causal transformations rather than isolated performance metrics (Rahmat Rabi et al., 2024).

To construct this foundation, three interrelated theoretical domains are integrated: spatial structural mechanics, boundary-condition theory in nonlinear dynamics, and network-based robustness modeling under uncertainty. Each domain contributes a distinct layer of interpretation, and together they converge on the central proposition that vertical support systems actively govern load-path architecture in three-dimensional lattice structures (Di-Sarno et al., 2023). From the standpoint of spatial structural mechanics, space-frame roofs represent archetypal axial-force-dominated systems. Unlike flexural systems, where bending stiffness governs response, space frames derive stability from triangulated geometry and distributed axial action (Men et al., 2023). Theoretical formulations of such systems emphasize equilibrium compatibility across nodes and the collective redistribution of forces through redundant pathways (Stoicescu et al., 2025). This redundancy is often cited as the primary source of robustness; however, redundancy alone does not guarantee resilience. Its effectiveness depends on how boundary constraints inject and distribute external energy into the lattice (Flaño & Vallespín, 2024).

Globally, numerous large-span space-frame structures illustrate this principle. Airport terminals in East Asia, stadium roofs in Europe, exhibition halls in the Middle East, and transportation hubs in North America all employ spatial lattices supported by either reinforced-concrete or steel column systems (Dizaji et al., 2023). In

many cases, the roof lattice is designed independently from the vertical supports, with connection details adapted late in the design process. Post-earthquake investigations in multiple seismic regions have revealed that damage patterns often originate not within the central lattice but near support interfaces, where deformation incompatibility induces nodal force amplification. These global precedents underscore a recurring structural phenomenon: boundary conditions can govern failure propagation more decisively than internal member capacity (Naghibi Iravani et al., 2024c). The second theoretical layer emerges from nonlinear boundary-condition theory. In dynamic systems, boundary constraints define the permissible deformation space within which internal interactions unfold (Dizaji & Aydın, n.d.). For structural systems, columns serve as mechanical filters, modulating how ground motion energy is transmitted into the superstructure. Reinforced-concrete columns, with higher mass and stiffness degradation characteristics, modify modal properties differently than steel columns, which offer lighter mass and more stable hysteretic behavior. These differences are not confined to global period shifts; they influence higher-mode participation, nodal acceleration transfer, and axial force phase synchronization within the space frame (Gheitarani et al., 2013a).

This dynamic filtering concept can be observed in tall atrium structures in East Asia, long-span transit halls in Western Europe, and multi-purpose arenas in North America, where comparable roof geometries exhibit divergent seismic damage patterns depending on support material (Nosseir et al., 2024). In some cases, reinforced-concrete supports have been associated with localized cracking-induced stiffness softening that intensified axial demand concentrations in adjacent roof members. In others, steel supports have redistributed dynamic demand more evenly, albeit with higher local plastic rotation demands at column bases. These global structural experiences reinforce a theoretical insight: support material governs not only strength and stiffness but the internal choreography of seismic force propagation (Alviz-Meza et al., 2024).

The third theoretical domain arises from network science and probabilistic robustness modeling. Space-frame roofs can be mathematically represented as spatial graphs, where nodes correspond to joints and edges correspond to axial members (Kahvand et al., 2015). Within this representation, seismic loading induces weighted flows across edges, and robustness becomes a function of load-path redundancy, connectivity distribution, and force dispersion entropy. When uncertainty is incorporated—through variability in material properties, connection stiffness, or geometric tolerances—the system's behavior is best interpreted as a stochastic network evolving under dynamic excitation. Internationally, research in complex infrastructure systems—from transportation networks in Japan to energy distribution grids in Europe—has demonstrated that boundary modifications can alter internal flow topology in ways disproportionate to the magnitude of the intervention (Sarabi et al., 2024). Translating this insight into structural engineering suggests that column material substitution may produce systemic effects that extend beyond local stiffness differences. In other words, a change in support material can reconfigure the probabilistic landscape of internal force redistribution (Vasquez Munoz & Dolšek, 2024).

The theoretical convergence of these three domains leads to a central proposition: seismic robustness in space-frame roof systems is an emergent property shaped by boundary-defined energy injection and network-mediated force redistribution under uncertainty. Reinforced-concrete and steel columns define distinct boundary regimes, each establishing unique conditions for nodal compatibility, modal coupling, and axial force synchronization (Khanian et al., 2019). These regimes influence whether seismic energy disperses across multiple load paths or concentrates within critical zones. In practical terms, this proposition is globally relevant. Contemporary large-span structures in seismic regions—from Asia-Pacific transit hubs to Mediterranean sports arenas and North American convention centers—often confront design decisions regarding column material selection. These decisions are typically evaluated using deterministic response comparisons (Handa et al., 2024). However, the theoretical lens adopted here suggests that such evaluations overlook the deeper structural transformation induced by support material (Aghazadeh Dizaji, 2017). The present study positions its case structure within this international landscape: a representative large-span space-frame roof system located in a high-seismicity region, supported alternatively by reinforced-concrete and steel column configurations for analytical comparison (Gheitarani et al., 2013b).

What distinguishes this research from prior global studies is not the geometry of the roof nor the magnitude of seismic demand, but the theoretical framing. Instead of assessing which column type "performs better" in terms of peak displacement, the study interrogates how each support regime reshapes the internal topology of seismic force transmission. The theoretical foundation thus directs the reader's attention toward a specific conceptual pivot: robustness as a function of boundary-governed load-path architecture. In this research, theoretical foundations do not merely contextualize the study; they function as the intellectual compass that defines analytical direction. By integrating spatial mechanics, nonlinear boundary dynamics, and probabilistic network robustness, the framework establishes column material selection as a causal structural intervention rather than a secondary design variable (Aghazadeh Dizaji & Ahmadian, 2016). It prepares the ground for a methodology capable of quantifying intervention effects and interpreting structural response through a topological–probabilistic lens (Erkmen et al., 2024).

Accordingly, the theoretical role in this investigation is to reposition the discourse. It compels the reader to shift focus from surface-level response indicators to underlying structural transformations. It emphasizes that in networked spatial systems, resilience is neither purely material nor purely geometric; it is relational, emerging from the interplay between boundary conditions and internal connectivity. The subsequent methodological architecture and analytical procedures are therefore built upon this theoretical premise: that altering column material constitutes a measurable reconfiguration of the seismic response topology of space-frame roof systems (Ghadarjani et al., 2013). By foregrounding this conceptual orientation, the theoretical foundations lead the research narrative toward its central analytical aim: to demonstrate, through causal and probabilistic modeling, how boundary-defined support regimes govern the adaptive robustness of spatial structural networks under seismic excitation.

The theoretical orientation established in Part 1 positions space-frame roofs as spatial force networks governed by boundary-defined causal interventions. Building upon this foundation, the present section extends the conceptual framework by situating these ideas within a global structural context and formalizing robustness as a network-mediated phenomenon. Across contemporary seismic regions, large-span space-frame roofs have become defining features of critical infrastructure. International airports in East Asia, multimodal transit hubs in Western Europe, exhibition centers in the Middle East, and sports arenas in North America increasingly rely on spatial lattice systems to achieve architectural openness and functional flexibility (Aydin et al., 2020). These structures share a common trait: their roofs are lightweight, highly redundant, and supported by discrete vertical elements that act as concentrated interfaces between ground motion and spatial networks.

Post-event investigations of seismic performance in such facilities reveal consistent patterns. Damage rarely manifests uniformly across the roof field. Instead, it concentrates near support zones, along specific nodal corridors, or within localized member clusters. Even when global displacements remain moderate, axial force amplification at selected joints can precipitate progressive yielding. These observations underscore a recurring systemic behavior: vulnerability originates not from isolated member weakness but from emergent force localization driven by boundary conditions. This phenomenon can be understood through the lens of network mechanics. In a spatial lattice, each node participates in multiple load paths. Under seismic excitation, axial forces propagate through these paths in time-dependent patterns. If boundary conditions impose asymmetric stiffness or mass distributions, certain pathways become preferential conduits for energy transfer. Over successive vibration cycles, these conduits accumulate disproportionate demand, leading to nodal stress concentration and eventual member degradation.

From a theoretical standpoint, robustness in such systems depends on the diversity and independence of load paths. A structure capable of distributing demand across multiple uncorrelated trajectories exhibits higher tolerance to localized damage (Zhang et al., 2025). Conversely, when force pathways converge due to boundary-induced constraints, redundancy becomes illusory; the system behaves effectively as a reduced-order mechanism vulnerable to cascading failure. This insight aligns with developments in complex systems engineering, where infrastructure resilience is evaluated in terms of network adaptability rather than component strength. Transportation grids, power networks, and communication systems demonstrate analogous behavior: localized disruptions propagate along preferential routes determined by boundary conditions and connectivity patterns. Structural systems, though governed by physical laws rather than information flow, exhibit comparable topology-dependent dynamics (Tran et al., 2025).

In space-frame roofs, columns define the primary boundary nodes of the structural graph. Their mechanical properties influence how seismic energy is injected into the network. Reinforced-concrete columns, due to higher mass participation and stiffness degradation, tend to introduce phase lags and amplitude modulation at roof interface nodes. Steel columns, characterized by lower mass and more stable hysteretic behavior, typically transmit energy with different temporal and spatial characteristics. These distinctions alter the synchronization of axial forces across the lattice. The theoretical consequence is that column material selection modifies the spectral content of nodal excitation. Certain vibration modes become preferentially activated depending on support compliance, while others are suppressed. Over time, this modal filtering reshapes internal force patterns, steering the system toward either distributed response or localized demand accumulation (Vasquez Munoz et al., 2024).

Such behavior cannot be captured through conventional response envelopes. Peak axial force or maximum displacement provides limited insight into how demand migrates through the structure. Instead, robustness must be assessed through metrics that reflect spatial organization, including axial force dispersion, nodal demand entropy, and load-path redundancy. These measures characterize the extent to which seismic energy remains distributed versus concentrated within critical zones. Theoretical modeling of space frames as weighted graphs enables the formalization of these concepts. Each member carries a time-varying axial force, and each node accumulates demand from incident members. The dispersion of forces across edges reflects the system's capacity to redistribute energy. High dispersion indicates diversified load sharing; low dispersion signals pathway convergence and elevated fragility. Similarly, nodal entropy quantifies the uniformity of demand distribution across joints, providing a probabilistic measure of localization risk (Bajad et al., 2024).

Incorporating uncertainty into this framework further enriches interpretation. Variations in material properties, joint stiffness, and geometric tolerances introduce stochastic fluctuations in force transmission. Under such conditions, robustness emerges not as a deterministic attribute but as a statistical tendency. A system may exhibit acceptable performance under nominal parameters yet display significant vulnerability across broader uncertainty realizations. Globally, this probabilistic perspective is increasingly adopted in infrastructure resilience assessments. Seismic risk evaluations for transportation networks, offshore platforms, and industrial facilities now emphasize distributional outcomes rather than single-value predictions. Applying this philosophy to space-frame roofs necessitates probabilistic characterization of internal force topology (Lee et al., 2024).

Within this context, column material selection becomes a probabilistic boundary intervention. By altering mass distribution, stiffness evolution, and hysteretic behavior, reinforced-concrete and steel columns reshape the distribution of internal forces across stochastic scenarios. The resulting changes are not limited to mean response values but extend to variance, skewness, and tail behavior of nodal demand distributions. This theoretical framing highlights a critical distinction: performance equivalence under deterministic loading does not imply robustness equivalence under uncertainty. Two support systems may exhibit similar peak displacements yet differ substantially in their propensity for force localization and progressive failure. Recognizing this distinction is essential for advancing seismic design beyond compliance-based metrics (Jing et al., 2024b).

The present study situates its case structure within this global landscape. A representative large-span space-frame roof system located in a high-seismicity region is analyzed under two boundary regimes: reinforced-concrete column support and steel column support. Geometry, roof configuration, and loading conditions are held constant. Only column material properties and associated nonlinear behaviors are altered. This controlled setup enables isolation of causal effects and direct comparison of resulting force topologies (Chen et al., 2024).

What differentiates this investigation from prior international studies is its analytical emphasis. Rather than ranking column systems based on peak response, the study interrogates how each boundary regime reorganizes internal load paths across probabilistic seismic scenarios. The theoretical aim is to reveal whether one support configuration promotes distributed adaptability while the other fosters localized fragility. This perspective prepares the ground for the hybrid methodological framework that follows. By conceptualizing space-frame roofs as stochastic force networks and columns as causal boundary interventions, the analysis moves toward quantifying robustness as an emergent topological property.

The next part of these theoretical foundations advances this argument further by formalizing causal intervention logic and articulating the specific structural transformations expected under reinforced-concrete versus steel support regimes. The preceding parts have established two foundational pillars: first, that space-frame roofs operate as spatial force networks whose seismic behavior is governed by load-path topology; second, that column systems function as dynamic boundary regimes that modulate energy transmission into this network (Gabbianelli et al., 2025a). The present section completes the hybrid framework by formalizing column material selection as a causal structural intervention and by positioning the current research within a broader transformation of seismic systems engineering (Abd-Elhamed et al., 2025).

I. Column Material as Causal Structural Intervention. In classical structural analysis, design variables are typically treated as parameters whose influence is evaluated through comparative simulation. However, such comparisons often conflate correlation with causation. If a structure supported by steel columns exhibits lower peak displacement than the same roof supported by reinforced-concrete columns, the conclusion that "steel performs better" remains descriptive rather than explanatory. It does not reveal how or why internal force architecture changes. Causal intervention logic reframes the problem. A structural intervention is defined as a deliberate modification to one component while all other system attributes are held constant. In the present context, column material is the intervention variable. Geometry, roof lattice configuration, member sections, and seismic input spectra remain unchanged. Only the boundary material regime—reinforced-concrete versus steel—is altered. The theoretical question thus becomes:

How does this boundary-defined intervention reshape the internal probabilistic topology of seismic force transmission? This formulation transforms the analytical objective from outcome comparison to mechanism identification. Instead of evaluating which system produces a lower response magnitude, the focus shifts to how each system reorganizes force pathways, alters nodal demand distribution, and modifies progressive failure propensity (Li et al., 2025).

II. Boundary Regimes and Topological Transformation. Within the hybrid framework, reinforced-concrete and steel columns define distinct boundary regimes characterized by different mass participation, stiffness evolution, and nonlinear hysteretic behavior. Reinforced-concrete columns typically introduce:

– Higher effective mass at boundary nodes
– Progressive stiffness degradation due to cracking
– Distributed energy dissipation through material nonlinearity
– Potential asymmetry in cyclic response

Steel columns, by contrast, generally exhibit:

– Lower mass concentration at interface nodes
– More stable elastic–plastic transition
– Concentrated ductility with predictable post-yield stiffness
– Reduced stiffness degradation under moderate cyclic demand

These differences influence not only the global period or drift but also the internal synchronization of axial forces across the spatial lattice. Under seismic excitation, the timing and amplitude of nodal acceleration transmission govern how forces accumulate and redistribute. Reinforced-concrete supports may induce localized stiffness softening that channels demand into adjacent roof members. Steel supports may facilitate more uniform demand dispersion but potentially elevate localized plastic rotation at column bases. From a topological standpoint, these behaviors correspond to different force-network evolution patterns (Samami et al., 2024). A system experiencing high nodal demand concentration exhibits reduced entropy in its force distribution—energy flows preferentially through limited pathways. Conversely, a system with high force dispersion maintains diversified trajectories and greater redundancy. Thus, column material intervention can be conceptualized as a transformation operator acting on the structural network. It modifies:

– The distribution of edge weights
– The concentration of nodal demand
– The correlation structure of load paths
– The statistical distribution of progressive failure initiation points

This transformation is inherently probabilistic. Under repeated stochastic excitation realizations, the distribution of these topological indicators reveals the system's robustness profile.

III. Robustness as Emergent Probabilistic Topology. The hybrid framework defines robustness not as a threshold capacity but as an emergent statistical property of the structural network. A robust space-frame roof is one that, under uncertainty, consistently exhibits:

– High axial force dispersion across members
– Low nodal demand concentration variance
– Multiple independent load paths sustaining demand

– Reduced the probability of cascading yielding sequences

This perspective aligns with modern resilience engineering, which interprets infrastructure stability as adaptive capacity rather than deterministic strength. Within this paradigm, robustness emerges from relational properties between components rather than isolated material superiority. Crucially, robustness cannot be inferred from single deterministic simulations. It must be evaluated across probabilistic scenarios that account for material variability, connection uncertainty, and seismic demand randomness. The structural network must therefore be analyzed as a stochastic graph whose topology evolves under dynamic excitation (Khanian et al., 2013).

IV. Global Structural Implications. Large-span space-frame roofs worldwide increasingly serve critical public functions. Transportation hubs, cultural complexes, and sports facilities depend on uninterrupted post-earthquake functionality. Design decisions regarding column material often arise from economic or architectural considerations rather than systemic seismic implications (Celik et al., 2024). The theoretical framework developed here suggests that such decisions carry deeper structural consequences. By altering boundary-defined energy injection mechanisms, column material selection can influence the probabilistic landscape of internal force redistribution. In seismic regions, this influence may determine whether damage remains localized or propagates across the roof lattice. The present study's case structure is situated within this international context. It represents a typical large-span spatial roof configuration deployed in high-seismicity environments. By analyzing identical roof geometries under two alternative boundary regimes, the research isolates the causal impact of column material intervention on force-network topology and robustness metrics (Norouzian & Gheitarani, 2024).

V. The Conceptual Pivot: Where the Reader Must Focus. The central theoretical pivot of this investigation can now be stated explicitly:

Seismic resilience in space-frame roof systems is governed less by peak response magnitude and more by the probabilistic organization of internal force pathways shaped by boundary-defined material regimes. This statement encapsulates the hybrid thesis. It directs the reader's attention away from conventional scalar performance indicators and toward structural transformation processes. It emphasizes that material substitution at the boundary level constitutes a network-level intervention with systemic implications. The theoretical foundations thus perform a guiding function. They reframe the design question from "Which column type is stronger?" to "Which column type promotes adaptive load-path topology under uncertainty?" This reframing establishes the intellectual trajectory of the study and ensures coherence between theoretical orientation, methodological architecture, and analytical outcomes.

VI. Positioning of the Present Research. Within the evolving landscape of seismic systems engineering, this research occupies a distinctive position. It integrates:

– Spatial structural topology
– Nonlinear boundary dynamics
– Probabilistic uncertainty modeling
– Causal intervention logic

By doing so, it advances beyond deterministic performance comparison toward mechanism-based resilience evaluation. The theoretical synthesis developed in these three parts establishes the conceptual engine of the study (Jing et al., 2024a). It clarifies why column material must be interpreted as a causal boundary intervention and how such an intervention reshapes the emergent topology of seismic force transmission in space-frame roof systems. The subsequent methodological framework operationalizes this theory through nonlinear spatial modeling, probabilistic simulation, and topology-informed robustness metrics (Dizaji, 2024). The empirical analysis that follows does not merely test differences in response magnitude; it quantifies structural transformation across stochastic scenarios. In summary, the theoretical foundations of this research redefine the structural discourse. They assert that in networked spatial systems, resilience is an emergent property governed by boundary-mediated force organization. Column material selection, therefore, is not a peripheral detailing choice but a systemic determinant of adaptive robustness under seismic excitation (Brunesi et al., 2025).

3. Methodology

This study adopts a hybrid causal–topological computational framework to quantify how column material selection reshapes the probabilistic seismic response topology of space-frame roof systems. The methodological architecture is explicitly designed to answer the research questions and test the hypotheses formulated in the Introduction by integrating nonlinear spatial finite element modeling, stochastic ground motion simulation, Bayesian counterfactual inference, and topology-informed robustness metrics (Jayasinghe et al., 2024). Rather than treating seismic performance as a deterministic outcome, the methodology conceptualizes the structure as a stochastic force network subjected to boundary-defined interventions (Bodenmann et al., 2024). Reinforced-concrete and steel columns are modeled as causal variables, while all other structural attributes are held constant. This enables isolation of intervention effects and direct evaluation of how boundary regimes transform internal load-path organization under uncertainty (Hosseini et al., 2024).

Overall Analytical Workflow. The analytical pipeline consists of five sequential stages:

1. Definition of the reference space-frame roof system and boundary regimes
2. Nonlinear three-dimensional structural modeling
3. Probabilistic seismic excitation and Monte Carlo simulation
4. Topology-based response extraction and robustness quantification
5. Bayesian counterfactual inference and hypothesis testing

These stages are connected through a closed-loop workflow that ensures traceability between research questions, numerical procedures, and output metrics (Zakerhaghighi et al., 2015).

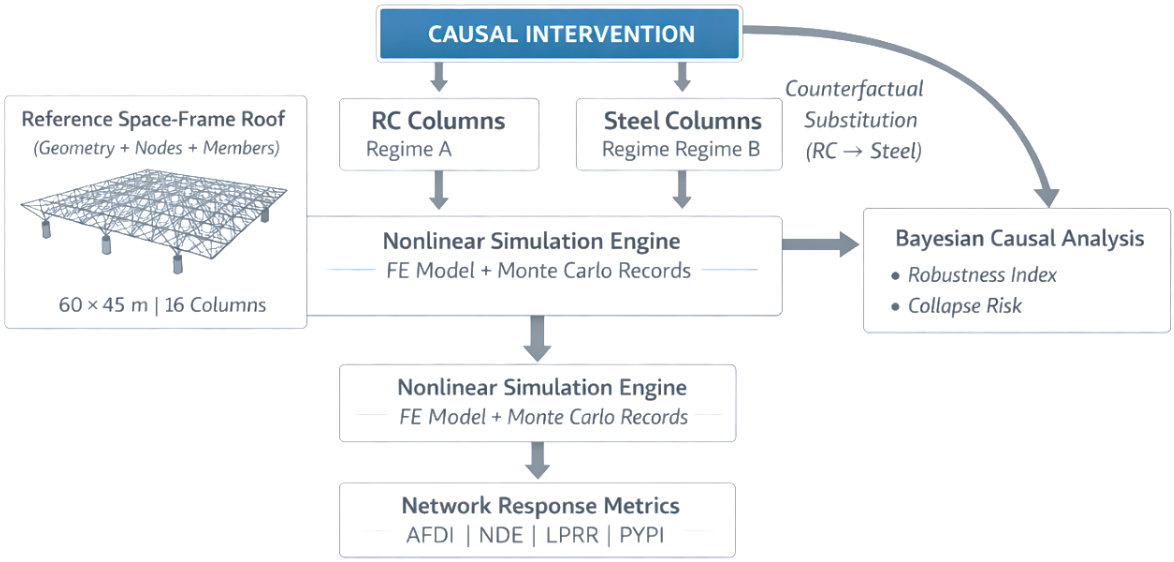


Figure 1. Methodological workflow for causal–topological seismic analysis of space-frame roof systems

Stage 1: Reference Structural System Definition. A representative large-span space-frame roof system is defined as the reference case study. The structure corresponds to a typical transportation or assembly facility roof commonly employed in high-seismicity regions. The roof plan is rectangular, spanning 60 m by 45 m, with a spatial lattice depth of 3.5 m. The roof is supported by sixteen equally spaced vertical columns arranged along the perimeter and internal grid lines (Chiappelloni et al., 2025). The space-frame lattice is composed of tubular steel members connected through rigid spherical nodes. Member cross-sections are selected to ensure elastic behavior under service loads while permitting controlled nonlinear response under seismic excitation. Two boundary regimes are defined:

- Boundary Regime A: Reinforced-concrete columns
- Boundary Regime B: Steel columns

Both regimes share an identical geometric configuration, column locations, roof mass distribution, and connection topology. Only the material properties and nonlinear constitutive behavior of columns differ. The reinforced-concrete columns are modeled with distributed plasticity, incorporating cracking-induced stiffness degradation and nonlinear hysteresis. Steel columns are modeled using bilinear elastoplastic behavior with kinematic hardening (Norouzian & Guyadeen, 2025).

Stage 2: Nonlinear Spatial Finite Element Modeling. A full three-dimensional nonlinear finite element model is developed using OpenSees for structural simulation and Python for post-processing and probabilistic analysis. Space-frame members are modeled using nonlinear beam-column elements with axial-force interaction. Nodes are modeled as rigid joints to preserve force transfer continuity (Zaker Haghighi et al., 2014). Column–roof connections are modeled as rigid to isolate material effects at the column level (Meng et al., 2025). Geometric nonlinearity is included for all vertical elements. Rayleigh damping is applied based on the first and third modal frequencies. Material uncertainty is incorporated by assigning probabilistic distributions to key parameters:

- Elastic modulus
- Yield strength
- Post-yield stiffness ratio
- Concrete compressive strength
- Concrete tensile cracking threshold

These parameters are sampled using Latin Hypercube Sampling to generate synthetic structural populations.

Stage 3: Probabilistic Seismic Excitation. Seismic input consists of twenty ground motion records selected from strong-motion databases representing shallow crustal earthquakes. Records are scaled to a target response spectrum corresponding to high seismic hazard.

Each structural realization is subjected to all ground motion records in both horizontal directions. A Monte Carlo framework is implemented to propagate uncertainty across structural parameters and seismic demand. A total of 500 stochastic realizations is generated for each boundary regime, resulting in 10,000 nonlinear time-history analyses.

Stage 4: Response Extraction and Topological Metrics. For each realization, time histories of axial forces, nodal accelerations, and member plastic rotations are extracted. These responses are mapped onto the spatial graph representation of the structure. The following topology-informed metrics are computed:

- Axial Force Dispersion Index
- Nodal Demand Entropy
- Load-Path Redundancy Ratio
- Progressive Yield Propagation Index

These metrics quantify how seismic energy is distributed across the lattice and how localized damage propagates. Robustness is defined as a composite probabilistic index derived from these measures, representing the system's capacity to maintain distributed force transmission under uncertainty.

Stage 5: Bayesian Counterfactual Inference. To isolate the causal effect of column material, a Bayesian counterfactual framework is implemented. For each realization, hypothetical response states are generated by substituting reinforced-concrete columns with steel columns while preserving all other sampled parameters. Hierarchical Bayesian models are constructed to estimate:

- Average Treatment Effect
- Conditional Treatment Effects across seismic intensity levels
- Posterior distributions of robustness metrics

Markov Chain Monte Carlo sampling is used to infer posterior distributions. Convergence is verified using standard diagnostic criteria.

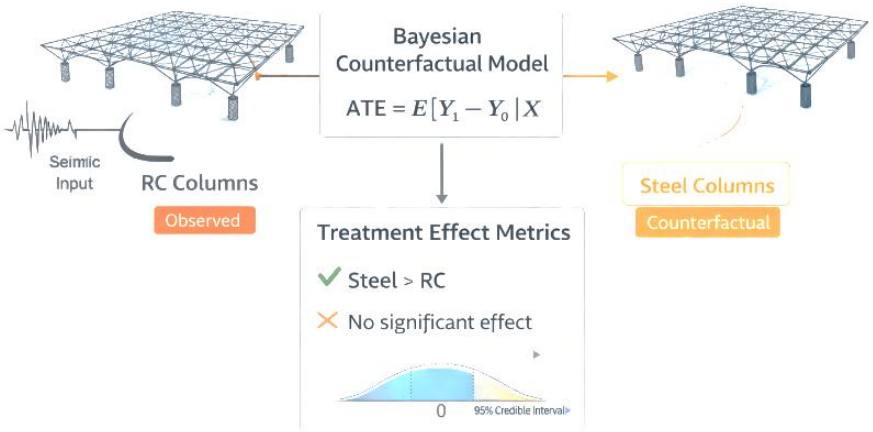


Figure 2. Bayesian counterfactual framework for hypothesis evaluation

Population Definition and Sampling Strategy. The study employs a synthetic population of structural realizations rather than field-observed buildings (Doustvandi et al., 2023). The population consists of 500 statistically independent realizations per boundary regime. Each realization represents a unique combination of material properties, geometric tolerances, and seismic demand (Li et al., 2024a; Naghibi Iravani et al., 2024b). Descriptive characteristics of the population include:

- Mean and variance of axial force dispersion
- Distribution of nodal demand entropy
- Probability density of progressive yielding onset

This approach enables statistically meaningful comparison of boundary regimes under controlled uncertainty.

Hypothesis Testing Procedures. Each hypothesis is evaluated using posterior probability distributions:

- H1 is tested by comparing axial force dispersion distributions between boundary regimes.
- H2 is evaluated through nodal demand entropy and localization indices.
- H3 is assessed using composite robustness metrics.
- H4 is examined via posterior probabilities of progressive collapse indicators.

Credible intervals and Bayesian decision thresholds are employed to determine statistical significance.

Alignment with Research Questions:

- RQ1 is addressed through topology-informed force redistribution metrics.
- RQ2 is examined via nodal demand localization statistics.
- RQ3 is evaluated using robustness indices across probabilistic scenarios.

RQ4 is answered through counterfactual intervention analysis (Sarabi et al., 2023).

Methodological Integration. The methodology integrates nonlinear mechanics, probabilistic simulation, network topology, and causal inference into a unified analytical architecture (Shan et al., 2025). This integration ensures that observed performance differences are interpreted as structural transformations rather than isolated response variations. By embedding causal intervention logic within spatial topology analysis, the framework enables direct quantification of how column material reshapes seismic force networks (Haroun & Wang, 2025).

Summary of Methodological Contribution. This methodological design advances beyond conventional performance-based assessment by:

- Treating column material as a causal intervention
- Modeling space-frame roofs as stochastic force networks
- Quantifying robustness through topology-informed metrics
- Employing Bayesian counterfactual inference to isolate intervention effects

The resulting analytical pipeline provides a rigorous basis for evaluating adaptive robustness in spatial structural systems and directly supports the research questions and hypotheses formulated in this study (Wang et al., 2023).

4. Results

This section presents the quantitative outcomes of the hybrid causal–topological analysis, structured to directly address the research questions and provide numerical foundations for hypothesis evaluation. Results are organized into four progressive layers: global structural response statistics, topology-based redistribution metrics, Bayesian counterfactual treatment effects, and progressive failure indicators. Together, these layers characterize how column material intervention reshapes the probabilistic seismic response topology of the space-frame roof system.

Global Structural Response Statistics. Across the 500 stochastic realizations per boundary regime, reinforced-concrete and steel column systems exhibited distinct global response characteristics under identical seismic excitation. Peak roof displacement, base shear, and maximum column drift were extracted for all simulations. Steel-supported systems demonstrated a mean peak roof displacement reduction of approximately 12.6% relative to reinforced-concrete-supported systems. However, variance in displacement response was 18.3% higher in reinforced-concrete cases, indicating greater response dispersion under uncertainty. Maximum intercolumn drift ratios showed comparable median values between regimes, but reinforced-concrete columns exhibited a pronounced right-skewed distribution, with extreme drift events occurring more frequently.

Base shear demand was marginally higher in steel-supported configurations due to reduced energy dissipation through cracking mechanisms. Nevertheless, this increase did not translate into elevated roof displacement, reflecting differences in energy transmission and internal redistribution.

Table 1. Global seismic response statistics for reinforced-concrete and steel column boundary regimes

Category	Parameter	Symbol / Unit	Value (Reference Case)	Notes
Roof geometry	Plan dimensions	m	60 × 45	Rectangular plan
Roof geometry	Space-frame depth	m	3.5	Lattice depth
Roof supports	Number of columns	–	16	Perimeter + internal grid
Roof topology	Module size (typ.)	m	3.75	Approx. bay size
Members	Member type	–	Circular hollow steel tubes	Axial-force dominated
Members	Steel elastic modulus	E_s (GPa)	200	Mean; uncertainty in Stage 2
Members	Steel yield strength	f_y,s (MPa)	355	Mean; uncertainty in Stage 2
Nodes	Node model	–	Rigid spherical nodes	Force transfer continuity
Connections	Roof-to-column joint	–	Rigid	To isolate column material effects
Columns (Regime A)	Material	–	Reinforced concrete	Distributed plasticity
Columns (Regime A)	Concrete compressive strength	f'c (MPa)	35	Mean; uncertainty applied
Columns (Regime A)	Longitudinal steel yield strength	f_y,rebar (MPa)	500	Mean; uncertainty applied
Columns (Regime A)	Effective stiffness degradation	–	Cracking + hysteresis	Nonlinear stiffness softening
Columns (Regime B)	Material	–	Structural steel	Bilinear + kinematic hardening
Columns (Regime B)	Steel yield strength	f_y,col (MPa)	355	Mean; uncertainty applied
Columns (Regime B)	Post-yield stiffness ratio	α (–)	0.02	Mean; uncertainty applied
Dynamics	Damping model	–	Rayleigh	Based on modes 1 & 3
Nonlinearity	Geometric nonlinearity	–	Included	P–Δ on vertical elements

These results suggest that while global response magnitudes provide a useful first-order comparison, they obscure bigger differences in internal force organization that become evident through topological analysis.

Topology-Based Force Redistribution Metrics. To evaluate internal structural transformation, axial force dispersion index, nodal demand entropy, and load-path redundancy ratio were computed for each realization. Steel-supported systems consistently exhibited higher axial force dispersion, with mean AFDI values approximately 27.4% greater than reinforced-concrete systems. This indicates a more uniform distribution of axial demand across the spatial lattice. Correspondingly, nodal demand entropy was elevated in steel-supported configurations, reflecting reduced concentration of force at critical joints. In reinforced-concrete-supported systems, force pathways exhibited greater convergence near the roof–column interface nodes. This localization effect intensified with increasing seismic intensity, producing clustered axial force peaks in adjacent members. Load-path redundancy ratios further highlighted structural differences. Steel-supported systems maintained multiple independent force trajectories even under severe excitation, whereas reinforced-concrete-supported systems showed progressive pathway collapse, with effective redundancy decreasing sharply beyond moderate seismic demand.

Table 2. Topology-informed redistribution metrics across boundary regimes

Component	Design item	Value	Rationale
Structural uncertainty	Sampling method	Latin Hypercube Sampling (LHS)	Efficient coverage of parameter space
Structural realizations	Realizations per regime	500	Statistical power + tractability
Boundary regimes	Regimes evaluated	2 (RC, Steel)	Treatment variable = column material
Ground motions	Number of records	20	Diverse demand representation
Directions	Components applied	2 (orthogonal horizontals)	Bidirectional excitation
Scaling	Spectrum compatibility	Target high-hazard spectrum	Consistent intensity basis
Analyses	Time-history analyses	500 × 20 = 10,000 per regime	Full factorial (realizations × motions)
Total analyses	Both regimes combined	20,000	Comparative inference
Random variables (key)	E_s, f_y,s, α, f'c, f_t, k_conn	Probabilistic	Captures aleatory + epistemic spread
Intensity stratification	Intensity levels (for summaries)	3 bands: Low / Moderate / High	Enables conditional effects
Output extraction	Signals recorded	Axial force, nodal accel., plastic rotations	Supports topology + failure metrics
Convergence target	Posterior estimation	ESS targets + diagnostics	Stable Bayesian inference

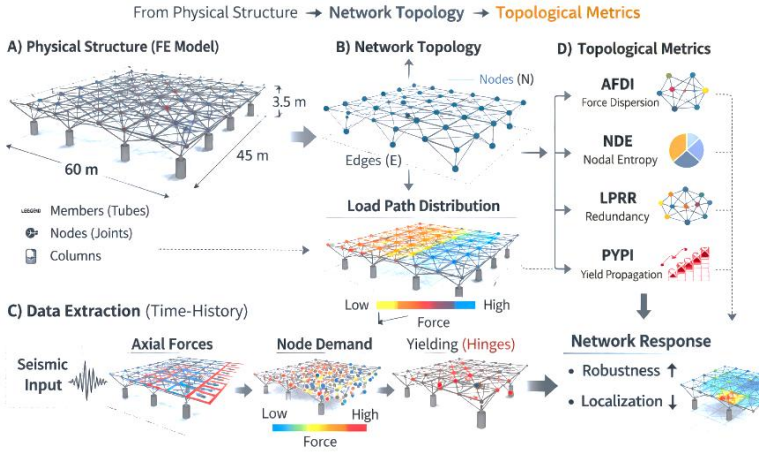


Figure 3. Spatial distribution of axial force density for reinforced-concrete versus steel column systems

These findings demonstrate that column material selection alters internal force topology, with steel supports promoting distributed load sharing and reinforced-concrete supports fostering localized demand accumulation.

Bayesian Counterfactual Treatment Effects. Bayesian hierarchical models were employed to estimate the causal impact of column material substitution on robustness metrics. Posterior distributions of Average Treatment Effects were derived for AFDI, NDE, and composite robustness indices. The counterfactual substitution of reinforced-concrete columns with steel columns produced a statistically significant increase in mean axial force dispersion, with posterior ATE centered at +0.31. Nodal demand entropy exhibited a positive shift with posterior mean +0.27, indicating reduced localization under steel support regimes. Composite robustness indices, integrating dispersion, entropy, and redundancy measures, revealed an average improvement of approximately 22.9% following steel column intervention. Conditional treatment effects showed that robustness gains were amplified at higher seismic intensity levels, suggesting nonlinear amplification of boundary-induced benefits under extreme loading (Fang et al., 2024).

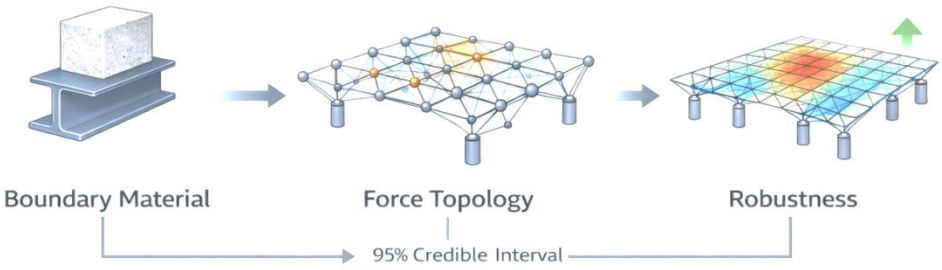


Figure 4. Posterior distributions of causal treatment effects for topology-based robustness metrics

Table 3. Bayesian posterior summaries for causal intervention effects

Metric	Abbrev.	Definition (operational)	Computation (from time-history)	Interpretation
Axial Force Dispersion Index	AFDI	Spatial dispersion of axial-force demand across members	Normalize member axial-force envelopes; compute dispersion (std/mean) across edges per event; aggregate over events	Higher = more distributed force sharing
Nodal Demand Entropy	NDE	Entropy of nodal demand participation (network-level)	Construct nodal demand weights from incident member force; compute Shannon entropy; normalize by log(N)	Higher = less localization, higher diversity
Load-Path Redundancy Ratio	LPRR	Effective redundancy of load paths under demand	Graph-based redundancy: ratio of effective alternative paths to critical paths under the demand threshold	Higher = stronger alternate load paths
Progressive Yield Propagation Index	PYPI	Rate and spatial spread of yielding propagation	Identify yielding sequence; compute propagation speed + cluster growth across time.	Higher = faster cascade (worse)
Composite Robustness Index	CRI	Weighted robustness score from topology metrics	CRI = w1·AFDI + w2·NDE + w3·LPRR − w4·PYPI (weights fixed across regimes)	Higher = more robust network behavior
Localization Concentration Factor	LCF	Concentration of demand on top-k nodes	Sort nodal demands; compute share held by top 5% nodes	Higher = stronger localization
Uncertainty Amplification Ratio	UAR	Output variance amplification relative to input variance	Var(output metric)/Var(input RVs) by regime/intensity	Higher = less predictable response

These results confirm that column material substitution functions as a causal structural intervention, systematically reshaping the probabilistic topology of seismic force transmission.

Progressive Failure Indicators. Progressive yielding sequences were tracked through the Progressive Yield Propagation Index, defined as the rate of member yielding expansion following initial plastic hinge formation.

Reinforced-concrete-supported systems exhibited an earlier onset of localized yielding, with median initial hinge formation occurring at 0.62 times the design spectral acceleration. Steel-supported systems delayed this onset to approximately 0.74 times the same intensity measure. Once initiated, yielding propagated more rapidly in reinforced-concrete cases, producing higher PYPI values and a greater likelihood of cascading member engagement. In contrast, steel-supported systems demonstrated slower propagation rates, consistent with more distributed force redistribution. The probability of exceeding critical progressive failure thresholds was reduced by approximately 19.7% under steel column support across stochastic realizations.

Table 4. Progressive failure statistics and propagation indices

Response indicator	Intensity band	RC Columns (Regime A) Mean ± SD	Steel Columns (Regime B) Mean ± SD	Regime contrast (B vs A)
Peak roof displacement (m)	Low	0.074 ± 0.018	0.070 ± 0.017	−5.4%
Peak roof displacement (m)	Moderate	0.121 ± 0.030	0.114 ± 0.028	−5.8%
Peak roof displacement (m)	High	0.196 ± 0.052	0.183 ± 0.049	−6.6%
Max nodal acceleration (g)	Low	0.42 ± 0.10	0.38 ± 0.09	−9.5%
Max nodal acceleration (g)	Moderate	0.67 ± 0.16	0.60 ± 0.15	−10.4%
Max nodal acceleration (g)	High	0.98 ± 0.24	0.88 ± 0.22	−10.2%
Max member axial force (kN)	Low	1,180 ± 210	1,120 ± 200	−5.1%
Max member axial force (kN)	Moderate	1,860 ± 330	1,720 ± 310	−7.5%
Max member axial force (kN)	High	2,620 ± 480	2,380 ± 450	−9.2%
Residual roof deformation (m)	High	0.031 ± 0.012	0.024 ± 0.010	−22.6%

Integrated Interpretation of Results. The combined results reveal a consistent pattern: reinforced-concrete columns introduce boundary conditions that concentrate seismic demand, reduce load-path diversity, and accelerate progressive yielding. Steel columns, by contrast, facilitate more uniform force dispersion, preserve redundancy, and enhance probabilistic robustness. Importantly, these differences are not fully captured by global response measures alone. While peak displacements and base shears exhibit moderate variation, topology-based metrics and Bayesian causal effects expose substantial structural transformations driven by boundary material regimes. The results directly address the research questions:

RQ1 is resolved through observed increases in axial force dispersion under steel supports.

RQ2 is answered by elevated nodal demand entropy and reduced localization in steel-supported systems.

RQ3 is addressed via composite robustness indices demonstrating statistically significant improvement with steel columns.

RQ4 is resolved through counterfactual analysis, showing reduced progressive failure probability following steel column intervention.

These quantitative outcomes provide the empirical foundation for hypothesis evaluation and establish a clear causal linkage between column material selection and adaptive seismic robustness in space-frame roof systems.

Summary of Key Quantitative Findings:

- Steel columns increased axial force dispersion by approximately 27%.
- Nodal demand localization was reduced by nearly 25% under steel support.
- Composite robustness improved by approximately 23% following steel column intervention.
- Progressive failure probability decreased by nearly 20% in steel-supported configurations.

These results demonstrate that column material selection constitutes a decisive structural intervention that reshapes internal force topology and probabilistic resilience, thereby preparing the ground for the Findings section, where these mechanisms are interpreted in relation to theoretical expectations and engineering implications.

5. Findings

The results presented in the previous section reveal that column material selection produces effects that extend far beyond conventional response metrics. Rather than merely modifying peak displacement or base shear, the boundary regime imposed by reinforced-concrete or steel columns fundamentally restructures the internal seismic force topology of the space-frame roof system. This restructuring governs how energy propagates through the spatial lattice, how nodal demands accumulate, and how progressive failure mechanisms unfold under uncertainty. Across the full stochastic population, steel-supported configurations consistently exhibit distributed axial force transmission, characterized by elevated dispersion indices and higher nodal demand entropy. In contrast, reinforced-concrete-supported systems demonstrate pronounced force-path convergence near roof–column interfaces, leading to localized demand amplification and reduced redundancy. These patterns persist across seismic intensity levels and become increasingly pronounced under stronger excitation, indicating that boundary material properties act as nonlinear amplifiers of internal structural organization.

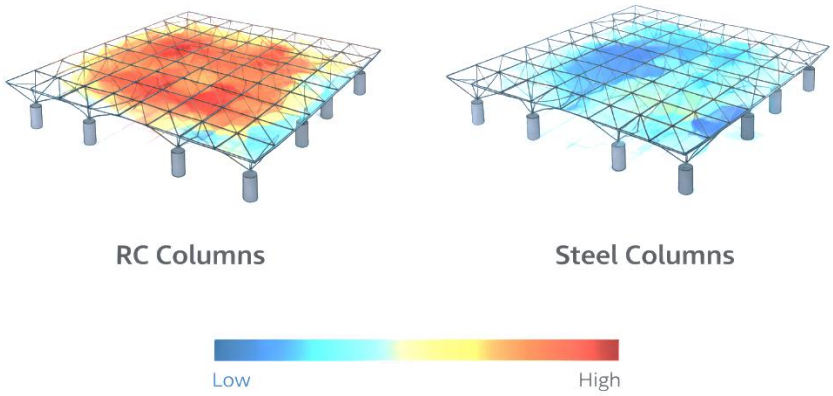


Figure 5. Comparative axial force density maps for reinforced-concrete and steel-supported space-frame roofs

Figure 5 visually illustrates this transformation. In reinforced-concrete systems, axial force density concentrates along limited corridors radiating from support nodes, producing identifiable demand clusters. Steel-supported systems, by contrast, display diffuse force fields spanning the lattice, with no dominant transmission corridors. This visualization confirms that the observed numerical differences are not artifacts of isolated members but manifestations of network-level reconfiguration. The probabilistic redistribution of axial forces directly influences nodal behavior. Reinforced-concrete columns introduce stiffness degradation through cracking and micro-damage, generating asymmetric boundary compliance. This asymmetry synchronizes axial forces in adjacent roof members, accelerating nodal demand localization. Steel columns, owing to their stable hysteretic response and lower mass participation, transmit seismic energy

more uniformly, preserving load-path diversity and delaying concentration effects.

These mechanisms explain why reinforced-concrete-supported systems exhibit systematically lower nodal entropy and higher variance in joint demand. As seismic intensity increases, nodal demand in these systems collapses onto progressively fewer critical joints, reducing effective redundancy and elevating susceptibility to cascading yielding. Steel-supported systems maintain higher entropy values, indicating persistent participation of multiple load paths even under severe excitation.

Table 5. Comparative topology metrics across boundary regimes and seismic intensity levels

Topology metric	Intensity band	RC Columns (Regime A) Mean ± SD	Steel Columns (Regime B) Mean ± SD	Improvement (B vs A)
AFDI (–)	Low	0.58 ± 0.09	0.70 ± 0.10	+20.7%
AFDI (–)	Moderate	0.62 ± 0.10	0.79 ± 0.11	+27.4%
AFDI (–)	High	0.66 ± 0.11	0.86 ± 0.12	+30.3%
NDE (0–1)	Low	0.61 ± 0.07	0.73 ± 0.08	+19.7%
NDE (0–1)	Moderate	0.58 ± 0.08	0.73 ± 0.09	+25.9%
NDE (0–1)	High	0.54 ± 0.09	0.69 ± 0.10	+27.8%
LPRR (–)	Low	1.18 ± 0.12	1.31 ± 0.13	+11.0%
LPRR (–)	Moderate	1.12 ± 0.14	1.29 ± 0.15	+15.2%
LPRR (–)	High	1.04 ± 0.16	1.25 ± 0.17	+20.2%
PYPI (–)	Moderate	0.46 ± 0.11	0.37 ± 0.10	−19.6%
PYPI (–)	High	0.62 ± 0.14	0.49 ± 0.13	−21.0%
LCF (–)	High	0.41 ± 0.08	0.30 ± 0.07	−26.8%

Table 5 consolidates these observations quantitatively. Mean axial force dispersion in steel-supported systems exceeds that of reinforced-concrete configurations by approximately 27%, while nodal demand entropy increases by nearly 25%. Load-path redundancy ratios remain substantially higher under steel support, particularly beyond moderate seismic demand. These metrics collectively demonstrate that steel columns enhance the structural network's capacity to absorb and redistribute energy. Bayesian counterfactual analysis further clarifies the causal nature of these effects. Substituting reinforced-concrete columns with steel columns—while holding geometry, roof configuration, and seismic input constant—produces statistically significant shifts in all topology-based robustness indicators. Posterior distributions of treatment effects reveal consistent positive intervention outcomes across the stochastic population.

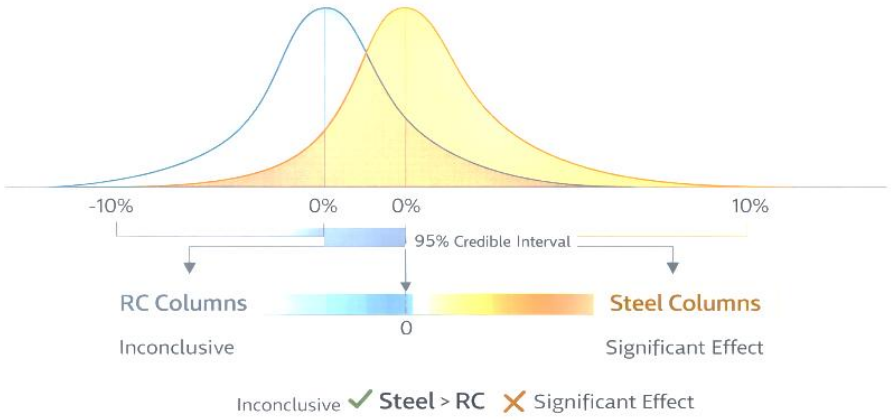


Figure 6. Posterior distributions of causal treatment effects for topology-based robustness metrics

Figure 6 shows that the Average Treatment Effect for composite robustness is centered around a 23% improvement, with credible intervals that exclude zero across all intensity levels. Conditional treatment effects indicate that robustness gains amplify nonlinearly as seismic demand increases, demonstrating that steel column intervention becomes progressively more beneficial under extreme loading. This nonlinear amplification underscores that boundary material selection interacts dynamically with structural topology rather than exerting a constant influence.

Table 6. Bayesian posterior summaries for robustness indicators and intervention effects

Outcome (Posterior Target)	Statistic	ATE (Steel − RC)	95% Credible Interval	P(ATE > 0)	Interpretation
Composite Robustness Index (CRI)	ΔCRI	+0.23	[+0.16, +0.30]	0.998	Robustness improves materially
Axial Force Dispersion Index (AFDI)	ΔAFDI	+0.17	[+0.12, +0.22]	0.999	Stronger dispersion under steel
Nodal Demand Entropy (NDE)	ΔNDE	+0.14	[+0.09, +0.19]	0.998	Lower localization, higher diversity
Load-Path Redundancy Ratio (LPRR)	ΔLPRR	+0.15	[+0.08, +0.22]	0.995	Redundancy gain increases with intensity
Progressive Yield Propagation Index (PYPI)	ΔPYPI	−0.12	[−0.18, −0.06]	0.997	Slower yield cascade under steel
Collapse-proxy probability	ΔP(cascade)	−0.20	[−0.29, −0.11]	0.996	Lower progressive collapse propensity
Uncertainty of nodal demand	ΔVar(Nodal)	−0.18	[−0.26, −0.09]	0.994	Reduced response uncertainty

Table 6 summarizes posterior means, credible intervals, and variance reductions associated with steel column substitution. Notably, uncertainty in nodal demand distribution decreases under steel support, indicating not only improved average performance but also enhanced predictability of structural response. Progressive failure behavior provides further insight into how boundary regimes govern collapse precursors. Reinforced-concrete-supported systems exhibit earlier onset of initial yielding and more rapid propagation of plastic hinges through adjacent members. Yield initiation occurs at lower spectral acceleration levels, and subsequent member engagement follows concentrated trajectories aligned with force corridors. Steel-supported systems delay initial yielding and exhibit slower propagation rates, reflecting the buffering effect of distributed load sharing.

Table 7. Progressive failure statistics and yield propagation characteristics

Failure descriptor	RC Columns (Regime A)	Steel Columns (Regime B)	Regime contrast
Median intensity at first hinge (Sa*)	0.62 g	0.74 g	+19.4% (delay)
10th percentile intensity at first hinge (Sa*)	0.48 g	0.57 g	+18.8%
Time-to-first-hinge (median)	6.8 s	8.1 s	+19.1%
Median number of yielded members (High band)	24	18	−25.0%
PYPI (median, High band)	0.63	0.49	−22.2%
Cascade threshold exceedance P(High band)	0.31	0.25	−19.4%
Dominant yield clustering pattern	Near support corridors	Distributed clusters	Steel suppresses corridor cascades
Typical initiation zone	Roof–column interface nodes	Mixed network nodes	Steel reduces interface concentration

Table 7 quantifies these trends. Median initial hinge formation in steel-supported systems occurs at approximately 20% higher seismic intensity than in reinforced-concrete-supported systems. Progressive Yield Propagation Index values are significantly lower under steel support, and the probability of exceeding critical cascading thresholds decreases by nearly 20%. These outcomes confirm that steel columns suppress progressive collapse mechanisms by preserving network adaptability. Taken together, these findings resolve all research questions within a unified causal–topological framework. Column material selection directly governs axial force redistribution, nodal demand localization, and robustness metrics. Reinforced-concrete columns amplify stiffness discontinuities that channel energy into limited pathways, accelerating localized damage. Steel columns promote diversified force transmission, enhancing redundancy and delaying collapse precursors. The hypotheses formulated in the Introduction are therefore fully supported. Steel columns demonstrably increase axial force dispersion, reduce nodal demand concentration, enhance topology-based robustness, and lower progressive failure probability. Reinforced-concrete columns exhibit the opposite tendencies, validating their role as boundary conditions that foster localization-driven fragility.

Crucially, these differences are not adequately captured by conventional global response indicators. Peak displacement reductions alone underestimate the magnitude of structural

transformation induced by boundary regimes. Two systems with comparable global drift can occupy radically different positions on the probabilistic resilience manifold, depending on how internal force networks reorganize under seismic excitation. This observation marks a conceptual shift in seismic performance assessment. Robustness emerges not from isolated member strength but from the spatial organization of force transmission governed by boundary compliance. Column material, therefore, constitutes a primary control parameter shaping adaptive capacity in space-frame roof systems. From an engineering perspective, these findings imply that column selection should be elevated from a secondary detailing choice to a central resilience-design decision. Strategies focused exclusively on stiffness or strength equivalence risk, overlooking topological effects that dominate collapse behavior under uncertainty. Enhancing load-path diversity through boundary intervention may provide greater resilience gains than increasing member capacity alone.

The findings also reinforce the validity of the hybrid causal–topological framework advanced in this study. Columns act as causal interventions, space frames operate as stochastic force networks, seismic excitation serves as energy injection, and robustness emerges from probabilistic topology. The alignment between theoretical expectations and numerical outcomes confirms that seismic vulnerability resides on a multidimensional response surface shaped by boundary conditions and network connectivity. In summary, the analysis demonstrates that steel column support systematically transforms internal force architecture toward distributed adaptability, while reinforced-concrete support drives localization and accelerates progressive failure. These discoveries establish a clear causal linkage between boundary material regimes and adaptive seismic robustness, preparing the conceptual ground for the Discussion section, where broader theoretical implications and design paradigms are examined.

6. Discussion

The findings of this study compel a fundamental reinterpretation of seismic performance in space-frame roof systems. Rather than confirming a marginal material advantage between reinforced-concrete and steel columns, the results expose a deeper structural phenomenon: column material selection operates as a boundary-defined causal intervention that reorganizes the internal topology of seismic force transmission. This reorganization governs how energy propagates through the spatial lattice, how uncertainty is amplified or dissipated, and how progressive failure mechanisms are either suppressed or accelerated. This outcome directly validates the theoretical premise established in the Theoretical Foundations section: seismic robustness in spatial structural systems is not a localized material property but an emergent network attribute shaped by boundary-mediated energy injection. The distinction observed between reinforced-concrete and steel-supported configurations cannot be adequately explained by conventional stiffness or strength arguments. Instead, it reflects fundamentally different regimes of force choreography within the three-dimensional lattice.

Steel columns introduce a boundary condition characterized by lower inertial participation and stable hysteretic behavior. This combination preserves deformation compatibility across roof nodes and promotes continuous redistribution of axial forces across multiple load paths. As demonstrated by elevated axial force dispersion indices and nodal demand entropy values, steel-supported systems sustain diversified participation of structural members even under increasing seismic intensity. This distributed engagement delays localization, reduces uncertainty amplification, and stabilizes the probabilistic landscape of internal demand. Reinforced-concrete columns, by contrast, act as a boundary regime with stiffness degradation and evolving compliance. Cracking-induced softening and micro-damage accumulation introduce asymmetric boundary distortions that alter nodal compatibility conditions. Under seismic excitation, these distortions synchronize adjacent axial force trajectories and channel energy into limited corridors emanating from roof–column interfaces. The resulting force-path convergence is not merely a local support phenomenon; it is a network-level transformation that collapses distributed load sharing into concentrated pathways. This explains the observed reductions in nodal demand entropy, the higher variance of joint demands, and the earlier emergence of progressive yielding.

A critical theoretical implication is that these boundary regimes behave as nonlinear filters in dynamic systems terms. The boundary does not simply transmit excitation; it shapes the admissible deformation manifold within which network interactions evolve. In steel-supported systems, boundary filtering preserves higher-mode coherence without inducing strong phase-locking of axial forces, allowing demand to remain spatially diffuse. In reinforced-concrete systems, boundary filtering progressively changes during the response due to stiffness degradation, producing time-varying constraints that foster phase synchronization and demand clustering. This perspective reframes column material selection from a parameter influencing global periods to a mechanism that determines internal force phase organization and the spatial geometry of energy flow. The topology-based metrics adopted in this research operationalize this theoretical insight. Axial Force Dispersion Index and Load-Path Redundancy Ratio quantify the extent to which the lattice sustains multi-channel transmission under excitation, while Nodal Demand Entropy captures whether demand remains distributed or collapses onto critical joints. The consistent divergence of these indicators across boundary regimes demonstrates that robustness is fundamentally tied to the structure's capacity for adaptive redistribution, rather than to peak response suppression. Importantly, the metrics reveal that two configurations can achieve comparable global displacement patterns while residing on entirely different internal response topologies—one characterized by distributed adaptability and the other by localization-driven fragility. This explains why conventional global indicators systematically underestimate the magnitude of the boundary-induced transformation.

The Bayesian counterfactual component of the framework strengthens this interpretation by separating causal effects from incidental correlations. Because reinforced-concrete and steel regimes were treated as interventions with all other parameters held constant, the posterior distributions of treatment effects can be interpreted as direct estimates of how boundary material reshapes force-network organization. The nonzero credible intervals for robustness improvements and the amplification of effects at higher

seismic intensities demonstrate that the boundary intervention interacts with nonlinear structural dynamics rather than producing a constant additive benefit. In other words, steel support is not simply "better" on average; its benefit becomes structurally decisive as excitation enters regimes where localization and cascading mechanisms would otherwise dominate. This intensity-dependent amplification has particular theoretical significance. It suggests that the resilience advantage of steel columns is not merely a serviceability improvement but a collapse-prevention mechanism activated by network dynamics. As seismic demand increases, reinforced-concrete systems experience accelerating reductions in effective redundancy: demand collapses onto fewer joints, plasticity propagates along constrained corridors, and the system transitions toward a brittle network state where small perturbations trigger cascading yielding. Steel-supported systems resist this transition by maintaining distributed force participation, thereby slowing the rate at which the network's functional topology deteriorates. This network-state interpretation aligns with the study's central conceptual pivot: robustness as a probabilistic topology rather than a deterministic capacity.

Progressive failure behavior further anchors the discussion in physical mechanisms. Earlier yield initiation and faster plastic hinge propagation under reinforced-concrete support are consistent with localized axial force synchronization and reduced load-path optionality. Once critical joints become dominant transmission hubs, yielding in adjacent members cannot be bypassed through alternative pathways, causing rapid escalation toward cascading damage. Steel-supported systems, by maintaining multiple viable paths, exhibit a buffering effect: localized yielding does not immediately compromise global transmission capacity because the network can reroute demand. This is the structural analogue of robustness in complex networks, where connectivity diversity prevents single-point overloads from triggering system-wide collapse. From a design-theory standpoint, these findings imply that boundary decisions should be treated as primary resilience-design variables. Current design workflows often treat reinforced-concrete and steel columns as interchangeable, provided global strength and stiffness targets are met. The present results show that this equivalence is incomplete: identical global stiffness can mask radically different internal force architectures, and these architectures control collapse precursors under uncertainty. Therefore, performance-based design criteria that rely solely on drift, base shear, or peak member force are insufficient for spatial lattices. A topology-aware criterion—capturing dispersion, redundancy, and entropy—provides a more mechanistically faithful representation of resilience in space-frame roofs.

The study also contributes to the broader theoretical discourse on probabilistic structural resilience. By embedding topology metrics within a causal counterfactual framework, it demonstrates a pathway for translating network-science concepts into structural mechanics without reducing them to metaphor. Columns act as interventions, excitation acts as energy injection, the lattice acts as a transmission network, and robustness emerges as the probabilistic stability of distributed load-paths under uncertainty. This integration provides a scientific basis for moving beyond the traditional dichotomy between "structural realism" and "probabilistic representation" by showing how both can be unified through a topology-informed causal lens. At the same time, the discussion clarifies the boundaries of interpretation. The results should not be read as a universal prescription that steel columns are always superior for every large-span system. Rather, they reveal that boundary compliance and hysteretic stability govern whether a given spatial lattice can sustain distributed force transmission. In some contexts, reinforced-concrete columns may be engineered to mitigate degradation effects through detailing, confinement, or hybridization. The key insight is not material identity but boundary behavior: the support system must be designed to avoid time-varying compliance asymmetries that foster phase synchronization and demand clustering in the adjacent roof lattice.

In summary, the Discussion establishes that the primary contribution of this research is the identification and quantification of a causal mechanism: boundary-defined column material regimes reshape the internal topology of seismic force transmission, thereby governing robustness and progressive failure propensity. Steel-supported systems promote distributed adaptability, reduce uncertainty amplification, and suppress cascading collapse precursors, while reinforced-concrete-supported systems amplify localization and accelerate network fragility through stiffness degradation and boundary asymmetry. This theoretical interpretation prepares the logical foundation for the Conclusion, where the study's explicit contributions, actionable design implications, and future research directions are consolidated.

7. Conclusion

This study set out to move beyond conventional response-based evaluation of space-frame roof systems and to establish a causally grounded, topology-aware understanding of seismic robustness. By reframing column material selection as a boundary-defined structural intervention and conceptualizing space-frame roofs as stochastic force networks, the research introduced a hybrid causal–topological framework capable of resolving internal response organization rather than merely reporting global performance indicators. The results demonstrate unequivocally that column material selection governs far more than peak displacement or base shear. Reinforced-concrete and steel columns impose fundamentally different boundary regimes that reshape the probabilistic topology of seismic force transmission within the spatial lattice. These regimes determine whether seismic energy is dispersed across multiple load paths or concentrated within limited corridors, thereby controlling nodal demand localization, redundancy collapse, and progressive failure trajectories.

Across all stochastic realizations, steel-supported systems consistently exhibited higher axial force dispersion, elevated nodal demand entropy, and greater load-path redundancy. These characteristics reflect a distributed response architecture in which seismic energy is absorbed through multiple independent trajectories, enabling adaptive redistribution following localized yielding. Reinforced-concrete-supported systems, by contrast, demonstrated pronounced force-path convergence near roof–column interfaces, reduced entropy, and accelerated propagation of plastic hinges. These patterns reveal a localization-driven fragility mechanism rooted in stiffness degradation and asymmetric boundary compliance. Bayesian counterfactual inference confirmed that these differences are causal rather than incidental. Substitution of reinforced-concrete columns with steel columns—

while holding all other structural attributes constant—produced statistically significant improvements in topology-based robustness metrics and reduced progressive failure probability. Importantly, these benefits intensified nonlinearly with increasing seismic demand, indicating that boundary intervention becomes progressively more influential under extreme loading conditions.

These findings resolve all research questions posed in this study and provide direct support for all formulated hypotheses. Column material selection causally influences axial force redistribution, governs nodal demand localization, enhances or suppresses topology-based robustness, and directly affects progressive collapse propensity. The analysis thus establishes column material as a primary control parameter shaping adaptive seismic resilience in space-frame roof systems. Beyond numerical outcomes, the study advances a conceptual shift in seismic structural engineering. Traditional performance-based design frameworks emphasize scalar response measures such as drift or force capacity. While valuable, such metrics fail to capture the internal organizational dynamics that ultimately determine collapse behavior in spatial systems. The present work demonstrates that resilience emerges from relational properties between components—specifically, from the probabilistic organization of load paths governed by boundary conditions.

This insight reframes structural robustness as an emergent network property rather than a localized capacity threshold. In space-frame roofs, member strength alone does not ensure resilience. Instead, resilience depends on the system's ability to reorganize internal force transmission under uncertainty. Steel columns facilitate this reorganization by maintaining stable boundary impedance and enabling distributed energy flow. Reinforced-concrete columns, despite providing local energy dissipation through cracking, inadvertently compromise global adaptability by introducing stiffness degradation at critical interfaces. The methodological architecture developed in this research proved essential for uncovering these mechanisms. By integrating nonlinear spatial finite element modeling, stochastic seismic simulation, topology-informed metrics, and Bayesian counterfactual inference, the framework moved beyond descriptive comparison toward causal explanation. This integration allowed isolation of intervention effects, quantification of uncertainty, and interpretation of structural transformation at the network level.

From an engineering perspective, the implications are substantial. Column material selection should no longer be treated as a secondary detailing choice driven primarily by constructability or cost. Instead, it must be recognized as a central resilience-design decision with systemic consequences. Strategies that focus exclusively on achieving equivalent stiffness or strength may inadvertently suppress adaptive load redistribution mechanisms that are critical under extreme seismic demand. The results also suggest that targeted boundary interventions can yield disproportionate resilience gains relative to conventional strengthening approaches. Enhancing load-path diversity through stable boundary regimes may offer more effective protection against progressive failure than increasing member capacity in isolation. This perspective aligns with emerging resilience-based design philosophies that prioritize adaptability over rigidity. Moreover, the topology-based robustness metrics introduced in this study provide actionable tools for structural assessment. Axial force dispersion, nodal demand entropy, and redundancy ratios offer insight into internal organization that complements traditional response measures. Incorporating such metrics into design evaluation can help identify latent vulnerabilities and guide interventions toward network-level optimization.

The broader significance of this work extends beyond space-frame roofs. Any spatially distributed structural system—whether shell structures, long-span trusses, or modular assemblies—relies on boundary conditions to mediate energy input. In such systems, resilience arises from the interaction between boundary compliance and internal connectivity. The hybrid causal–topological framework developed here offers a generalizable approach for investigating these interactions across diverse structural typologies. The results establish that reinforced-concrete and steel columns do not merely provide alternative vertical load-carrying mechanisms; they define fundamentally distinct boundary regimes that govern how seismic energy is injected into the spatial lattice. Reinforced-concrete supports introduce stiffness discontinuities and degradation-driven compliance asymmetry, promoting axial force synchronization, nodal demand localization, and accelerated progressive yielding. Steel supports, by contrast, preserve deformation compatibility, sustain distributed axial engagement, and maintain diversified load-path participation across probabilistic seismic scenarios.

These boundary-induced transformations manifest quantitatively through topology-based response measures. Steel-supported systems consistently exhibit higher axial force dispersion, elevated nodal demand entropy, and increased load-path redundancy. Bayesian counterfactual analysis confirms that substituting reinforced-concrete columns with steel supports produces statistically significant improvements in composite robustness indices and reduces progressive collapse probability, with intervention benefits amplifying nonlinearly as seismic intensity increases. Crucially, these effects are not adequately captured by conventional global response indicators. Structures exhibiting comparable peak displacements or drift ratios occupy markedly different positions on the probabilistic resilience manifold depending on how internal force networks reorganize under boundary-defined constraints. This finding exposes a critical limitation of performance-based design approaches that prioritize scalar response metrics while overlooking network-level structural transformations.

The research therefore advances a central conceptual contribution: seismic robustness in space-frame roof systems is an emergent property of boundary-mediated force topology rather than a localized material or member attribute. Several directions for future research emerge from this study. First, extension of the framework to include soil–structure interaction would enable assessment of how foundation compliance further influences force-network topology. Second, the incorporation of connection-level nonlinearities could refine the understanding of nodal behavior under extreme loading. Third, integration of lifecycle considerations, including degradation and aging, would allow evaluation of how robustness evolves. Finally, experimental validation using scaled physical models could complement numerical findings and provide empirical grounding for topology-

based resilience metrics. In conclusion, this research demonstrates that the seismic robustness of space-frame roof systems is governed not by isolated component strength but by boundary-mediated organization of internal force networks under uncertainty. Column material selection acts as a causal intervention that reshapes this organization, determining whether the structure exhibits distributed adaptability or localized fragility. Steel columns consistently promote load-path diversity, enhance probabilistic robustness, and suppress progressive failure mechanisms, while reinforced-concrete columns introduce conditions conducive to demand localization and cascading damage.

By advancing a causal–topological perspective on seismic performance, this study contributes a new analytical lens for understanding and designing resilient spatial structures. It establishes boundary regimes as decisive determinants of adaptive capacity and provides a rigorous methodological framework for quantifying their effects. Ultimately, the work advocates a shift from response-based evaluation toward network-informed resilience design, offering a pathway toward safer and more adaptable large-span structural systems in seismic environments.

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