World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Research Article)

Systemic seismic vulnerabilities: Key construction failures and mitigation strategies

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World Journal of Advanced Engineering Technology and Sciences, 2025, 17(03), 121–128

Publication history: Received 30October 2025; revised on 06 December 2025; accepted on 09 December 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.17.3.1542

Abstract

This paper presents an analytical examination of pervasive construction malpractices systematically observed in highly seismic zones, with a particular focus on case studies from Turkey, where recurrent major earthquake events have critically exposed widespread systemic deficiencies in structural design, detailing, and material selection. Photographic evidence, referenced herein as illustrative placeholders, highlights six primary categories of critical failure: non-engineered roof systems, unbraced masonry infill partitions, brittle beam-column connections, discontinuity in lateral bracing load paths, inadequate geotechnical treatment for liquefaction mitigation, and insufficient seismic separation between adjacent structures. For each identified malpractice, a corresponding set of robust, engineering-based solutions is rigorously proposed. These mitigation strategies advocate for the adoption of modern structural systems, including Cold-Formed Steel (CFS) framing, three-dimensional (3D) structural panels, geotechnical soil stabilization techniques, and strict adherence to contemporary, performance-based seismic design codes. The overarching objective is to furnish a comprehensive and practical reference framework for significantly enhancing the structural resilience and overall seismic performance of the built environment in earthquake-prone areas.

Keywords: Seismic Malpractice; Structural Resilience; Cold-Formed Steel (CFS); 3d Panels; Liquefaction Mitigation; Seismic Pounding; Performance-Based Design

1. Introduction

Earthquakes continue to represent one of the most consequential natural hazards to life safety and the integrity of structural and infrastructural systems worldwide. In regions characterized by high seismic activity—such as the extensive fault zones across Turkey—recurrent large-magnitude events have repeatedly revealed systemic weaknesses within the existing building stock. Despite the presence of codified seismic design standards, their inconsistent enforcement or deliberate neglect, combined with the persistent use of traditional construction practices that fail to meet contemporary seismic performance requirements, has resulted in catastrophic structural collapses and widespread human and economic loss. This study systematically identifies and categorizes six prevalent forms of construction malpractice observed through post-earthquake reconnaissance in seismically active regions. For each identified deficiency, the paper proposes practical, evidence-based engineering interventions aimed at enhancing seismic resilience, improving structural performance, and mitigating earthquake-induced damage. Effective earthquake-resistant design necessitates not only the selection of materials with adequate mechanical strength but also the implementation of precise engineering detailing, uninterrupted load transfer mechanisms, sufficient ductility, and strict adherence to performance-based design principles outlined in modern seismic codes. The following sections present detailed case analyses of the documented malpractices alongside technically grounded mitigation strategies that collectively advance the goal of safer, more resilient built environments.

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2. Non-Engineered Roof Construction and Use of Brittle Materials

During a seismic event, roofing systems that are excessively heavy or insufficiently engineered, Fig 1, can experience a critical loss of diaphragm integrity, meaning the roof can no longer function as a stable horizontal element capable of collecting and transferring inertial forces to the primary vertical lateral force-resisting components such as shear walls or moment frames. When this integrity is compromised, the lateral load path becomes discontinuous, causing seismic forces to concentrate erratically within the structure. The problem is further amplified when roofs are constructed with high-mass materials, as the increased dead load directly magnifies the seismic inertia forces generated during ground motion. This additional demand can push supporting members and their connections beyond their deformation and strength capacities, resulting in overstress, punching, or shear-governed failures. In extreme cases, these mechanisms may initiate localized collapse that can propagate into a progressive collapse scenario, particularly when connection detailing is inadequate or brittle. Moreover, the brittle nature of many heavy traditional roofing materials means that once failure begins, large fragments can detach suddenly, creating a severe life-safety hazard for occupants and bystanders due to falling debris and uncontrolled structural disintegration.

To address these vulnerabilities, modern seismic engineering emphasizes the use of lightweight, ductile, and fully engineered roofing systems designed to maintain diaphragm continuity even under strong cyclic loading. Cold-formed steel (CFS), Fig 2a, roof systems offer substantial advantages, as their low mass reduces seismic demand while their ductility enhances energy dissipation and deformation capacity. These systems also rely on rigorously designed and tested connection details, ensuring a consistent, traceable load path from the diaphragm into the building's vertical resisting elements. Similarly, 3D structural panels, Fig 2b, consisting of welded steel reinforcement meshes surrounding an expanded polystyrene core, provide a high stiffness-to-weight ratio and superior energy absorption characteristics. Their integrated configuration allows them to perform effectively as both a diaphragm element and a lightweight mass-reduction solution. By adopting such engineered systems, the building experiences smaller inertia forces, more reliable force transfer, and significantly improved seismic safety and resilience.

Figure 1 Illustration of non-engineered, heavy roof construction vulnerable to seismic forces

Figure 2 Schematic of a proposed lightweight, engineered CFS (a) or 3D panel roof system (b)

3. Unbraced Masonry Infill Partitions

Unbraced masonry infill partitions made from unreinforced brick or concrete block, Fig 3, present a major seismic vulnerability when installed within reinforced concrete frames without proper anchorage or lateral bracing, as their inherently brittle behavior renders them unable to accommodate the in-plane drift and out-of-plane accelerations generated during strong ground shaking; while the primary RC frame may survive the event, these infills are highly susceptible to sudden out-of-plane collapse, creating a direct and severe life-safety hazard from falling debris. Their failure can also severely disrupt building functionality by blocking egress paths, damaging internal spaces, and complicating emergency response and post-earthquake recovery efforts. Additionally, when infills unintentionally contribute significant stiffness to the frame—especially when irregularly distributed—they can trigger dangerous interactions such as the short-column effect, leading to concentrated shear demands and potential damage in the structural members themselves. To mitigate these risks, modern seismic practice emphasizes replacing brittle infills with engineered, ductile wall systems such as 3D structural panels—capable of acting as either sacrificial elements or fully functional shear walls to improve energy dissipation—or cold-formed steel (CFS) partition walls, Fig 4, which provide lightweight, ductile, and well-braced configurations compatible with seismic deformation demands. Where the use of infills or engineered panels is unavoidable, proper anchorage detailing becomes essential, as shear connectors must be integrated to ensure composite action between the wall and surrounding RC frame, preventing dangerous out-of-plane detachment and ensuring that any damage follows a predictable, controlled, and non-life-threatening mechanism consistent with seismic design objectives.

Figure 3 Post-earthquake failure illustrating the collapse of unbraced brick partitions

Figure 4 Detailed drawing illustrating proper shear connectors anchoring walls to RC frame

4. Brittle Beam–Column Connections and Floor Diaphragm Discontinuity in Steel Structures

In steel moment-resisting and braced-frame systems, one of the most critical seismic vulnerabilities stems from poorly designed or improperly detailed beam–column connections, where inadequate weld toughness, insufficient panel-zone stiffness, weak bolt anchorage, or flawed weld-access-hole geometry can trigger brittle fracture at the connection zone, especially within heat-affected zones (HAZ) gravity and lateral load transfer. Compounding this problem, discontinuities within the floor-diaphragm system—whether caused by incomplete attachment of metal decking, improperly installed composite slabs, missing collectors, or poorly connected bracing elements—, Fig 5, significantly, reduce diaphragm integrity and stiffness, undermining its ability to channel inertial forces into the primary lateral-resisting frames and thereby increasing the risk of story-level instability. The consequences of these deficiencies are severe: brittle fracture can instantly sever the moment, shear, or axial load path between members; weak or undersized panel zones may deform excessively and concentrate drift demands, fostering dangerous soft-story mechanisms; and the failure of even a single critical connection can cause abrupt force redistribution, potentially initiating systemic progressive collapse. To address these issues, modern seismic design requires rigorous performance-based connection detailing in accordance with standards such as AISC 341, FEMA 350/352, Eurocode 3, or national steel seismic provisions, including the use of complete-joint-penetration welds with notch-tough materials and controlled welding procedures to prevent HAZ fracture, Fig 6, the installation of pre-tensioned high-strength bolts arranged to fully develop shear and moment capacity without slip, and the enforcement of full diaphragm continuity through proper attachment of decking, shear studs, chords, and collectors to ensure a robust and uninterrupted lateral load-transfer system.

Figure 5 Photographic evidence of weak steel beam–column connection and associated diaphragm separation

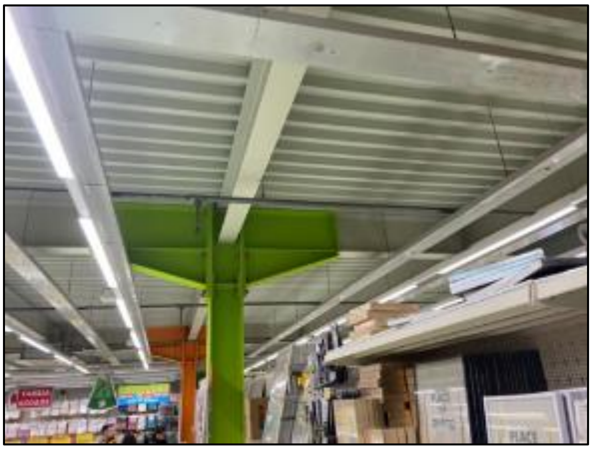

Figure 6 Schematic illustration of a ductile steel beam–column moment connection with adequate weld detailing, stiffened panel zone, and diaphragm anchorage

5. Discontinuity in the Lateral Bracing Load Path

A continuous, direct, and fully traceable lateral-load path is fundamental to the performance of any seismic lateral-force–resisting system, yet a frequent and serious deficiency occurs when the horizontal diaphragms—whether roof decks, concrete slabs, or metal floor systems—are not properly connected to the vertical resisting elements such as shear walls, braced frames, or moment frames ,Fig 7, resulting in a discontinuity that prevents seismic inertia forces from being reliably transferred into the primary structural system. When these diaphragm-to-brace interfaces are inadequately detailed, omitted, or improperly anchored, the load path becomes fractured, forcing lateral forces to accumulate at unintended locations and creating stress concentrations that exceed the capacity of local elements. Such discontinuities also diminish the global lateral stiffness of the building, leading to increased interstudy drift, heightened nonstructural damage risk, and greater vulnerability to functional disruption after an earthquake. In extreme cases, concentrated forces at weak or incomplete connections can induce brittle local failures before the global frame or wall system engages, undermining the intended seismic performance of the structure. To address these issues, modern seismic practice demands continuous and intentionally detailed bracing connections, beginning with properly designed gusset plates in steel structures that can fully transmit axial and shear forces between bracing members and diaphragm boundary elements. Roof and floor diaphragms must be positively anchored to vertical resisting systems through welded angles, shear studs, collectors, drag struts, or other engineered components that ensure uninterrupted force transfer, Fig 8. Finally, analytical verification using contemporary structural analysis tools is essential to confirm that all segments of the load path—from diaphragm shear to collector demands and brace connection strength—meet the of the design-basis earthquake and provide reliable, code-compliant seismic performance.

Figure 7 Photo illustrating missing or insufficient connections between horizontal diaphragms and vertical bracing elements

Figure 8 Photo demonstrating a properly detailed gusset plate connection ensuring a continuous lateral-load path

6. Inadequate Geotechnical Mitigation for Liquefaction Susceptibility

Buildings constructed on loose, saturated granular soils without adequate geotechnical investigation or soil improvement are highly vulnerable to liquefaction, a seismic phenomenon in which cyclic shaking drastically reduces soil shear strength, effectively transforming the supporting ground into a fluid-like mass; this malpractice is especially widespread in rapidly developing coastal and riverine regions where foundation work is often rushed or undervalued. When liquefaction occurs, the resulting loss of bearing capacity can produce severe differential settlement across the foundation, causing buildings to tilt, distort, or suffer major structural misalignment, while more abrupt loss of support beneath isolated footings may trigger punching shear failure in foundation elements. In lighter structures or those supported on shallow pads, the reduction in soil resistance can even induce gross instability, partial overturning, or upward flotation as buoyant forces exceed the weakened soil capacity, Fig 9. To prevent such failures, modern geotechnical engineering requires implementing advanced soil-stabilization measures that enhance strength, stiffness, and drainage characteristics prior to construction. Densification techniques such as vibro-compaction, dynamic compaction, or rapid impact compaction can significantly increase relative density and improve liquefaction resistance; alternatively, installing stone columns or using deep soil-mixing methods strengthens the soil matrix and accelerates dissipation of pore water pressures. When surface improvements are insufficient, deep foundations such as piles or caissons can bypass the liquefiable zone entirely, transferring loads to competent strata at greater depths. Complementing these methods, engineered drainage systems can lower groundwater levels and provide controlled dissipation of pore pressure during seismic events, collectively forming a comprehensive mitigation strategy against liquefaction-induced damage.

Figure 9 Building collapses caused by soil liquefaction during the February 2023 Kahraman Maras, Turkeyearthquake.[13]

7. Insufficient Seismic Separation Between Adjacent Buildings

In densely built urban areas, a frequent and critical oversight in seismic design is the failure to provide adequate separation gaps between adjacent buildings, particularly when structures differ significantly in height, floor elevation, stiffness, or mass, creating conditions for structural contact during strong ground shaking. When gaps are insufficient, Fig 10, neighboring buildings can collide—a phenomenon known as “pounding”—which generates high localized impact forces that often cause severe damage to columns, beams, and other structural elements at the points of contact. This pounding effect can not only result in localized partial collapse but also amplify vibrations in the impacted buildings, exacerbating structural distress and potentially initiating progressive damage in otherwise sound elements. To prevent such outcomes, modern seismic design requires precise evaluation of the dynamic interaction between adjacent structures, especially in constrained urban sites, using comprehensive nonlinear dynamic analyses that account for inelastic deformation and potential relative motion. The minimum seismic separation is typically determined based on the design displacements of both buildings, often calculated using the square-root-of-sum-of-squares (SRSS) method as specified in ASCE 7-22. Where physical separation is limited, the implementation of engineered seismic joints becomes essential; these joints, filled with highly compressible and non-structural materials, accommodate relative displacements without transferring damaging forces between structures. Proper detailing, maintenance, and verification of these joints ensure continuous safety, allowing adjacent buildings to move independently during seismic events while minimizing the risk of pounding, structural amplification, and localized collapse, thus preserving both life safety and functional integrity in densely built environments.

Figure 10 Visual evidence of inadequate seismic gap between two adjacent, dissimilar structures

8. Conclusion

The recurring structural failures documented in highly seismic regions, particularly those within Turkey, underscore a critical and urgent need for an aggressive shift toward rigorously enforced, modern engineering practices. The systemic malpractices identified—ranging from non-engineered roof systems and brittle components to profound omissions in geotechnical and site detailing—stem overwhelmingly from inadequate design, deficient detailing, and the perilous reliance on traditional materials and construction methods incompatible with contemporary seismic demands.

The systematic implementation of modern, performance-driven mitigation strategies—including the adoption of lightweight, ductile structural systems (CFS, 3D panels), meticulous detailing of beam-column joints to enforce the strong column weak beam philosophy, ensuring continuity in the lateral load path, aggressive soil stabilization for liquefaction, and strict adherence to code-mandated seismic separation—is essential. By integrating these robust engineering solutions, the risk of catastrophic structural failure and the associated loss of life in earthquake-prone areas can be drastically reduced, moving the focus from disaster response to true structural resilience.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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