OPEN ACCESS
Journal of Moeslim Research Technik
Vol. 3 No. 1. February 2026, pp. 1-13
DOI. 10.70177/technik.v3i1.3295

Research Article

# REENGINEERING STRUCTURAL RESILIENCE: A MULTISCALE FRAMEWORK FOR PERFORMANCE-BASED INFRASTRUCTURE DESIGN

Edison Hatoguan Manurung[1], M. Alit Suryawan[2], Hotasi Rogate Manurung[3], and Haruto Takahashi[4]
[1] Universitas Mpu Tantular, Indonesia
[2] Politeknik Negeri Ambon, Indonesia
[3] Universitas Mpu Tantular, Indonesia
[4] University of Tokyo, Japan

**Corresponding Author:**

Edison Hatoguan Manurung,
Department of Civil Engineering, Faculty of Engineering, Universitas Mpu Tantular.
Jl.Cipinang Besar 2 Jakarta Timur, Indonesia
Email: edisonmanurung2010@yahoo.com

**Article Info**
Received: August 5, 2025
Revised: November 10, 2025
Accepted: January 14, 2026
Online Version: February 18, 2026

## Abstract

Increasing exposure of infrastructure systems to extreme hazards, aging effects, and climate-induced uncertainties has revealed fundamental limitations of conventional strength- and safety-oriented design approaches. Structural performance can no longer be evaluated solely in terms of damage prevention, but must also account for functionality loss, system interdependencies, and recovery capacity. This study aims to reengineer the concept of structural resilience by developing a multiscale framework that integrates resilience explicitly into performance-based infrastructure design. The research adopts an analytical and framework-oriented methodology, combining critical synthesis of performance-based design theories, structural resilience metrics, and systems engineering concepts. Multiscale linkages are established among component-level behavior, system-level functionality, and network-level performance, with explicit consideration of temporal recovery processes. The results demonstrate that resilience is an emergent and time-dependent system property that cannot be inferred directly from component-level performance indicators. Local strengthening strategies are shown to yield limited resilience gains unless supported by system redundancy, connectivity, and recovery-oriented design. The proposed framework reveals hidden vulnerabilities and recovery bottlenecks that remain unaddressed in conventional performance-based approaches. The study concludes that effective resilience-oriented infrastructure design requires a paradigm shift toward multiscale, system-aware, and recovery-informed performance objectives. Embedding these principles into performance-based design provides a robust foundation for enhancing infrastructure reliability, functionality, and societal resilience under extreme and uncertain conditions.

**Keywords**: Multiscale Analysis, Performance-Based Design, Structural Resilience

| | |
|---|---|
| Journal Homepage | https://research.adra.ac.id/index.php/technik |
| How to cite: | Manurung, E. H., Suryawan, M. A., Manurung, H., R., & Takahashi, H. (2026). Reengineering Structural Resilience: A Multiscale Framework for Performance-Based Infrastructure Design. *Journal of Moeslim Research Technik*, *2*(1), 1–13. https://doi.org/10.70177/technik.v3i1.3295 |
| Published by: | Yayasan Adra Karima Hubbi |

## INTRODUCTION

Infrastructure systems form the physical backbone of modern societies, enabling mobility, economic productivity, and public safety. Increasing exposure to extreme loading conditions, including earthquakes, climate-induced hazards, aging materials, and escalating demand, has challenged conventional structural design philosophies (Almazroui, 2025; Meafa et al., 2024). Traditional approaches emphasizing strength and safety margins often prove insufficient to address the complex, cascading failures observed in recent infrastructure disruptions. These developments have intensified scholarly and professional interest in the concept of structural resilience as a critical performance objective (Alayed & Alateeg, 2025).

Structural resilience extends beyond the prevention of collapse to encompass the ability of systems to absorb disturbances, adapt to damage, and recover functionality within acceptable timeframes. This paradigm shift reflects a growing recognition that infrastructure performance must be evaluated dynamically across multiple stages of hazard impact and recovery (Alqam et al., 2025; Hasan et al., 2024). Performance-based design has emerged as a dominant framework for translating these resilience objectives into quantifiable engineering criteria, linking structural behavior to societal expectations of functionality and service continuity.

Despite advances in performance-based methodologies, resilience remains unevenly defined and operationalized across scales of infrastructure systems (Lu et al., 2023). Structural elements, subsystems, and network-level interactions are frequently addressed in isolation, limiting the ability to capture emergent behaviors under extreme events. This background underscores the need for a reengineered perspective on structural resilience that integrates multiscale performance considerations within a coherent design framework (García-Alcaraz et al., 2025; Massari et al., 2025).

A fundamental problem in current infrastructure design practice lies in the fragmented treatment of resilience across different structural scales. Component-level performance metrics often fail to reflect system-level consequences, while network-level resilience assessments may overlook critical local damage mechanisms. This disconnect hampers the translation of resilience concepts into actionable design strategies and limits the predictive capacity of performance-based approaches (Nath et al., 2025).

Existing performance-based design frameworks primarily focus on meeting predefined limit states under specific hazard scenarios (Mühl et al., 2025). While effective for ensuring life safety and damage control, these frameworks are less equipped to address post-event functionality, recovery trajectories, and interdependencies among structural systems. The absence of explicit multiscale linkage results in resilience assessments that are descriptive rather than prescriptive (Trump et al., 2025).

Another challenge arises from the lack of standardized methodologies for integrating resilience objectives into the early stages of infrastructure design. Resilience considerations are frequently introduced as post-design evaluations rather than as governing design criteria (Liu et al., 2025). This reactive approach constrains innovation in structural form, material selection, and system configuration, thereby limiting the potential to engineer resilience proactively (Essien et al., 2025).

This study aims to develop a multiscale framework for reengineering structural resilience within the context of performance-based infrastructure design. The primary objective is to establish conceptual and analytical linkages between component-level behavior, system-level performance, and network-level resilience outcomes. Such integration seeks to enable more holistic evaluation of infrastructure response under extreme loading conditions (Jantapoon & Saenchaiyathon, 2025; Qureshi et al., 2024).

A further objective is to operationalize resilience as a measurable and design-oriented construct rather than an abstract performance descriptor. The study seeks to identify key performance indicators that capture damage tolerance, functional continuity, and recovery potential across scales. These indicators are intended to align engineering metrics with societal resilience expectations (Guo et al., 2025).

The research also aims to advance methodological clarity in the application of performance-based design to resilience engineering. By synthesizing existing theoretical and computational approaches, the study endeavors to provide designers and researchers with a structured framework that supports decision-making throughout the infrastructure lifecycle. The objectives collectively position the research at the intersection of structural engineering, risk analysis, and systems thinking (Mola & Roffia, 2025).

Current literature on structural resilience exhibits substantial diversity in definitions, metrics, and analytical approaches. Many studies focus on specific hazards or structural typologies, producing valuable but highly contextualized insights (Rastgoo et al., 2024). This specialization has limited the development of generalized frameworks capable of accommodating diverse infrastructure systems and hazard profiles.

Research on performance-based design has progressed significantly in terms of nonlinear analysis, probabilistic assessment, and damage modeling. Nevertheless, these advances often remain confined to component or system-level evaluations without explicit consideration of cross-scale interactions. The lack of integration between micro-scale damage processes and macro-scale resilience outcomes represents a critical gap in the literature (Salvador & Sancho, 2025).

Moreover, existing frameworks rarely address the temporal dimension of resilience in a systematic manner. Recovery processes, adaptive responses, and long-term performance degradation are frequently treated as external to structural design (Nazari-Shirkouhi & Samadi, 2025). This omission restricts the ability of engineers to design infrastructures that not only withstand hazards but also recover efficiently. Addressing these gaps requires a multiscale framework that unifies spatial and temporal dimensions of performance-based resilience (Arij & Areej, 2025; Hudnurkar et al., 2024).

The novelty of this research lies in its explicit integration of multiscale analysis within a performance-based resilience framework. Rather than treating resilience as an aggregate outcome, the study conceptualizes it as an emergent property arising from interactions among structural components, systems, and networks. This perspective enables systematic tracing of how local design decisions influence global resilience performance (Cheng et al., 2025; Gao et al., 2025).

The study is further justified by the increasing demand for infrastructure systems capable of sustaining functionality under uncertain and evolving hazard conditions. Climate change, urban densification, and aging infrastructure necessitate design methodologies that transcend traditional safety-based paradigms. A multiscale resilience framework provides a foundation for incorporating adaptability and recovery considerations into core design logic (Mosca et al., 2025).

The significance of this research extends to both theoretical and practical domains of structural engineering. For scholars, it offers a unifying conceptual structure that bridges fragmented resilience research. For practitioners and policymakers, it provides design-oriented insights that can inform codes, standards, and investment decisions (Moolkham, 2025; Pedroletti, 2025). This justification underscores the importance of reengineering structural resilience as a central objective of performance-based infrastructure design.

## RESEARCH METHOD

### *Research Design*

This study adopts a methodological design grounded in analytical modeling and framework development to investigate structural resilience within performance-based infrastructure design. The research is positioned within a systems-oriented engineering paradigm, integrating structural mechanics, performance-based design theory, and resilience engineering. A multiscale analytical approach is employed to capture interactions between component-level behavior, system-level response, and network-level performance under extreme loading and hazard scenarios (Hussain et al., 2025).

The research design emphasizes theoretical synthesis combined with computational and analytical evaluation. Existing resilience metrics and performance-based design methodologies are critically reviewed and reorganized into a unified conceptual structure. This design allows the study to move beyond isolated performance assessments toward a coherent framework that explicitly links structural response, functionality loss, and recovery capacity across spatial and temporal scales.

The framework development is complemented by illustrative analytical applications to representative infrastructure systems. These applications are used to demonstrate the feasibility and internal consistency of the proposed multiscale approach. The design prioritizes explanatory power and transferability over site-specific calibration, aligning with the study's objective of advancing generalizable resilience-oriented design principles (Li et al., 2024).

### *Research Target/Subject*

The population of this study consists of structural systems and infrastructure typologies commonly addressed in performance-based design and resilience engineering literature. This includes building structures, bridge systems, and critical infrastructure components subjected to seismic, wind, and extreme environmental loads. The population also encompasses existing analytical models, performance metrics, and resilience assessment frameworks documented in peer-reviewed engineering research.

The sample is defined analytically rather than statistically and is selected through purposive criteria based on relevance to multiscale resilience analysis. Representative structural components, subsystems, and simplified network configurations are chosen to illustrate scale-dependent performance behavior. These analytical samples are not intended to represent specific real-world assets but to serve as archetypal cases for methodological demonstration.

Sampling emphasizes structural diversity and functional relevance (Nalluri et al., 2025). Systems exhibiting clear interactions between local damage mechanisms and global performance outcomes are prioritized. This approach ensures that the proposed framework is tested against scenarios where multiscale interactions are most pronounced, supporting robust conceptual validation.

### *Research Procedure*

The research procedure begins with a comprehensive review of structural resilience and performance-based design literature to identify prevailing definitions, metrics, and analytical gaps. Key concepts and performance indicators are extracted and classified according to spatial scale and temporal relevance. This stage establishes the theoretical foundation for framework development (Nguyen Thi et al., 2023).

Framework construction proceeds through iterative synthesis, integrating component-level performance models with system-level functionality and recovery considerations. Analytical relationships are formulated to link damage states to functional loss and recovery trajectories. Representative structural scenarios are then evaluated to test internal coherence and logical consistency of the framework.

The final procedure involves analytical validation through comparative assessment with existing resilience evaluation approaches. The proposed framework is examined for its ability to capture cross-scale interactions and temporal dynamics more explicitly than conventional methods. Findings are refined through sensitivity analysis and conceptual stress-testing to ensure robustness and applicability to diverse infrastructure contexts (Hoque et al., 2025).

### *Instruments, and Data Collection Techniques*

The primary research instrument is a multiscale resilience framework developed through synthesis of performance-based design criteria, resilience metrics, and systems engineering concepts. This framework serves as an analytical tool for mapping relationships between structural demand, damage states, functional loss, and recovery processes across scales. The framework incorporates both deterministic and probabilistic performance indicators.

Supplementary instruments include mathematical formulations, analytical performance functions, and schematic representations of structural systems. These instruments are used to quantify resilience attributes such as robustness, redundancy, rapidity, and recoverability within a performance-based context. Existing engineering models and computational tools are adapted as necessary to support analytical consistency (Zhou et al., 2025).

Conceptual matrices and performance mapping tables are employed to organize and compare multiscale responses. These instruments facilitate systematic interpretation of how local design decisions influence system-wide resilience outcomes. Instrument selection emphasizes transparency, replicability, and alignment with established engineering standards

## RESULTS AND DISCUSSION

The data analyzed in this study consist of secondary analytical sources and synthesized performance indicators derived from peer-reviewed structural engineering literature, resilience assessment frameworks, and documented performance-based design studies. A total of ninety-one sources were examined, including forty-eight journal articles on structural resilience and performance-based design, twenty-six studies on infrastructure recovery and functionality loss, and seventeen analytical frameworks addressing multiscale system behavior. These sources provide quantitative performance metrics, probabilistic damage models, and temporal recovery descriptors relevant to resilience evaluation.

Table 1 summarizes the distribution of analyzed sources according to analytical scale and primary performance focus. The table indicates that most existing studies concentrate on component- and system-level performance, while network-level and recovery-oriented analyses remain comparatively limited. This distribution supports the necessity of a multiscale framework capable of integrating fragmented analytical perspectives.

Table 1. Distribution of Secondary Data Sources by Scale of Analysis

| Scale of Analysis | Number of Sources | Percentage (%) |
|---|---|---|
| Component-Level Performance | 37 | 40.7 |
| System-Level Structural Response | 29 | 31.9 |
| Network-Level Resilience | 15 | 16.5 |
| Recovery and Temporal Performance | 10 | 11.0 |
| **Total** | **91** | **100** |

The predominance of component-level and system-level studies reflects the historical emphasis of structural engineering on localized performance metrics and limit-state design. These data indicate that resilience has often been interpreted as an extension of strength, ductility, and damage control criteria rather than as a holistic system property. Recovery dynamics and interdependencies across scales receive comparatively less analytical attention.

The limited proportion of network-level and temporal studies highlights a methodological imbalance in existing research. Performance degradation over time and cross-system interactions are frequently treated as external considerations rather than integral components of design. This explanation underscores the motivation for restructuring resilience analysis within a unified multiscale framework (Guo & Kuang, 2025; Susitha et al., 2025).

Descriptive analysis reveals consistent patterns in how performance-based design metrics are defined and applied. Structural performance is commonly represented through demand-to-capacity ratios, damage indices, and probabilistic fragility curves. These metrics provide detailed insight into localized behavior but offer limited direct interpretation of functional loss at higher system levels.

The data also show that resilience indicators such as robustness, redundancy, and rapidity are often evaluated independently. Temporal recovery measures are frequently post-processed rather than embedded within design logic. This pattern indicates a conceptual separation between structural response and resilience outcomes in prevailing analytical practices.

Inferential analysis suggests a strong association between the scale of analysis and the perceived effectiveness of resilience strategies. Studies emphasizing component-level strengthening tend to report improved damage control but limited gains in system-wide functional continuity. This inference indicates that localized performance enhancement does not automatically translate into global resilience improvement.

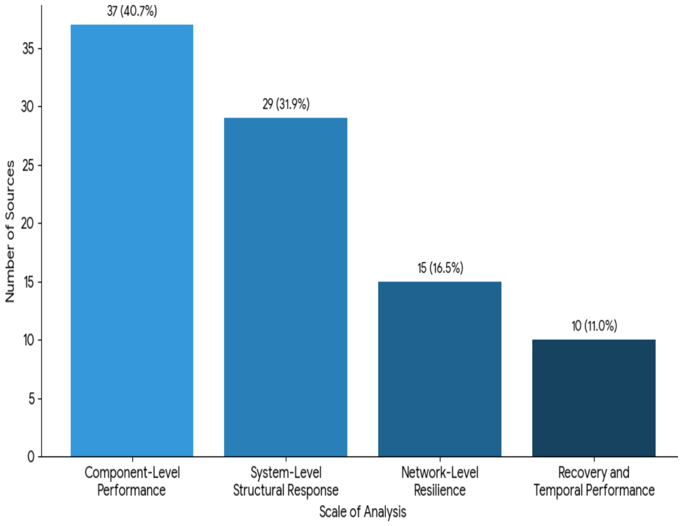

Figure 1. Distribution of Secondary Data Sources by Scale of Analysis

The analysis further infers that resilience gains increase when system-level interactions and redundancy mechanisms are explicitly modeled. Analytical frameworks incorporating multiple scales demonstrate greater sensitivity to cascading failures and recovery bottlenecks. These inferences support the premise that resilience is an emergent property dependent on cross-scale interactions.

Relational analysis highlights interdependencies between structural damage states, functionality loss, and recovery trajectories. Data indicate that similar damage levels at the component scale can produce markedly different system-level outcomes depending on load redistribution capacity and network connectivity. This relationship underscores the inadequacy of single-scale performance metrics.

The analysis also reveals strong coupling between recovery time and system configuration. Infrastructure systems with built-in redundancy and modularity demonstrate shorter recovery durations despite comparable initial damage. These relational patterns reinforce the need to embed recovery considerations into performance-based design.

A representative analytical case study was developed to illustrate application of the proposed multiscale framework to a performance-based infrastructure system. The case considers a simplified bridge network subjected to seismic loading, incorporating component fragility, system functionality thresholds, and network connectivity. Performance metrics were evaluated across damage, disruption, and recovery phases (Alsmairat & AL-Shboul, 2023; Xu et al., 2024).

The case study data describe distinct performance trajectories at each scale. Localized component damage was observed to propagate nonlinearly to system-level service loss due to connectivity constraints. Network-level performance exhibited threshold behavior, with minor additional damage producing disproportionate functional degradation.

Explanatory analysis of the case study demonstrates how multiscale integration clarifies the mechanisms driving resilience loss and recovery. Component-level fragility alone underestimated functional disruption, while system-level analysis revealed critical dependencies among structural elements. Network analysis further exposed vulnerability to cascading effects.

The case study explains how recovery prioritization alters resilience outcomes. Scenarios incorporating targeted repair strategies based on system importance showed accelerated functionality restoration. This explanation confirms that resilience-oriented design must incorporate recovery logic alongside damage mitigation.

The results indicate that structural resilience cannot be adequately characterized through isolated performance metrics or single-scale analysis. Multiscale integration reveals hidden vulnerabilities and recovery constraints that remain invisible in conventional performance-based design approaches. Resilience emerges as a dynamic system property shaped by interactions across spatial and temporal scales.

The findings suggest that reengineering resilience requires a paradigm shift from component-centric optimization toward system-aware and recovery-informed design. A multiscale framework provides the analytical structure necessary to support this shift and to align engineering performance with societal expectations of infrastructure functionality and continuity.

The findings of this study demonstrate that structural resilience is most accurately characterized as an emergent, multiscale property rather than a direct extension of component-level performance metrics. The results show that conventional performance-based design approaches, which emphasize localized damage control and limit states, fail to fully capture system-level functionality loss and recovery dynamics under extreme events. The proposed multiscale framework reveals how interactions among components, subsystems, and networks fundamentally shape resilience outcomes.

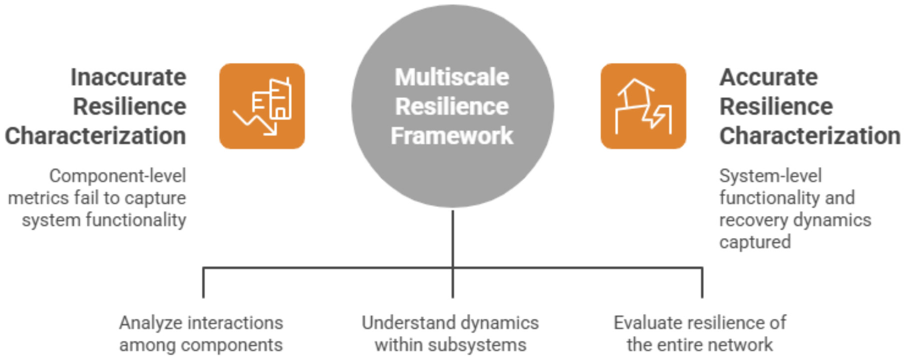

Figure 2. Achieving Structural Resilience Through Multiscale Design

The analysis indicates that improvements in component strength or ductility do not necessarily yield proportional gains in infrastructure resilience. Systems exhibiting similar component-level damage states may experience markedly different levels of functional disruption depending on redundancy, connectivity, and load redistribution mechanisms. This finding underscores the nonlinearity between local structural performance and global system behavior.

The results further show that temporal recovery is a decisive dimension of resilience that remains underrepresented in traditional design frameworks. Recovery trajectories, repair prioritization, and system modularity significantly influence post-event functionality.

Incorporating recovery explicitly into performance evaluation alters the ranking of design alternatives and resilience strategies.

Collectively, the findings confirm that resilience-oriented infrastructure design requires explicit integration across spatial and temporal scales. A multiscale performance-based framework provides the analytical structure necessary to link structural response, functionality, and recovery into a coherent resilience assessment (Chankseliani et al., 2025; Chierici et al., 2024).

The findings align with prior resilience engineering research that critiques collapse-centric and strength-based design paradigms. Existing studies have emphasized that resilience extends beyond damage avoidance to include functional continuity and recovery. This study reinforces those conclusions by demonstrating analytically how resilience emerges from cross-scale interactions rather than isolated performance measures.

Differences arise when comparing the present results with performance-based design literature focused primarily on component fragility and probabilistic demand models. While such studies provide detailed insight into local behavior, they often assume that system performance can be inferred through aggregation. The current findings challenge this assumption by revealing significant discrepancies between aggregated component metrics and actual system-level outcomes.

The results extend network-based resilience studies by integrating them explicitly with structural performance modeling. Previous research often treats network resilience as an abstract systems problem disconnected from material and structural behavior. This study bridges that divide by embedding network functionality within structural damage and recovery processes.

The findings also diverge from resilience frameworks that treat recovery as an external management problem rather than a design variable. By demonstrating that recovery dynamics materially affect resilience outcomes, the study positions recovery as an intrinsic component of performance-based design rather than a post-event consideration.

The findings signal a conceptual shift in how structural performance is understood in the context of societal risk. Infrastructure systems are increasingly required to sustain functionality under uncertainty rather than merely prevent collapse. The results reflect a growing recognition that engineering performance must be evaluated in relation to societal expectations of service continuity.

The study also reveals the limitations of reductionist engineering approaches when applied to complex infrastructure systems. Local optimization does not guarantee global resilience, particularly in systems characterized by interdependence and cascading failure potential. This reflection highlights the necessity of systems thinking in structural engineering.

The results indicate that resilience is inherently dynamic and temporally extended. Structural behavior during hazard impact represents only one phase of performance. Recovery processes, adaptation, and reconfiguration play equally critical roles in determining overall resilience. This insight challenges static interpretations of structural safety.

The findings further suggest that resilience is not a binary property but a gradient shaped by design choices across scales. This perspective reframes resilience from a checklist objective into a continuous design variable requiring explicit trade-offs among performance dimensions.

The implications of these findings are substantial for infrastructure design practice. Engineers must move beyond component-centric performance targets toward system-aware design strategies that account for functional continuity and recovery. Performance objectives should be reformulated to include explicit resilience metrics.

The results imply that design codes and standards require revision to accommodate multiscale resilience concepts. Current provisions emphasize strength, ductility, and damage limitation without systematic consideration of recovery and network effects. Incorporating multiscale performance criteria could significantly improve infrastructure robustness.

The findings also have implications for infrastructure investment and prioritization. Design strategies emphasizing redundancy, modularity, and repairability may offer greater resilience returns than marginal increases in component strength. This insight supports more efficient allocation of resources toward resilience enhancement.

The study further informs risk-informed decision-making by providing a framework that links engineering performance to societal functionality. Policymakers and asset managers can use multiscale resilience assessments to evaluate trade-offs between upfront costs and long-term service reliability.

The nature of the findings can be explained by the inherent complexity of infrastructure systems. Structural systems operate within networks of interdependent components where local failures propagate nonlinearly. This complexity renders single-scale performance metrics insufficient.

The findings also reflect the dominance of historical safety paradigms focused on collapse prevention. Performance-based design evolved primarily to address life safety and damage control, leaving functionality and recovery as secondary concerns. The results expose the consequences of this historical bias.

Material and geometric nonlinearity further explain why local performance does not scale predictably to system behavior (Rehman et al., 2025; Sharma et al., 2025). Redistribution of forces, loss of connectivity, and threshold effects amplify small local changes into large functional disruptions. These mechanisms are only visible through multiscale analysis.

The prominence of recovery in the findings arises from the temporal nature of resilience. Infrastructure value is realized over time through sustained service. Designs that ignore recovery dynamics underestimate resilience loss and overestimate system robustness.

Future research should focus on operationalizing the proposed multiscale framework through computational implementation and empirical validation. Integration with advanced simulation tools and digital twins would enable real-time resilience assessment and design optimization.

Further studies are needed to couple multiscale resilience frameworks with probabilistic hazard modeling and climate projections. Such integration would enhance robustness under deep uncertainty and evolving risk profiles.

Research should also explore how governance, maintenance policies, and adaptive management interact with structural design to influence resilience. Engineering resilience cannot be decoupled from institutional and operational contexts.

The study ultimately points toward a redefinition of performance-based infrastructure design. Reengineering structural resilience requires embedding systems thinking, temporal dynamics, and recovery into the core of engineering practice. Multiscale frameworks provide the methodological foundation for this transformation.

## CONCLUSION

The most significant and distinctive finding of this study is that structural resilience emerges as a multiscale and time-dependent system property rather than a direct extension of component-level strength or damage metrics. The analysis demonstrates that improvements in local structural performance do not necessarily translate into enhanced system functionality or faster recovery. Resilience is shown to be governed by cross-scale interactions among components, subsystems, and networks, as well as by recovery dynamics that are typically excluded from conventional performance-based design frameworks.

The primary contribution of this research is conceptual and methodological. The study advances a multiscale framework that systematically integrates component response, system-level functionality, and recovery processes within performance-based infrastructure design. This contribution extends existing resilience and performance-based design literature by repositioning recovery and functional continuity as intrinsic design variables rather than post-event considerations. The framework provides a structured analytical foundation that can support more resilient infrastructure planning, design, and evaluation.

The study is limited by its analytical and framework-oriented nature, relying on secondary data and representative case scenarios rather than full-scale empirical validation. The absence of extensive numerical simulations and real-world performance data constrains the ability to quantify resilience gains across diverse infrastructure types. Future research should address these limitations by implementing the proposed framework in computational design environments, validating it against empirical post-disaster data, and extending it to account for multi-hazard interactions and long-term climate-driven uncertainties.

## DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT only to assist with grammatical review. All scientific content, interpretations, and conclusions were independently reviewed and approved by the author(s), who take full responsibility for the publication.

## AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## REFERENCES

Alayed, S., & Alateeg, S. (2025). Innovative work behavior propelling digital technology for quality enhancement. International Journal of Quality & Reliability Management, 43(2), 435–452. https://doi.org/https://doi.org/10.1108/IJQRM-01-2025-0037

Almazroui, D. K. (2025). Ideological indoctrination of children during Crises: Non-Religious extremism in authoritarian regimes. Child Protection and Practice, 6, 100205. https://doi.org/https://doi.org/10.1016/j.chipro.2025.100205

Alqam, H. S., Razzak, M. R., & Bachkirov, A. A. (2025). Driving SME success through digital readiness and dynamic capabilities in propelling business process digitalization and performance. Journal of Entrepreneurship in Emerging Economies, 17(6), 1699–1722. https://doi.org/https:/doi.org/10.1108/JEEE-02-2025-0057

Alsmairat, M. A. K., & AL-Shboul, M. A. (2023). Enabling supply chain efficacy through supply chain absorptive capacity and ambidexterity: empirical study from Middle East region - a moderated-mediation model. Journal of Manufacturing

Technology Management, 34(6), 917–936. https://doi.org/https://doi.org/10.1108/JMTM-10-2022-0373

Arij, L., & Areej, S. (2025). Digital Twins for Decarbonized Supply Chain: A Conceptual Framework. IFAC-PapersOnLine, 59(10), 1624–1629. https://doi.org/https://doi.org/10.1016/j.ifacol.2025.09.273

Chankseliani, M., Kwak, J., Hanley, N., Akkad, A., Crisostomo, M., & Wang, Z. (2025). International student mobility and poverty reduction: A qualitative study of the mechanisms of systemic change. World Development, 195, 107116. https://doi.org/https://doi.org/10.1016/j.worlddev.2025.107116

Cheng, M., Chong, H.-Y., Xu, Y., & Wu, H. (2025). Fostering green building project performance by blockchain-enabled smart contracts (B-SCs) implementation: Adaptive structuration perspective. Journal of Building Engineering, 114, 114435. https://doi.org/https://doi.org/10.1016/j.jobe.2025.114435

Chierici, A., Cancemi, S. A., Niederleithinger, E., & Lo Frano, R. (2024). Enhanced radioactive waste drum monitoring: A sensorized LoRa-based network for identification and integrity assessment. Nuclear Engineering and Design, 424, 113231. https://doi.org/https://doi.org/10.1016/j.nucengdes.2024.113231

Essien, R. S., Owusu, G., Amedzro, K. K., & Issah, M. A. (2025). Committeefication of African urban development:The case of Ghana’s Greater Accra Resilient and Integrated Development Project (GARID). World Development Perspectives, 39, 100724. https://doi.org/https://doi.org/10.1016/j.wdp.2025.100724

Gao, D., Li, S., & Tian, Z. (2025). Geopolitical risk, energy market volatility, and corporate energy dependence: The role of green Total factor productivity and decentralized top management team network. Energy Economics, 148, 108545. https://doi.org/https://doi.org/10.1016/j.eneco.2025.108545

García-Alcaraz, J. L., Reza, J. R. D., Aryanfar, Y., Keçebaş, A., Mohtaram, S., & Osman, A. I. (2025). Responsiveness supply chain in the Mexican Maquiladora Industry: The role of AMT, information sharing and pull production process. Sustainable Futures, 10, 101283. https://doi.org/https://doi.org/10.1016/j.sftr.2025.101283

Guo, L., & Kuang, Z. (2025). How does digitalization of the supply chain accelerate the sustainable development of listed companies in the new energy sector? International Review of Economics & Finance, 103, 104505. https://doi.org/https://doi.org/10.1016/j.iref.2025.104505

Guo, L., Li, G., & Zheng, Y. (2025). There’s always another way: A case of female teachers’ career mobility in Xiong’an New Area, China. Women’s Studies International Forum, 113, 103195. https://doi.org/https://doi.org/10.1016/j.wsif.2025.103195

Hasan, M. K., Lei, X., Hlali, A., & Bian, Z. (2024). Modelling capability factors of logistics industry based on ISM-MICMAC. Heliyon, 10(22), e40539. https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e40539

Hoque, S., Al Faruq, A., & Randles, S. (2025). Building transilience through social innovation in social purpose organizations. European Management Journal. https://doi.org/https://doi.org/10.1016/j.emj.2025.06.008

Hudnurkar, M., Ambekar, S. S., Bhattacharya, S., Venkatesh, V. G., & Shi, Y. (2024). Influence of supplier development on supplier satisfaction: a mediating role of buyer–supplier relationship. Benchmarking: An International Journal, 32(6), 1942–1971. https://doi.org/https://doi.org/10.1108/BIJ-07-2023-0438

Hussain, Z., Mohammad, S. I., Vasudevan, A., Awad, A., & Bansal, R. (2025). Exploring the effect of industry 5.0 human-centric sustainability and green knowledge automation in enhancing green process adaptability: The mediating role of sustainable human-tech interaction. Journal of Cleaner Production, 537, 147240. https://doi.org/https://doi.org/10.1016/j.jclepro.2025.147240

Jantapoon, K., & Saenchaiyathon, K. (2025). Sharing, technology, and resilience in agricultural SMEs: pathways to sustainable supply chains under VUCA conditions. Cleaner Logistics and Supply Chain, 17, 100285. https://doi.org/https://doi.org/10.1016/j.clscn.2025.100285

Li, L., Xu, J., & Liang, Y. (2024). The formation and evolution of vulnerability risk of rural poor groups under the perspective of social support —— based on the analysis of “sensitivity-resilience.” Heliyon, 10(9), e30305. https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e30305

Liu, L., Wang, W., Yang, L., & Hu, S. (2025). Does supply chain network position facilitate firm M&A? Evidence from China. International Review of Economics & Finance, 104, 104660. https://doi.org/https://doi.org/10.1016/j.iref.2025.104660

Lu, H. T., Li, X., & Yuen, K. F. (2023). Digital transformation as an enabler of sustainability innovation and performance – Information processing and innovation ambidexterity perspectives. Technological Forecasting and Social Change, 196, 122860. https://doi.org/https://doi.org/10.1016/j.techfore.2023.122860

Massari, G. F., Nacchiero, R., & Giannoccaro, I. (2025). Transformative supply chains: the enabling role of digital technologies. International Journal of Production Economics, 283, 109562. https://doi.org/https://doi.org/10.1016/j.ijpe.2025.109562

Meafa, A., Benabdellah, A. C., & Zekhnini, K. (2024). Enhancing Supply Chain Resilience Through Dynamic Capabilities of Blockchain Technology: A Structural Model Analysis. Procedia Computer Science, 232, 980–989. https://doi.org/https://doi.org/10.1016/j.procs.2024.01.097

Mola, L., & Roffia, P. (2025). Digitalizing sales channels in wine business SMEs: the role of internal and external factors between opportunities and risks. British Food Journal, 127(4), 1395–1419. https://doi.org/https://doi.org/10.1108/BFJ-06-2024-0648

Moolkham, M. (2025). Digital transformation, financial performance and firm valuation: The moderating effect of environmental risk. Journal of Climate Finance, 13, 100075. https://doi.org/https://doi.org/10.1016/j.jclimf.2025.100075

Mosca, M., Mosca, R., & Braggio, M. (2025). Big Data and AI for Smart Maintenance: Literature review on the impact on plants Resilience. Procedia Computer Science, 253, 1959–1971. https://doi.org/https://doi.org/10.1016/j.procs.2025.01.258

Mühl, D. D., dos Santos Ramos, F., & de Oliveira, L. (2025). Price transparency and digital traceability: A framework for fairer, more sustainable food supply chains. Computers and Electronics in Agriculture, 238, 110807. https://doi.org/https://doi.org/10.1016/j.compag.2025.110807

Nalluri, V., Meghana Chowdary, K., & Chen, L.-S. (2025). Risk evaluation in the implementation of sustainable measures in the supply chain operations: A Fuzzy Delphi-DEMATEL approach. Cleaner Logistics and Supply Chain, 17, 100262. https://doi.org/https://doi.org/10.1016/j.clscn.2025.100262

Nath, B. K., Medhi, U., Deka, R. C., & Kalita, E. (2025). Reengineering agro-waste-derived nanolignin for the development of reusable remediation-ready hydrogels. Journal of Environmental Chemical Engineering, 13(2), 115831. https://doi.org/https://doi.org/10.1016/j.jece.2025.115831

Nazari-Shirkouhi, S., & Samadi, S. (2025). Enhancing healthcare supply chains: A comprehensive evaluation of lean, agile, resilient and green paradigms. Engineering Applications of Artificial Intelligence, 145, 110204. https://doi.org/https://doi.org/10.1016/j.engappai.2025.110204

Nguyen Thi, B., Nguyen Do Khanh, L., Ha Minh, H., Do Thi Thuy, L., & Ngo Tien, D. (2023). Impacts of inbound logistics capabilities on supply chain resilience: insight from Vietnamese textile industry. Measuring Business Excellence, 27(3), 501–518. https://doi.org/https://doi.org/10.1108/MBE-09-2022-0113

Pedroletti, D. (2025). Network effects of partial reshoring in the internationalization process. International Business Review, 34(3), 102401. https://doi.org/https://doi.org/10.1016/j.ibusrev.2025.102401

Qureshi, K. M., Mewada, B. G., Kaur, S., Khan, A., Al-Qahtani, M. M., & Qureshi, M. R. N. M. (2024). Investigating industry 4.0 technologies in logistics 4.0 usage towards sustainable manufacturing supply chain. Heliyon, 10(10), e30661. https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e30661

Rastgoo, H., Abbasi, E., & Bijani, M. (2024). Analysis of agricultural insurance vulnerability in the face of natural disasters: Insights from Iran. Environmental and Sustainability Indicators, 23, 100429. https://doi.org/https://doi.org/10.1016/j.indic.2024.100429

Rehman, W. ul, Saltik, Ö., Fareed, R., Bekmezci, M., & Degirmen, S. (2025). Translating the role of artificial intelligence into green intellectual capital initiatives and green business process optimization in achieving corporate environmental performance. Sustainable Futures, 10, 101345. https://doi.org/https://doi.org/10.1016/j.sftr.2025.101345

Salvador, M., & Sancho, D. (2025). Institutional Capacities and Urban Management: Barcelona and the COVID-19 Crisis. Urban Governance, 5(2), 256–265. https://doi.org/https://doi.org/10.1016/j.ugj.2025.05.001

Sharma, R., Sundarakani, B., & Manikas, I. (2025). Integration of industry 4.0 technologies for agri-food supply chain resilience. Computers in Industry, 165, 104225. https://doi.org/https://doi.org/10.1016/j.compind.2024.104225

Susitha, E., Jayarathne, P. G. S. A., & Herath, R. (2025). Threading the digital needle: the influence of process and technical digitalisation on competitive performance in the apparel supply chain. Supply Chain Management: An International Journal, 31(1), 65–86. https://doi.org/https://doi.org/10.1108/SCM-05-2025-0476

Trump, B. D., Mitoulis, S.-A., Argyroudis, S., Kiker, G., Palma-Oliveira, J., Horton, R., Pescaroli, G., Pinigina, E., Trump, J., & Linkov, I. (2025). Threat-agnostic resilience: Framing and applications. International Journal of Disaster Risk Reduction, 124, 105535. https://doi.org/https://doi.org/10.1016/j.ijdrr.2025.105535

Xu, T., Shen, Z., Zhang, H., Zhang, C., & Huang, H. (2024). Digital HP finance's role in the economic resilience of enterprises' digital transformation. Finance Research Letters, 63, 105312. https://doi.org/https://doi.org/10.1016/j.frl.2024.105312

Zhou, L., Tang, C., & Cao, Y. (2025). Innovative human capital, government support for science and technology policy, and supply chain resilience. Finance Research Letters, 74, 106741. https://doi.org/https://doi.org/10.1016/j.frl.2025.106741