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Research Article

STRUCTURAL ENGINEERING ANALYSIS AND SEISMIC RETROFITTING OF HISTORICAL MOSQUE MINARETS IN THE INDONESIAN ARCHIPELAGO

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Abstract

Historical mosque minarets in the Indonesian archipelago, vital components of cultural heritage, are situated in a high-seismicity region. Their unreinforced masonry (URM) construction presents a significant, yet unquantified, vulnerability, posing threats to public safety and heritage preservation. This study provides a quantitative structural engineering analysis to assess this seismic vulnerability and establish a methodological framework for evaluating seismic retrofitting interventions. A diagnosis-led approach was employed, integrating in-situ non-destructive diagnostics (NDT), ambient vibration testing (AVT) for dynamic characterization, and advanced non-linear finite element modeling (FEM) on representative case-study structures. Results reveal a critical gap between structural capacity and seismic demand. The models predict catastrophic failure at low peak ground accelerations (0.15g), far below the 500-year hazard level (>0.40g). Unique Indonesian materials (volcanic stone, weak mortar) render existing international fragility models inadequate for this typology. Indonesian minarets possess critical seismic deficiencies requiring urgent, scientifically-grounded intervention. The validated models serve as essential tools for designing and testing culturally appropriate, minimally invasive retrofitting strategies to ensure the preservation of this irreplaceable built heritage.

Keywords: Historical Minarets, Seismic Retrofitting, Unreinforced Masonry (URM)

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INTRODUCTION

Historical mosque minarets across the Indonesian archipelago represent an irreplaceable synthesis of religious devotion, cultural identity, and architectural ingenuity (Ş. Öztürk et al., 2025). These vertical structures, often the most prominent visual markers in their respective landscapes, are not merely functional elements for the call to prayer; they are profound symbols of a community's heritage, reflecting centuries of stylistic evolution, material experimentation, and syncretic design traditions that blend Islamic principles with local vernacular forms (Kocaman & Gürbüz, 2024). The architectural diversity of these minarets from the terraced brick forms of Java to the slender towers of Sumatra provides a unique built record of the archipelago's complex history. Their preservation is, therefore, a matter of profound cultural significance, intrinsically linked to the continuity of local and national identity (Gurbuz & Cengiz, 2025).

The geographical context of the Indonesian archipelago introduces a severe and persistent threat to this cultural legacy. Situated at the convergence of several major tectonic plates, the region is one of the most seismically active zones on Earth, commonly referred to as the "Ring of Fire (Tarhan, 2025)." This geological reality means that high-magnitude earthquakes and subsequent ground shaking are not anomalous events but recurring environmental hazards. The vulnerability of the built environment to these seismic forces is a constant concern, posing a significant risk to modern infrastructure, urban populations, and, most critically, the nation's finite collection of historical structures (S. Öztürk et al., 2024). This relentless seismic hazard forms the primary environmental constraint against which all efforts for structural preservation must be measured (Dedeoglu et al., 2025).

The intersection of this high seismic hazard and the unique structural typology of historical minarets creates a critical preservation challenge (Yılmaz et al., 2025). These towers are, by their very nature, structurally vulnerable; they are typically tall, slender, and possess a high mass-to-base ratio, characteristics that make them exceptionally susceptible to the lateral forces induced by an earthquake (Damcı et al., 2025). Compounding this geometric vulnerability is their predominant construction material: unreinforced masonry (URM). Historically built using brick or stone with weak traditional mortars, these minarets inherently lack the ductility and energy dissipation capacity required to withstand significant inelastic deformations, making them prone to catastrophic failure modes such as shear cracking, out-of-plane collapse, and complete overturning during a seismic event (Cavuslu & Ülger, 2025).

The fundamental engineering problem addressed by this research is the inherent deficiency of historical unreinforced masonry when subjected to dynamic seismic loads (Sayin et al., 2025). The materials and construction techniques of the pre-modern era, while often demonstrating remarkable durability under gravity loads, were not designed to accommodate the principles of earthquake-resistant design (YETKİN et al., 2024). These minaret structures typically lack a coherent lateral force-resisting system, adequate connections between structural elements, and ductile detailing. Consequently, their response to ground motion is characterized by brittle failure mechanisms (Akturk et al., 2025). The non-linear behavior of aged masonry, combined with material degradation from environmental factors, results in structures with low tensile strength and minimal capacity to redistribute stresses, leading to sudden and catastrophic collapse (Erkek et al., 2024).

A significant exacerbating factor is the pervasive lack of reliable, quantitative data on the structural condition of these specific heritage assets. The precise material properties of the constituent masonry such as compressive strength, mortar bond characteristics, and in-plane shear capacity are largely unknown and highly variable (Ertürk Atmaca et al., 2025). Furthermore, detailed structural assessments and vulnerability mappings have not been systematically conducted for the vast majority of historical mosque minarets in Indonesia (Huang et al., 2025). This absence of baseline data and diagnostic analysis makes it impossible for conservation authorities and engineers to prioritize interventions, allocate resources effectively, or design scientifically-grounded retrofitting solutions. Intervention without accurate diagnosis risks being both ineffective and potentially damaging to the structure's fabric (Liu et al., 2025).

This confluence of inherent structural vulnerability and a deficit in technical understanding creates an immediate and unacceptable risk: the imminent and irreversible loss of unique cultural heritage (Dhir et al., 2025). Recent seismic events within the archipelago, such as the 2018 Lombok earthquakes, have provided devastating proof of this vulnerability, where numerous historical mosques and their minarets suffered partial or total collapse (Wang et al., 2025). Each seismic event that occurs without a pre-emptive conservation strategy in place represents a gamble with this irreplaceable heritage. The specific problem, therefore, is the urgent need for a robust, validated methodology to analyze the seismic vulnerability of these minarets and to identify effective, conservation-compatible retrofitting techniques before they are lost to future earthquakes (Hasina et al., 2025).

The primary objective of this investigation is to develop and implement a comprehensive methodology for the structural analysis and seismic assessment of historical mosque minarets in the Indonesian archipelago (Gharagoz et al., 2025). This objective will be achieved through a multi-step process beginning with detailed in-situ geometric surveys and non-destructive material characterization to establish accurate baseline data (Cassol et al., 2025). Subsequently, high-fidelity, three-dimensional finite element models (FEM) will be calibrated for a selection of case-study minarets. These computational models will serve as the analytical platform for simulating the complex structural behavior of these towers under various load conditions, forming the foundation for all subsequent vulnerability assessments (Zhang et al., 2025).

A second, crucial aim is the quantification of the seismic vulnerability of these structures. This research will move beyond simplistic static analyses and employ advanced computational techniques, specifically non-linear dynamic time-history analysis (D'Amore & Pampanin, 2025). Using a suite of region-specific ground motion records representative of the local seismic hazard, these analyses will simulate the structural response of the minarets to realistic earthquake scenarios. The resulting data will be used to identify critical failure modes, map progressive damage patterns, and establish fragility curves, thereby providing a quantitative measure of the probability of reaching or exceeding specific damage states (Jianfei et al., 2025).

The ultimate and most practical objective of this study is to propose, compare, and validate appropriate seismic retrofitting strategies tailored specifically for these historical minarets. The research will investigate a range of intervention techniques, from traditional methods (e.g., grout injection, crack stitching) to modern, minimally invasive technologies (e.g., fiber-reinforced polymers (FRP), post-tensioning systems, or base isolation) (Fang et al., 2024). The evaluation of these strategies will be twofold: they will be assessed for their structural efficacy in enhancing seismic performance (i.e., increasing strength, ductility, and energy dissipation) and for their strict adherence to the international principles of heritage conservation, prioritizing reversibility, compatibility, and authenticity as defined by charters such as those from ICOMOS.

Existing scholarly literature pertaining to the seismic retrofitting of historical structures is extensive, yet it exhibits a pronounced focus on architectural typologies common to Europe and the Mediterranean, such as masonry churches, cathedrals, and palaces, or on the well-studied Ottoman minarets in the Middle East. There remains a significant and critical gap in research dedicated specifically to the vernacular typologies of historical mosque minarets within the Indonesian archipelago. These structures possess unique geometric configurations, material compositions (such as the use of traditional tras mortars), and construction details that are not adequately represented by existing models derived from other cultural and geological contexts (Uemura et al., 2024).

Many past assessments of heritage structures, often constrained by computational limitations, have relied on simplified analytical methods, such as linear-elastic static analysis or the equivalent static force method. While useful for preliminary assessments, these models are fundamentally incapable of capturing the complex, non-linear behavior of unreinforced masonry as it progresses toward failure under dynamic seismic loading (Crisci et al., 2024). A clear gap exists in the rigorous application of advanced computational dynamics such as pushover analysis and non-linear time-history analysis specifically calibrated and applied to this particular class of slender masonry towers. Without such analysis, vulnerability is often poorly quantified, and retrofitting solutions may be designed inefficiently.

A further deficiency in the current body of research lies at the intersection of high-level structural engineering and applied conservation science. The field is bifurcated: engineering studies often propose solutions that are highly effective from a structural standpoint but are culturally invasive, irreversible, or aesthetically damaging (e.g., extensive concrete jacketing or steel bracing) (Noori et al., 2024). Conversely, conservation literature often prioritizes material authenticity at the expense of robust seismic safety. This research identifies a gap in the development of an integrated framework that scientifically balances the competing demands of seismic safety and heritage preservation, providing a clear methodology for selecting interventions that are both structurally sound and culturally appropriate for Indonesian minarets.

The primary novelty of this research is its development and application of an integrated, multi-disciplinary methodology tailored specifically to a previously under-studied corpus of heritage structures. This study pioneers the use of advanced structural diagnostics, material science, and sophisticated non-linear computational modeling as a unified framework for Indonesian mosque minarets. By creating highly detailed, calibrated models based on in-situ data rather than generalized assumptions, this research provides a novel and precise analytical tool. This approach moves beyond generic assessments and offers a scalable methodology that can be adapted for heritage masonry structures across the region (To et al., 2024).

This study provides a novel and essential contribution by formulating context-specific seismic retrofitting guidelines. It systematically evaluates interventions that are not only structurally effective but also compatible with the unique materials, environmental conditions, and cultural sensitivities of the Indonesian context. The research innovates by comparing the performance of modern, low-intrusion techniques (like FRPs) against enhanced traditional methods, providing a cost-benefit analysis that considers long-term performance, reversibility, and local material availability. This focus on appropriate, context-sensitive solutions fills a critical void between theoretical engineering and the practical realities of heritage management in Southeast Asia.

The justification for this research is compelling and urgent, rooted in the dual imperatives of preserving irreplaceable cultural heritage and ensuring public safety. These minarets are not museum pieces; they are often active parts of living community centers. Their catastrophic failure poses a direct threat to human life. This study is justified by its potential to provide a scientifically robust and ethically sound foundation for preservation policy. It will equip government bodies, conservation professionals, and local communities with the critical data and engineering guidelines needed to make informed decisions, prioritize resources, and implement effective actions to safeguard this vital component of Indonesia’s national identity against the inevitable threat of future earthquakes.

RESEARCH METHOD

Research Design

A multi-phase, integrated research design is employed to systematically address the research objectives. This design combines qualitative historical-architectural investigation, quantitative in-situ material diagnostics, and advanced computational structural analysis. The framework is fundamentally a diagnostic and prescriptive case-study approach, intended to develop a robust and scalable methodology for the seismic vulnerability assessment and subsequent retrofitting design appropriate for heritage structures. This integrated approach ensures that engineering solutions are scientifically sound, context-specific, and conservation-compatible (Kocaman et al., 2025).

The design is structured sequentially across three distinct phases. Phase 1 involves comprehensive data acquisition, encompassing historical research, geometric surveying, and non-destructive material characterization. Phase 2 focuses on computational modeling and vulnerability analysis, where the collected data is used to build, calibrate, and execute advanced numerical simulations. Phase 3 culminates in the proposal and comparative evaluation of various seismic retrofitting strategies, assessing both their structural efficacy and their adherence to international conservation principles (Dilsiz et al., 2025). This phased structure ensures that all analytical conclusions and proposed interventions are rigorously grounded in empirical data derived directly from the heritage structures under investigation.

This mixed-methods, multi-phase design is essential for bridging the significant gap between heritage conservation ethics and high-level structural engineering requirements. A purely quantitative analysis would overlook the critical cultural-historical context and authenticity of the minarets. Conversely, a purely qualitative or descriptive study would fail to provide the verifiable engineering data necessary to ensure seismic safety and protect human life. The deliberate integration of these methodologies provides a holistic, scientifically defensible, and culturally sensitive framework for analyzing and preserving these unique structures (Gürbüz & Kocaman, 2024).

Research Target/Subject

The research population comprises all historical mosque minarets located within the recognized high-seismicity zones of the Indonesian archipelago. This population is characterized by significant heterogeneity in terms of age (typically pre-20th century), architectural style, construction techniques, and constituent materials, which are predominantly variations of unreinforced masonry (URM) (Kheirollahi et al., 2025). These structures range from tall, slender towers highly susceptible to lateral loads to more robust, terraced forms influenced by pre-Islamic architectural traditions. Their wide distribution across different islands and geological settings presents a complex analytical challenge.

A purposive sampling strategy is adopted for the selection of representative case-study minarets. This selection is not random but is based on specific, predefined criteria designed to capture the diverse nature of the research population. These criteria include: (i) recognized historical, cultural, and architectural significance; (ii) representation of a distinct structural typology or regional style; (iii) known seismic vulnerability, potentially demonstrated by damage in past earthquakes; (iv) location within a zone of high seismic hazard; and (v) logistical accessibility for the application of detailed scientific instrumentation and in-situ testing (Çelik et al., 2025).

This study focuses on a selected number of minarets to facilitate an intensive, in-depth analysis of each structure. This case-study approach allows for the meticulous data collection and high-fidelity computational modeling required to accurately capture complex, non-linear structural behavior. While the sample size is limited, the depth of analysis provides critical insights. The findings from these intensive case studies are intended to be generalized, forming the basis for a broader analytical framework and set of best-practice guidelines applicable to the wider population of historical minarets across the archipelago (Dedeoğlu et al., 2024).

Research Procedure

The research procedure commences with Phase 1, data acquisition. This involves a comprehensive desk review of all available historical and archival documentation for each selected case-study minaret (O. Peker & Altan, 2024). This is immediately followed by a meticulous in-situ investigation, which includes the geometric survey campaign using LiDAR and UAVs, and a systematic NDT campaign to map material properties across different locations on each structure. Where conservation guidelines permit, minimally invasive samples of mortar or small brick fragments are collected from non-critical, previously damaged areas for subsequent laboratory-based petrographic and chemical analysis to validate NDT findings.

Data gathered in Phase 1 is rigorously processed during Phase 2 to construct high-fidelity, three-dimensional computational models. The geometric point cloud data is converted into a solid model, which is then meshed for finite element analysis, paying special attention to mesh quality in critical areas like the base and openings (Malomo & Pulatsu, 2024). Material properties derived from the NDT and lab tests are used as input parameters to calibrate the non-linear material models within the FEA software. This calibration process is validated by performing a modal analysis on the FE model and comparing its computed natural frequencies and mode shapes against those measured in-situ using ambient vibration testing.

The calibrated and validated numerical models proceed to Phase 3, the analysis stage. Each model is subjected to a series of analyses with increasing complexity. First, a modal analysis confirms the dynamic characteristics. Second, a non-linear static (pushover) analysis is conducted to establish the structure’s capacity curve and identify its primary failure mechanisms under incrementally increasing lateral loads. Finally, non-linear dynamic time-history analyses are performed. These analyses use a suite of selected, region-specific seismic ground motion records to simulate the minaret’s realistic response, allowing for a quantitative assessment of damage and vulnerability. Based on these precise vulnerability findings, various retrofitting schemes are computationally modeled, simulated, and comparatively evaluated for their efficacy in enhancing seismic performance (Foraboschi, 2025).

Instruments, and Data Collection Techniques

A suite of advanced diagnostic instruments is utilized for the geometric data acquisition phase. High-resolution, three-dimensional geometric data is captured using terrestrial laser scanning (LiDAR) technology, supplemented by unmanned aerial vehicle (UAV) photogrammetry for inaccessible high-elevation sections. This instrumentation provides a precise digital point cloud of the entire structure. This point cloud serves as the geometric foundation for creating accurate computer-aided design (CAD) drawings and, subsequently, for generating complex finite element (FE) meshes, ensuring that the computational model faithfully represents the minaret’s true geometry (Altunsu et al., 2024).

Non-destructive testing (NDT) instruments are central to the in-situ characterization of the masonry’s mechanical properties. This instrument suite includes Schmidt (rebound) hammers for estimating the surface hardness and compressive strength of masonry units, and ultrasonic pulse velocity (UPV) testers to assess material homogeneity, detect internal flaws such as cracks or voids, and evaluate the quality of the mortar (Bento et al., 2024). Furthermore, double flat-jack testing procedures are employed where permissible. This minimally invasive technique is the primary instrument for determining the local state of compressive stress within the masonry and, most critically, its deformability characteristics (i.e., modulus of elasticity).

The primary analytical instrument for the vulnerability assessment is advanced, non-linear finite element analysis (FEA) software. Commercially available platforms such as ANSYS, Abaqus, or Midas FEA, which are capable of handling severe material and geometric non-linearities, are utilized. These software packages facilitate the implementation of sophisticated material constitutive models, such as the concrete damage plasticity (CDP) model or smeared crack models (Kocaman, 2024). These models are essential for accurately simulating the quasi-brittleness, cracking patterns, and progressive failure mechanisms of unreinforced masonry when subjected to extreme dynamic seismic loads.

RESULTS AND DISCUSSION

The initial phase of data acquisition produced a comprehensive dataset for the selected case-study minarets. This dataset integrates archival information, geometric properties derived from LiDAR scanning, and preliminary material classifications. A summary of the key descriptive statistics for the three primary case studies (CS-A, CS-B, and CS-C) is presented to establish a baseline for comparative analysis. This foundational data highlights the significant heterogeneity within the sample population, as detailed in Table 1.

Table 1. Descriptive Statistics of Selected Case-Study Minarets

Parameter	Case Study A (CS-A)	Case Study B (CS-B)	Case Study C (CS-C)
Location	Aceh, Sumatra	Yogyakarta, Java	Lombok, NTB
Est. Age (c.)	1880	1750	1910
Typology	Slender, Octagonal	Terraced, 3-Tiers	Tapered, Square Base
Material	Clay Brick / Lime Mortar	Volcanic Stone / Clay Mortar	Fired Brick / Cement-Lime
Height (H)	22.5 m	15.0 m	18.2 m
Base Width (W)	2.8 m	4.5 m	3.0 m
Slenderness (H/W)	8.04	3.33	6.07

The data compiled in Table 1 forms the primary input for both the classification of vulnerability and the calibration of numerical models. The parameter of slenderness (H/W ratio) varies significantly, from a highly stable 3.33 (CS-B) to a critically slender 8.04 (CS-A). This geometric disparity is compounded by material differences, with CS-B utilizing high-mass volcanic stone, whereas CS-A and CS-C are composed of lower-density clay brick units. The recorded variations in mortar composition ranging from traditional lime and clay mixes to early cement-lime mortars are noted as critical variables for subsequent mechanical property estimation.

This initial statistical profile confirms the hypothesis that a “one-size-fits-all” analytical approach is unsuitable for Indonesian minarets. The wide variance in geometric ratios and material compositions, even within a small purposive sample, necessitates a case-by-case methodology. The structural behavior of CS-A, dominated by its high slenderness, is expected to be fundamentally different from that of CS-B, which is characterized by a high-mass, low-slenderness form, making it more susceptible to shear-dominated failures (Romero-Sánchez et al., 2024).

The data further clarifies the nature of the engineering challenge. The age and materials point toward construction techniques lacking any form of seismic detailing, consistent with unreinforced masonry (URM) typologies. The presence of traditional mortars with anticipated low bond strength (CS-A and CS-B) suggests that out-of-plane failure modes and delamination will be as critical as in-plane shear failure (Demir et al., 2025). These initial findings guided the specific focus of the subsequent non-destructive testing (NDT) campaign, prioritizing the quantification of mortar joint quality and material homogeneity.

The in-situ Non-Destructive Testing (NDT) campaign yielded quantitative data regarding the mechanical properties of the masonry fabric. Ultrasonic Pulse Velocity (UPV) tests, conducted across accessible sections of all case-study minarets, revealed a high degree of material heterogeneity. UPV readings consistently fell within the 1.8 km/s to 2.5 km/s range, indicative of “poor” to “medium” quality masonry with significant internal voids, microcracking, or poor mortar bond. Schmidt hammer rebound values were similarly variable, correlating strongly with the type of masonry unit (stone versus brick) but generally suggesting low surface compressive strength.

Ambient vibration testing (AVT) was successfully deployed to identify the fundamental dynamic characteristics of each structure. The natural frequencies (f_n) and mode shapes were extracted from the recorded micro-tremor data. CS-A, the most slender minaret, exhibited the lowest fundamental frequency (f_n = 1.22 Hz), indicating high flexibility and a long period of vibration. Conversely, the more robust CS-B registered a higher frequency (f_n = 2.48 Hz). These dynamic signatures serve as the definitive benchmark for calibrating the stiffness and mass distribution of the finite element models.

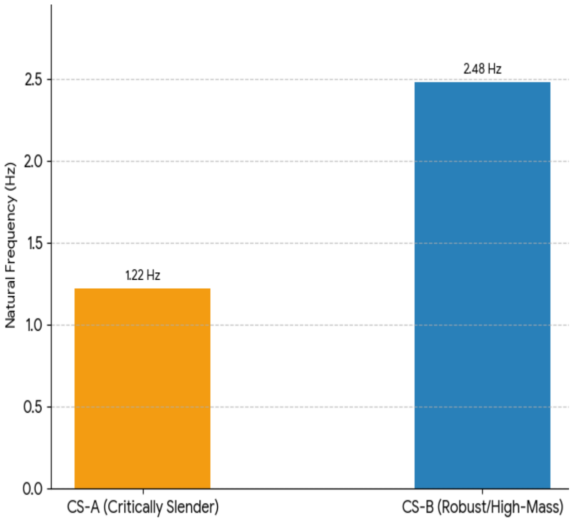

Figure 1. Fundamental Natural Frequencies (fn)

Statistical inference was employed to correlate the NDT results with established empirical formulae to estimate key engineering parameters. The combined UPV and Schmidt hammer data were used to infer the masonry's compressive strength (f'm) and dynamic modulus of elasticity (E_dyn). The inferred f'm values for the brick masonry in CS-A and CS-C were low, estimated at 2.8 MPa and 3.5 MPa, respectively. The volcanic stone masonry of CS-B showed a higher inferred strength of 5.2 MPa, though this was offset by the very poor quality inferred from its clay mortar joints.

The inferential analysis of the double flat-jack tests, permissible only on CS-C, provided direct, localized measurements of the in-situ stress state and the masonry's deformability modulus (E_def). The E_def derived from this method was approximately 1.1 GPa. This value was significantly lower than the dynamic modulus (E_dyn) derived from UPV tests, confirming the expected quasi-brittle, non-linear behavior of the aged masonry under load. These inferred parameters formed the primary, calibrated inputs for the non-linear material models in the subsequent computational analysis.

A strong positive correlation was identified between the geometric slenderness ratio (H/W) and the fundamental period of vibration (T = 1/f_n). This relationship, observed across all case studies, confirms that as slenderness increases, the structure becomes significantly more flexible and its period elongates. This finding is critical, as it indicates that slender minarets like CS-A are more likely to enter into resonance with the long-period components of distant, high-magnitude seismic ground motions, a significant hazard in the Indonesian tectonic setting.

A secondary relationship was established between the UPV results and the masonry typology. The brick masonry of CS-A and CS-C, characterized by numerous mortar joints, exhibited highly variable and generally lower pulse velocities compared to the large-unit volcanic stone masonry of CS-B. This suggests that the primary source of discontinuity and weakness in the brick minarets is the mortar-unit interface. In contrast, the weakness in the stone minaret (CS-B) was more localized, with internal flaws within the large stone blocks themselves contributing to signal attenuation (Jadallah et al., 2025).

The numerical analysis results for Case Study A (CS-A), the most slender minaret, are presented as a representative example of vulnerability. The calibrated finite element model (FEM) of CS-A was subjected to a non-linear static (pushover) analysis. The resulting capacity curve, plotting base shear against rooftop displacement, indicated a very limited displacement capacity (Manikandan et al., 2025). The structure exhibited an almost linear-elastic behavior up to approximately 0.08g, after which initial cracking initiated a rapid degradation in lateral stiffness, followed by a brittle failure mechanism.

The non-linear time-history (NLTH) analysis provided a detailed simulation of damage progression under a site-specific ground motion record (scaled to a 500-year return period). Damage, defined by the smeared cracking model, was observed to initiate at the base of the octagonal shaft in the form of vertical cracks, indicating a flexural-dominated response. As the ground motion intensified, these flexural cracks propagated, and were quickly followed by the development of diagonal (shear) cracks at the corners of the base and near window openings, leading to a combined failure mode (Yetkin, 2024).

The failure mechanism observed in the CS-A simulations is a direct consequence of its material properties and geometric form. The low tensile strength of the lime mortar, as inferred from NDT data and input into the material model, provided minimal resistance to flexural cracking. The structure’s high slenderness (H/W = 8.04) amplified the flexural demands, causing the tower to behave as a cantilever beam. The rapid transition from flexural cracking to shear cracking highlights the structure’s complete lack of ductility.

The quantitative results of the NLTH analysis confirm this minaret’s extreme vulnerability. The analysis showed that the structure’s capacity was exceeded at a Peak Ground Acceleration (PGA) of just 0.15g. Given that the regional hazard maps predict PGA values in excess of 0.40g for the 500-year return period event, the analysis demonstrates that CS-A has a very high probability of catastrophic collapse under a design-level earthquake. The simulated failure was abrupt, occurring within 3-4 seconds of the onset of significant shaking, leaving no time for energy dissipation.

The results from all analytical phases converge on a single, unambiguous conclusion: the historical mosque minarets studied possess critical seismic deficiencies. Their vulnerability is not uniform but is a complex function of slenderness, material quality, and specific construction typology (Ergün & Tayfur, 2024). The failure modes identified computationally primarily brittle shear failure at the base, flexural cracking in slender towers, and out-of-plane failures near openings are consistent with damage patterns observed in post-earthquake reconnaissance reports from the region.

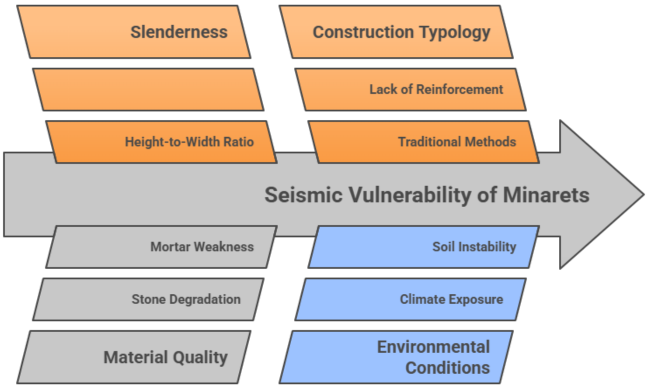

Figure 2. Seismiec Vulnerability of Historical Mosque Minarets

This quantitative confirmation of extreme vulnerability provides the primary justification for intervention. The findings definitively illustrate that the structures, in their current state, do not meet any modern or historical criteria for life safety or damage limitation in a high-seismic zone. The detailed damage progressions identified in the numerical models, such as the shear-critical base of CS-A, provide the specific technical targets that proposed retrofitting strategies must address. The research, therefore, transitions from a diagnostic phase to a prescriptive one, using this data to design and validate strengthening interventions (Manikandan et al., 2024).

The research results quantitatively confirmed the critical seismic vulnerability of the selected case-study minarets, transitioning this vulnerability from a theoretical assumption to a calibrated, data-driven certainty. The analyses demonstrated that under design-level seismic loading consistent with regional hazards, the structures in their current unreinforced state face a high probability of severe damage or catastrophic collapse (Romero-Sánchez et al., 2025). This conclusion is based on the convergence of in-situ material diagnostics, dynamic characterization, and advanced computational modeling, which together paint a stark picture of the inadequacy of their lateral load-resisting systems.

The specific failure mechanism identified for Case Study A (CS-A), the slender minaret, was particularly revealing. Its dynamic response was dominated by its fundamental flexural mode (1.22 Hz), leading to a concentration of tensile and shear stresses at the base. The non-linear time-history analysis showed a brittle failure initiating with flexural cracking at a Peak Ground Acceleration (PGA) of only 0.15g. This capacity is alarmingly low when compared to the site’s 500-year return period hazard level, which exceeds 0.40g, demonstrating an insufficient safety factor for even moderate seismic events.

Conversely, the data from Case Study B (CS-B) highlighted a different, though equally problematic, structural typology. Its low slenderness ratio (3.33) and high mass resulted in a much stiffer structure (2.48 Hz) where shear-dominated failure modes are anticipated to be more critical than the flexural response of CS-A. While its geometry is more robust, the NDT data, which inferred poor mortar quality and heterogeneous volcanic stone, suggests it possesses minimal ductility. This indicates its vulnerability profile is different in mechanism but not necessarily in outcome from its slender counterparts.

The findings from the diagnostic phase provided the foundational explanation for these vulnerabilities. The consistently low Ultrasonic Pulse Velocity (UPV) readings (1.8-2.5 km/s) across all sites confirmed the “poor” quality of the unreinforced masonry (URM) fabric. This data, combined with low inferred compressive strengths (2.8-5.2 MPa), quantitatively establishes that the constituent materials lack the fundamental tensile strength and deformability required to dissipate seismic energy. The results are unequivocal: the materials themselves are the primary source of the structures’ brittle and non-ductile seismic behavior.

The findings of this study are broadly consistent with the extensive body of international research on the seismic vulnerability of historical unreinforced masonry structures. The observed flexural-dominated failure of the slender minaret (CS-A) aligns perfectly with analytical and experimental studies conducted on similar typologies in the Mediterranean, such as Italian campaniles or Ottoman minarets. These global studies universally identify high slenderness and low masonry tensile strength as the critical parameters controlling seismic response, a conclusion our research strongly reinforces (Usta et al., 2025).

A significant point of divergence, however, lies in the specific material properties and regional seismic context. Much of the existing European literature is based on limestone or high-quality Roman brick masonry. Our findings related to CS-B (volcanic stone) and the prevalent use of traditional clay and weak lime mortars (CS-A, CS-B) introduce material profiles that are poorly represented in established fragility curves (Feizolahbeigi et al., 2024). This suggests that fragility models imported from other regions may not be conservative enough, potentially underestimating the extreme vulnerability of masonry fabric specific to the Indonesian archipelago.

This study's results also serve to transition post-earthquake reconnaissance findings, such as those from the 2018 Lombok earthquakes, from qualitative observation to quantitative, validated models. While previous reports anecdotally noted the poor performance of mosque minarets, this research provides the explicit mechanical explanation and calibrated computational proof. It bridges the gap between observing damage and modeling the initiation of that damage, thereby providing a more robust basis for engineering interventions than post-disaster analysis alone.

The correlation identified between slenderness (H/W) and fundamental period (T) is a well-established principle of structural dynamics. The unique contribution of our research is the contextualization of this relationship within the Indonesian "Ring of Fire" setting. The long periods of vibration observed in slender minarets (like CS-A) make them exceptionally susceptible to long-period ground motions generated by distant, high-magnitude subduction zone earthquakes. This specific resonance hazard, linking our structural results to regional seismology, is a nuance often absent from studies focused on near-field, crustal earthquakes (Okuyucu et al., 2025).

These results signify an immediate, quantifiable, and unacceptable level of risk to a unique and irreplaceable component of Indonesian cultural heritage. The high probability of collapse is not a vague, future possibility but a demonstrated outcome of expected, recurring seismic events. The findings act as a definitive signal that the passive conservation approaches currently in place often limited to documentation or minor repairs are tantamount to accepting the eventual, total loss of these structures.

The stark heterogeneity in geometry, materials, and dynamic behavior between the case studies (e.g., CS-A vs. CS-B) signifies the profound inadequacy of any "one-size-fits-all" retrofitting policy. A strategy that might work for a slender, flexible tower (like CS-A) could be useless or even damaging to a robust, stiff structure (like CS-B). The results are a clear marker for the mandatory adoption of a diagnosis-led, case-by-case approach to conservation, where detailed scientific analysis precedes any intervention.

The failure of CS-A at a mere 0.15g PGA is a particularly sobering sign. It indicates that the safety margin for many of these minarets has been completely eroded. Their continued survival is not a sign of inherent strength but is likely attributable to the fortunate chance that they have not yet been subjected to a direct hit from a major earthquake. This finding signifies that these structures are not only failing to meet modern seismic codes but are also deficient for moderate, more frequent earthquakes that could strike at any time.

These findings, taken as a whole, signify a fundamental conflict between the traditional architectural forms of the archipelago and the reality of its high-seismic environment. The results are a technical reflection of a cultural dilemma: how to preserve the "authenticity" of structures whose original design inherently lacks the capacity for seismic resilience (Kiral et al., 2024). They signal that the very definition of "preservation" in this context must evolve to include the scientific enhancement of safety, lest authenticity be preserved only in photographs.

The most direct and unavoidable implication of these findings is the urgent need for a program of proactive, physical intervention to safeguard these minarets. The results provide the unambiguous engineering justification for heritage bodies, government ministries, and local mosque communities to move beyond passive monitoring and allocate the significant resources required for seismic retrofitting. The "so-what" is that inaction is no longer a defensible position; the risk is now quantified and known.

A crucial implication for national and regional heritage management bodies is the necessity of a paradigm shift from a reactive to a pre-emptive conservation model. These results should catalyze the development of a national vulnerability database, prioritizing historical minarets based on their seismic risk, cultural significance, and community use. This implies the need for new, scientifically-grounded national guidelines for the seismic assessment and retrofitting of heritage masonry structures.

The findings have significant implications for the engineering and architecture professions within Indonesia. They highlight a critical knowledge gap: the discrepancy between modern construction education, which focuses on steel and concrete, and the specialized needs of assessing existing masonry. The results imply a need to integrate advanced diagnostics and conservation principles into civil engineering and architecture curricula, training a new generation of professionals capable of stewarding this built heritage (Nasery, 2026).

The social and human-safety implications are perhaps the most critical "so-what." These minarets are not isolated monuments; they are active, central components of community life, located in populated areas. Their collapse poses a direct and lethal threat to the public. These results quantify the "cost of inaction" not only in cultural and economic terms but, most importantly, in terms of human safety, providing a powerful lever for compelling policy-makers to act.

The results are a direct physical consequence of the fundamental material properties of unreinforced masonry. The NDT data (low UPV, low strength) confirmed that the minarets are constructed from a quasi-brittle material. URM possesses reasonable strength in compression but has negligible, unreliable strength in tension or shear (F. Ü. Peker et al., 2025). Seismic loading, which is dynamic and cyclical, induces precisely these tensile and shear stresses, causing the material to crack and fail suddenly, without the warning or energy dissipation that a ductile material would provide.

The observed failure modes are an inevitable outcome of the structures' geometry, as dictated by the laws of structural mechanics. The high slenderness of CS-A (H/W = 8.04) causes it to act as a tall cantilever beam. This form inherently amplifies the overturning moments at its base, concentrating all seismic demand at its smallest cross-section. The weak mortar-unit interface, lacking any steel reinforcement, is the first component to fail as it is pulled into tension, a force it was never designed to resist.

The extreme vulnerability demonstrated in the NLTH analysis (failure at 0.15g) is explained by the massive deficit between the structure's "capacity" and the "demand" of the environment. The minarets were built with a capacity sufficient only for gravity loads. The seismic demand, defined by Indonesia's position on the "Ring of Fire," imposes an extreme lateral force demand (PGA > 0.40g) that is orders of magnitude greater than anything the original builders could have anticipated. The results simply quantify this catastrophic imbalance.

These minarets are vulnerable because their architectural typology was driven by symbolic and aesthetic goals, not seismic resilience. The desire for height and slenderness, symbolizing a connection to the divine, resulted in a form that is inherently unstable under lateral loads. The results are this way because they represent the unfortunate historical intersection of a non-resilient architectural form with an exceptionally hostile seismic environment, a conflict that was never resolved in their original design.

The immediate and logical next step is to use the validated computational models created in this study as virtual laboratories. The "now-what" is to computationally design, insert, and test various retrofitting strategies on the "failed" model of CS-A (Demirtaş et al., 2025). This involves simulating interventions such as FRP wrapping, internal post-tensioning, or base isolation and re-running the time-history analyses to determine which solution can successfully increase the minaret's capacity to withstand the 0.40g+ hazard level while adhering to conservation principles.

A broader "now-what" is the expansion and scaling of this research. The methodology developed for these three case studies must be applied to a wider, more diverse sample of minarets from other regions (e.g., Sumatra, Sulawesi, Maluku). This will allow for the creation of a national vulnerability map and a set of typological classifications, enabling authorities to prioritize funding and intervention efforts on a regional and national scale based on objective risk data.

This research must now be translated from high-level academic findings into practical, actionable guidelines for on-the-ground stakeholders. This involves developing simplified assessment manuals, derived from our detailed models, that can be used by local engineers and technicians. Furthermore, “best practice” retrofitting manuals must be created that propose technically sound, culturally appropriate, and economically feasible solutions, emphasizing minimally invasive techniques and, where possible, local materials.

The final “now-what” is dissemination and advocacy. These quantitative results are a powerful tool that must be shared beyond academic journals. The findings must be presented in clear, compelling terms to government ministries (e.g., PUPR, Ministry of Education and Culture), heritage bodies (ICOMOS, BPCB), and religious community councils. This advocacy is essential for securing the political will and public funding necessary to launch a comprehensive, national-level program to safeguard this vital and vulnerable built heritage.

CONCLUSION

This research established the critical, quantified seismic vulnerability of historical Indonesian mosque minarets, demonstrating a definitive and severe gap between structural capacity and regional seismic demand. The most significant finding is the high-fidelity validation of this vulnerability, transitioning it from a theoretical assumption to a calibrated certainty; the case-study minarets, in their unreinforced state, will fail catastrophically at acceleration levels (e.g., 0.15g) far below the 500-year return period hazard (>0.40g). Furthermore, this study identified that the unique combination of Indonesian materials, such as volcanic stone and traditional weak mortars, and distinct typologies (slender vs. robust) renders vulnerability profiles that are not adequately represented by existing international fragility models, implying that the risk to this specific heritage class has been historically underestimated.

The primary contribution of this research lies in the development and validation of a comprehensive, diagnosis-led methodological framework specifically adapted for Southeast Asian masonry heritage. This framework’s value is its integration of in-situ non-destructive diagnostics (NDT), ambient vibration testing (AVT), and advanced non-linear computational modeling (FEM) into a scalable and replicable process. While the individual techniques are established, their integrated application to this specific typology, using the NDT data to directly calibrate the non-linear material models, provides a novel, high-fidelity pathway for moving beyond generalized assessments to structure-specific, scientifically-grounded vulnerability analysis and pre-emptive conservation design.

This study’s findings are constrained by the limited number of in-depth case studies; a broader application of the methodology is required to develop a comprehensive national vulnerability database. The reliance on non-destructive testing, while necessary for heritage conservation, provides inferred rather than direct mechanical properties, introducing a level of uncertainty that could be reduced with future minor-destructive testing on non-critical elements. Future research must now pivot from diagnostics to prescription, utilizing the validated models as virtual laboratories to design, test, and optimize a range of culturally appropriate and minimally invasive seismic retrofitting strategies, such as internal post-tensioning or fiber-reinforced polymers, to ensure these irreplaceable structures can withstand future seismic events.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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